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INVESTIGATION OF THE GEOTHERMAL POTENTIAL OF THE UK: A PRELIMINARY ASSESSMENT

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Preface

The era of cheap energy ended in 1973, and since then, increasing attention has been given to the search for sources alternative to fossil fuels and nuclear energy. Of the possible substitutes, only geothermal resources are currently making a significant contribution to the world's energy needs. Although first impressions may be that the United Kingdom is not favourably placed for such resources, the geothermal gradient is high enough for groundwaters to have temperatures that are suitable for space heating — 60°C or more — at depths of about 2 to 3 km. Active geothermal fields exist near Paris where geological conditions are similar to those in the United Kingdom. As a consequence, a programme designed to make a preliminary assessment of the potential for geothermal energy in the United Kingdom was carried out by the Institute of Geological Sciences in the three-year period 1977 to 1979. It was funded jointly by the Department of Energy and the Commission of the European Community.

The initial stage of the programme was the compilation of a 'Catalogue of geothermal data for the land area of the U.K.' by Dr A. J. Burley and Dr W. M. Edmunds. This summarised and reviewed historical data covering subsurface temperatures and relevant hydrochemical data and was published by the Department of Energy in 1978. The subsequent programme was a coordinated investigation by a team of geologists, geophysicists, hydrogeologists and hydrochemists, the objectives being to relate the deep structure of Britain to the occurrence and circulation of fluids in deep, permeable rocks and also to identify, if possible, the likely presence of hot dry rock at relatively shallow depths. This report summarises the findings of the programme; it has been edited by Dr R. A. Downing.

The studies were conducted by staff of the Geophysics and Hydrogeology Division under the general supervision of the Assistant Director, Mr D. A. Gray, with team members drawn from both the Applied Geophysics Unit (AGU) and the Hydrogeology Unit (HY). The main part of the programme has been the responsibility of Dr A. J. Burley (AGU), Dr W. M. Edmunds (HY), W. G. Burgess (HY), M. K. Lee (AGU) and I. F. Smith (AGU), but major contributions in particular areas have been made by E. M. Andrew (AGU), M. J. Arthur (AGU), J. R. P. Bennett (HY, Northern Ireland), R. M. Carruthers (AGU), Dr R. A. Downing (HY/AGU) and M. T. Houghton (AGU). Numerous members of the Field Survey Divisions also provided geological assistance, particularly Dr E. C. Freshney for the Wessex Basin. Dr J. N. Andrews, of the University of Bath, contributed to the studies of the thermal waters of the Bath—Bristol Basin and the Cornish granite.

A significant part of the programme involved the collection and collation of data that existed in many diverse forms. In the course of this, considerable information and assistance was readily given by many individuals, university departments and commercial companies too numerous to identify separately. Grateful thanks are extended to all for this active cooperation.

The conclusions of the report on the occurrence of geothermal resources in the United Kingdom are sufficiently encouraging to merit further investigation. To prove these conclusions will require a drilling programme to confirm that low enthalpy heat can be developed economically. Also, the completion of the investigation of the potential for hot dry rock will necessitate some heat flow studies in exposed granites which have abnormally high heat production owing to their content of radiogenic minerals.

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15 January 1980

Summary

Geologically, Britain is an extremely stable area without active volcanism. In this situation the development of geothermal resources depends upon the occurrence of permeable rocks in deep sedimentary basins or the successful development of the hot dry rock concept.

The average geothermal gradient is about $25^{\circ}\text{C}/\text{km}$, but two belts of above average heat flow extend across northern and south-western England. In these areas the gradient can be $30^{\circ}\text{C}/\text{km}$ or more.

The principal aquifers occur in the Mesozoic and the greatest geothermal potential is in sandstones of the Permo-Triassic where their occurrence at depth coincides with the high heat flow belts. This situation exists in several major Mesozoic basins, including the East Lincolnshire, the Wessex, the Cheshire, the West Lancashire and the Carlisle basins and also the basins in Northern Ireland.

Currently, the Northern Ireland and Cheshire basins offer the best prospects of developing geothermal resources as the Permo-Triassic sequence has been proved at appropriate depths and thicknesses. Prospects in the southern part of the Wessex Basin are also good. In Lincolnshire, the only post-Carboniferous aquifer at depths where temperatures may be expected to exceed 60°C is the Lower Permian. Although it is relatively thin, the permeability may be high. Prospects are also encouraging but less certain in the West Lancashire and Carlisle basins.

In rocks older than the Mesozoic, sandstones in the Carboniferous and Devonian are the most likely source rocks. The principal surface manifestations of geothermal activity in the UK are in Carboniferous rocks at Bath and Bristol, where the relatively high temperatures are caused by the deep circulation of meteoric waters.

The best prospects for the application of the hot dry rock concept appear to be in Caledonian and Hercynian granites that have high radioactive heat productions. On the basis of geochemical and geophysical characteristics, the Cairngorm, Etive, Loch Doon and Fleet granites in Scotland, the Cheviot and Lake District granites in northern England and the Newry granite in Northern Ireland may have some potential for hot dry rock development.

Du point de vue géologique, la Grande-Bretagne est une région extrêmement stable, sans volcanisme actif. Dans ce contexte, la mise en valeur des ressources géothermiques est tributaire de la présence de roches perméables dans des bassins sédimentaires profonds ou du succès de développement du concept de la roche sèche chaude.

Le gradient géothermique moyen est d'environ $25^{\circ}\text{C}/\text{km}$, mais deux zones de température

supérieure à la moyenne s'étendent dans le nord et le sud-ouest de l'Angleterre. Dans ces régions, le gradient peut s'élever à $30^{\circ}\text{C}/\text{km}$ ou plus.

Les principaux aquifères se présentent dans le Mésozoïque et le potentiel géothermique est à son maximum dans les grès du Permo-Triasique dont la présence en profondeur coïncide avec les zones de haute intensité thermique. Cette situation existe dans plusieurs grands bassins du Mésozoïque, notamment ceux de l'est du Lincolnshire, du Wessex, du Cheshire, de l'ouest du Lancashire et de Carlisle, ainsi que dans les bassins d'Irlande du Nord.

A l'heure actuelle, ce sont les bassins d'Irlande du Nord et du Cheshire qui présentent les meilleures possibilités de développement des ressources géothermiques car la séquence du Permo-Triasique y est prouvée aux profondeurs et puissances appropriées. Les Perspectives sont également favorables dans la partie sud du bassin du Wessex. Dans le Lincolnshire, le seul aquifère postérieur à la période Carbonifère à des profondeurs où les températures pourraient vraisemblablement dépasser 60°C est le Permien Inférieur. Bien que relativement mince, la perméabilité pourrait être élevée. Les perspectives sont également encourageantes, mais moins certaines dans les bassins de l'ouest du Lancashire et de Carlisle.

En ce qui concerne les roches antérieures au Mésozoïque, les grès du Carbonifère et Dévonien sont les roches-mères les plus probables. Les principales manifestations en surface d'activité géothermique au Royaume-Uni surviennent dans les roches du Carbonifère à Bath et à Bristol, où les températures relativement élevées sont causées par la circulation en profondeur d'eaux météoriques.

Quant à l'application du concept de la roche sèche chaude, ce sont les granites du Calédonien et du Hercynien, à production élevée de chaleur de radioactivité, qui offrent les meilleures perspectives. D'après leurs caractéristiques géochimiques et géophysiques, les granites de Cairngorm, Etive, Loch Doon et Fleet, en Ecosse, les granites de Cheviot et du Lake District, dans le nord de l'Angleterre et le granite de Newry en Irlande du Nord pourraient offrir des possibilités à cet égard.

CHAPTER 1. INTRODUCTION

Geologically, Britain is an extremely stable area. It is remote from active plate margins and the last period of igneous activity was some 40 to 70 million years ago during the Tertiary. Crystalline bodies emplaced at that time have long since cooled to equilibrium temperatures. Visible manifestations of geothermal activity are restricted to a few thermal springs of which the best known are at Bath and Bristol in Avon and at Buxton and Matlock in Derbyshire (Plate 1). Hot waters are also encountered in metalliferous mines in Cornwall. All these waters are generally considered to be meteoric waters that have been heated by circulation to significant depths below the surface. While the source of heat for the Cornish mine-waters may have been equivocal, studies carried out during the course of the work programme described in Chapter 11, suggest that they are also meteoric waters.

In such a stable environment as Britain, exploration for geothermal resources must concentrate on seeking permeable rocks in deep sedimentary basins where the geothermal gradient ensures that water is at a high enough temperature to make development economic. The deep Mesozoic basins that originated at the close of the Hercynian earth-movements (Fig. 1.1) readily spring to mind as regions that may have geothermal potential and much of the work to date has concentrated on these structures.

The average heat flow from the earth's continental areas is about 60 mW/m^2 . In England there are believed to be two belts where values are above this (Fig. 1.2): one is aligned north-west to south-east across northern England and into Northern Ireland and the other lies across southern England (Oxburgh and others, 1978; Richardson and Oxburgh, 1979; Cermak and Rybach, 1979). Heat flows in these belts may be significantly greater than the mean and in Cornwall values are consistently greater than 125 mW/m^2 . One of these belts of above average heat flow intersects the southern part of the East Yorkshire and Lincolnshire Basin and Northern Ireland, and the other intersects the Wessex Basin. In addition the West Lancashire Basin may lie within the belt that crosses northern England. Regions that are particularly favourable for exploratory studies are where permeable sediments occur at depth within the high heat flow belts, for example the Lincolnshire and Hampshire coastal zones and Northern Ireland.

Heat flow measurements are required at more sites before the existence and the boundaries of the heat flow belts are confirmed. If they do exist the cause could be (Richardson and Oxburgh, 1979) zones of the crust that are enriched in radiogenic heat production to a depth of about 15 km, the enrichment being introduced into the crust by

granitic magmas.

In Mesozoic basins where high heat flow is believed to occur, the mean geothermal gradient to at least 2 km is 30°C/km or more. This leads to temperatures of 70°C at 2 km and possibly 100°C at 3 km, well within the capability of modern drilling rigs.

In addition to a high temperature at depth, the rocks must be sufficiently permeable to yield hot water by which means the thermal energy is brought to the surface. In this respect the most important potential thermal reservoirs in the Mesozoic sedimentary basins are the sandstone units that occur in the Permian and at the base of the Triassic. Unfortunately in several areas the base of the sandstones attain maximum depths where the temperature is only 55 to 60°C , which is close to the currently accepted limit for development for space heating. This is the case, for example, in the Worcester Basin and the East Yorkshire and Lincolnshire Basin.

Only limited attention has been given in the present programme to the geothermal potential of rocks older than the Permian but below many of the Mesozoic basins permeable rocks are known to exist in the Upper Coal Measures, the Namurian and the Devonian. Favourable structures are also known in Palaeozoic rocks outside the region where Permian and Mesozoic rocks are found but these remain to be studied in detail.

The only pre-Permian basin investigated comprehensively is the Bath-Bristol Carboniferous Basin (Fig. 1.1), of which the structure is an important contributory factor to the presence of thermal springs at Bath and Bristol. The Carboniferous Limestone is believed to be the key geological formation allowing deep circulation of meteoric water and this is likely to be the case with other thermal springs associated with this formation in south Wales and Derbyshire.

Emphasis has been placed upon the need for a geothermal resource to have a temperature in excess of 55 to 60°C for use in space heating. This would not be the case, however, if heat pumps could be incorporated in the system. The design of heat pumps has improved considerably in recent years, so much so that waters with temperatures as low as 20°C may in the not too distant future be used as energy sources. This would mean that aquifers in the U.K. lying at depths greater than 500 m would contain water with a geothermal potential. Many deposits meet this requirement and some are referred to in later chapters, but the aquifers with greatest potential are again the Permo-Triassic sandstones because of their particularly favourable hydraulic properties.

In addition to the potential source of geothermal energy in waters in deep sedimentary basins, it may also be possible to obtain energy by circulating water through an artificially created fracture system in impermeable rocks lying at

Figure 1.1 Sedimentary basins and principal igneous intrusions in the United Kingdom

Figure 1.2 Heat flow measurements for the U.K

sufficient depth for temperatures to be at least 150 to 200°C. Field trials of the feasibility of this concept are being carried out in the USA by the Los Alamos Scientific Laboratory. Preliminary studies of methods of artificially fracturing rocks at depth have been made by the Camborne School of Mines in the Cornubian granite, a crystalline mass that has a high heat flow. Very little is known about the heat flow from most other crystalline intrusions but investigations into this aspect (Chapter 10) have led to the conclusion that the best prospects are those Caledonian and Hercynian granites (Fig. 1.1) which have a high content of radioactive minerals which provide abnormally high heat production, particularly where the temperatures are enhanced by the insulating effects of a low conductivity sedimentary cover.

The groundwaters in sedimentary basins that may have potential for geothermal development are invariably brines. The water would not flow naturally from wells, and pumps would be required capable of operating at relatively high temperatures. The chemical nature of the brines introduces problems because of their corrosive character and tendency for salts to precipitate, both in the well and in pipes at the surface, as temperatures and pressures are reduced. Consideration would have to be given to the means of overcoming such problems when designing a geothermal development project. Because of the nature of the water, its disposal after use must not have deleterious effects on the environment. Therefore, in areas away from the coast it would be necessary to reinject it into the ground through injection wells. The development problems mentioned in this paragraph have been overcome successfully overseas where geothermal energy is being developed.

The data base used in the study is extensive. The basic geological information was derived from the geological memoirs and maps, published by the Institute of Geological Sciences. The Institute has also prepared Bouguer Gravity Anomaly Maps of the U.K., many of which have been published. Extensive seismic surveys have been made, mainly in the course of oil exploration, in the East Yorkshire and Lincolnshire, the Cheshire and the Wessex basins. Some surveys have also been made in the West Lancashire, Worcester and Carlisle basins but only very limited surveys have been made in the Midland Valley of Scotland and Northern Ireland.

Many deep boreholes (i.e. drilled to depths of more than 1500 m) exist in the East Yorkshire and Lincolnshire Basin but in the remaining Mesozoic basins the numbers are much more limited and do not exceed ten in any individual basin. Because of this the information about the hydrogeology and aquifer properties of potential geothermal reservoirs is limited in the deeper

parts of the Mesozoic basins, although the extensive off-shore exploration programmes in the North Sea and Irish Sea have provided valuable indications of the nature of the rocks at depth.

The available temperature data have been summarised in a 'Catalogue of geothermal data for the land area of the U.K.' (Burley and Edmunds, 1978) and heat flows have been calculated at some 80 sites (Richardson and Oxburgh, 1979). Much of the information about the deep geology of Britain, including thermal data, has become available as a result of oil and coal exploration programmes, and the results have been interpreted in the regional context.

The structure of the Mesozoic basins has been derived primarily from information provided by deep boreholes and an interpretation of reflection seismic data where available. However, it is only in the East Yorkshire and Lincolnshire Basin, where a large number of boreholes penetrate to the base of the Permo-Triassic and where there are extensive seismic data, that the structure is relatively well known. In the Wessex Basin there are few deep boreholes (apart from those in a small area around the Dorset oil field); although there is good seismic coverage it is of little use in determining the structure beneath the Jurassic, as reflections below this horizon are weak and discontinuous. Accordingly, the postulated structure of the Permo-Triassic is based on indirect geological and gravity evidence for the positions of major faults which probably controlled deposition in the area. This is not a problem in the Cheshire basin, where seismic data together with the information from two deep boreholes provide good evidence of the post-Carboniferous structure, which is supported by an interpretation of the gravity data. The deep structure of the Midland Valley of Scotland is not well understood and knowledge of it is based largely on surface geological data together with gravity data and the results of a north-south refraction seismic profile. The shapes of the Mesozoic basins beneath the cover of Tertiary basalt in Northern Ireland have been derived mainly from gravity data.

In view of the present interest in on-shore oil exploration in the U.K., it is likely that further deep boreholes will be drilled in major Mesozoic basins within the next few years and this will substantially improve our understanding of their structure.

In the U.K. studies are at the stage of assessing the resource and the following chapters in this report summarise the current knowledge about the geothermal potential. They give the results of a programme that was concerned with interpreting geological and geophysical data to elucidate the deep structure of selected areas of Britain. This has been related to hydraulic properties of the most favoured aquifers and to the chemical composition of their pore fluids with the overall objective of indicating the potential for geothermal development in the areas selected for investigation.

CHAPTER 2. EAST YORKSHIRE AND LINCOLNSHIRE BASIN

Introduction

The East Yorkshire and Lincolnshire Basin (Fig. 2.1) is the on-shore extension of the Southern North Sea Basin. The structure is of post-Hercynian age and contains a sequence ranging from the Permian to the Cretaceous. Along the east Yorkshire coast the base of the Permian has been depressed to depths of more than 2 km.

About 150 deep boreholes have been drilled in the basin principally by oil companies and the National Coal Board. Seismic reflection surveys have been conducted throughout the area and much of the data have been interpreted by Allsop and Savage (1978) who used parameters determined in boreholes as controls when tracing seismic reflectors. However, these surveys have been specifically directed at discrete hydrocarbon traps and they do not alter substantially the structural pattern based upon information provided by boreholes.

The hydrogeology of the main aquifers in the Mesozoic sequence is relatively well known in the outcrop areas and as far down-gradient as potable waters exist. At greater depths knowledge is much more limited but some information is available from oil exploration boreholes and also by interpreting data from off-shore wells in the Southern North Sea Basin.

Geology

The post-Carboniferous sequence in the basin is given in Table 2.1 and the geology is shown in Plate 1. The principal aquifers are the sandstones and limestones of the Permo-Triassic, the Lincolnshire Limestone, the Corallian (in Yorkshire), the Lower Cretaceous Spilsby Sandstone (in Lincolnshire), and the Chalk.

The structural development of the basin has had considerable bearing on the lithology of the Jurassic and Lower Cretaceous, but in general terms the regional structure is relatively simple with only minor folds modifying the general easterly dip. The Permian rests on an eroded Carboniferous sequence and is, in turn, overlain by the Triassic which overlaps in the south onto the London-Brabant Massif (Fig. 2.2). During the Triassic there were connections in the south with the basins of western England and also, via Worcestershire, with the Wessex Basin.

A major change occurred in the Lower Jurassic with the development of the Market Weighton Block (Fig. 2.2). This slowly subsiding region separated a stable shelf area in Lincolnshire from a subsidence area known as the Cleveland Basin, and it had considerable influence on the lithology of the Jurassic and Lower Cretaceous. The principal effect of this structure on the hydrogeology is that the Corallian is represented by grits and oolitic

Table 2.1. Geological sequence in the East Yorkshire and Lincolnshire Basin

<i>Yorkshire</i>	<i>Lincolnshire</i>
QUATERNARY	
CRETACEOUS	
Chalk	Chalk
Red Chalk	Red Chalk
Carstone	Carstone
Speeton Clay	Langton Series
	Tealby Series
	Spilsby Sandstone
JURASSIC	
Kimmeridge Clay	Kimmeridge Clay
Corallian	Amphill Clay
Oxford Clay	Oxford Clay
Kellaways Rock	Kellaways Rock and Clay
Cornbrash	Cornbrash
	Great Oolite Series
	Inferior Oolite Series
	Lias
PERMO-TRIASSIC	
	Penarth Group
	Mercia Mudstone Group
	Sherwood Sandstone Group
	Upper Permian (Zechstein)
	Lower Permian

limestones in the north but by the Amphill Clay in Lincolnshire. Similarly, the Speeton Clay is the equivalent in Yorkshire of the variegated Lower Cretaceous sequence in Lincolnshire. Movements of post-Cretaceous age resulted in the inversion of the Jurassic Cleveland Basin leading to the formation of the Cleveland Anticline.

Review of the principal aquifers

Cretaceous From the point of view of providing a potable water supply, the *Chalk* is the principal aquifer in the basin. It is a soft, fine-grained white limestone which crops out over much of the basin although in the east it is overlain by Quaternary deposits. In Yorkshire it is about 400 m thick but over much of Lincolnshire erosion has reduced it to about 100 m. Along the north Lincolnshire coast the base of the aquifer is about 200 m below sea level while on the Yorkshire coast, near Hornsea and Atwick (Fig. 2.1), the base is over 500 m below the surface. The temperature at the base probably exceeds 20°C in south-east Yorkshire. Along the east Yorkshire coast, where the greatest depth occurs, it is over 30°C, rather more than would be anticipated for this depth, possibly implying upward flow of water into the aquifer.

From the point of view of exploiting any warm water in the Chalk, interest would focus on the Yorkshire coast where the aquifer is confined by Quaternary deposits. Under this cover the permeability decreases rapidly away from the margin of the Quaternary and at distances greater

than 10 km values are likely to be low. Below the Quaternary the salinity of water in the Chalk increases indicating relatively stagnant flow conditions.

The Chalk is extensively used for water supply and abstraction in many areas is approaching the safe yield. However, it is not exploited where the aquifer contains water at temperatures that are of marginal interest as an energy resource, because of the relatively low permeability and brackish nature of the water. The higher temperatures are towards the base of the aquifer where the permeability would be particularly low. Although it is not impossible that a series of boreholes exploiting the basal part of the aquifer only, could develop, say, 20 l/s of water at a temperature above 20°C, continued pumping would tend to draw in overlying cooler water. On the basis of evidence currently available it must be concluded that the Chalk has no real significance as a geothermal prospect.

The Lower Cretaceous sequence contains several minor aquifers but the only one of any importance is the *Spilsby Sandstone* which is found in east Lincolnshire. Its maximum depth is 180 m along the east Lincolnshire coast and this relatively shallow depth means it is of no value as a geothermal resource.

Jurassic The complex Jurassic sequence contains a number of aquifers of which principal examples are the Corallian and the limestones and sandstones of the Great Oolite and Inferior Oolite series.

The *Corallian*, the highest major aquifer in the Jurassic, is mainly developed north of the Market Weighton Block. It comprises a series of sandstones, gritty limestones and oolitic limestones with occasional shales and mudstones. The formation crops out around the Vale of Pickering, where the thickness is 50 to 90 m.

Zones of high permeability in the Corallian are related to fissures, formed initially by weathering and subsequently enlarged by circulating groundwater. The matrix permeability is very low, typically less than 1 millidarcy (mD). The chemistry of the groundwater changes rapidly with distance from the outcrop to a sodium bicarbonate type, the zone of calcium bicarbonate waters, typical of outcrop conditions, being relatively narrow.

Although there is no information about the nature of the Corallian at depth, the impression, based on current knowledge of likely conditions in such a limestone, must be that it will have a low permeability.

The lithology of the Great Oolite and Inferior Oolite series of the Middle Jurassic is markedly different north and south of the Market Weighton Block. South of the block the major aquifer is the *Lincolnshire Limestone* which crops out along a north-south line between the Humber and

Kettering [SP 8778]. North of the Humber the equivalent horizon is the *Cave Oolite*.

The overall form of the Lincolnshire Limestone appears to be that of a large lens thinning away from the Grantham-Sleaford area, where it is 40 m thick. Of particular interest from the geothermal point of view is its thickness and depth towards the centre of the basin. In the Tetney Lock Borehole near Grimsby it is 22 m thick with the upper surface at 575 m below sea level.

The aquifer is particularly permeable where it is confined in south Lincolnshire and transmissivity values exceed 1500 Darcy-metres (Dm) and can be as high as 4000 Dm. Further north the permeability is lower but transmissivity values are in the range 450 to 1000 Dm.

The quality of water in the Lincolnshire Limestone decreases in a down-gradient direction below overlying confining strata and this happens more rapidly in north Lincolnshire than in the south, reflecting the greater permeability in the south. Near the east coast where the limestone lies at its greatest depth, and where any potential for geothermal development would exist, the water is almost certainly saline.

North of the Market Weighton Block the Middle Jurassic is represented by a deltaic sequence of sandstones, siltstones, shales and limestones which attain an overall thickness of 100 to 200 m. At the base there is a series of sandstones and ferruginous oolites, 10 to 15 m thick, known as the Dogger. From the point of view of providing potable water supplies this sequence is of no real significance but as a source of warm water from greater depths it may have some potential.

The Jurassic formations include a number of minor sandstones and ferruginous limestones which are of local value as aquifers and, although not significant in themselves, could contribute to a well drawing on the Jurassic sequence as a whole.

From the potable water supply point of view the major aquifers in the Jurassic are well recognised as the Lincolnshire Limestone and the Corallian. The remaining permeable horizons, referred to above, are of lesser significance. However, development of warm water from greater depths may require a different emphasis. Little is known about the properties of the Jurassic in the deep parts of the basin. Reasoned conjecture would suggest the limestones will be relatively impermeable and that the sandstones may be more important. Thus the Middle Jurassic as a whole, together with the Kellaways Beds at the base of the Upper Jurassic, should be regarded as a potential aquifer, the water-bearing horizons being the sandstones. If this is so the sequence north of the Market Weighton Block has more encouraging features from the point of view of geothermal development.

The base of the Middle Jurassic is over 600 m below sea level in south-east Yorkshire, north-

east Lincolnshire and below the Vale of Pickering. The maximum thickness is over 200 m but in general in the deeper parts of the basin, 50 m is more typical. There are two areas where the temperature at the base of the unit exceeds 20°C. The first is in south-east Yorkshire and east Lincolnshire and the second below the Vale of Pickering.

Triassic During the early part of the Triassic, continental, red, fluvial sandstones of the *Sherwood Sandstone Group* (which is equivalent to the *Bunter Sandstone Formation*) formed in the western part of the East Yorkshire and Lincolnshire Basin, passing laterally towards the east into argillaceous strata. Gradually arenaceous deposits extended across the entire basin. These sandstones attain a maximum thickness of more than 500 m near Hornsea and Bridlington (Fig. 2.1). Conglomerates occur in the south-west. The base of the sandstone falls gradually towards the east and lies at depths of over 900 m in Holderness and north-east Lincolnshire.

Over much of the area the porosity of the Sherwood Sandstone exceeds 20% increasing to more than 25% where the conglomerate facies occurs and also for some distance to the north. In north Yorkshire values are between 10 and 20%.

At and near the outcrop in Nottinghamshire the most common rock type is a medium to coarse grained, clean, well-graded sandstone with a permeability of 5000 to 10 000 mD. In this rock the porosity exceeds 30%. Values are lower in finer grained lithologies — sometimes as low as 1000 mD — and they may also be reduced by cementation to some 500 to 2000 mD (Lovelock 1977).

In Yorkshire, north of York, and in Cleveland there is a tendency for the sandstone to become finer grained and this is also observed in these regions with increasing depth. Generally the fine sandstones have permeability values of 200 to 300 mD, medium sandstones range up to 2000 to 3000 mD and coarse sandstones up to 10 000 to 15 000 mD — the grain size being the dominating factor controlling permeability (Lovelock 1977).

The above discussion refers to the sandstone at or near the outcrop and there is no information for areas where the sandstones may contain water with a geothermal potential. However, the Sherwood Sandstone is developed for gas in the Hewett Field which is some 25 km off the north Norfolk coast. In this field the porosity of the pay section averages 25% and the average permeability is 474 mD, although individual layers have much higher values (Cumming and Wyndham 1975).

Even allowing for the fact that the permeability of the sandstone probably declines towards the east below overlying sediments, the average

permeability is still likely to exceed 500 mD and will probably be much higher at particular horizons. Fractures provide the main channels for groundwater flow at and near the outcrop and greatly enhance the permeability. The importance of fractures is likely to decline towards the east, intergranular permeability becoming more important. If the rock should be cemented the yield of water to wells would depend upon small fractures connected to less cemented zones of higher permeability and probably of limited vertical distribution in the sequence.

Temperatures of more than 40°C are to be expected at the top of the sandstone unit below the east coast, where it is at its greatest depth.

Permian The Southern North Sea Basin and its on-shore margins in Lincolnshire and Yorkshire were the scene of a major marine transgression in *Upper Permian* times. Four carbonate-evaporite cycles are widely recognised together with a number of subsidiary cycles. The carbonate deposits in the lower three cycles are the Upper Magnesian Limestone, the Kirkham Abbey Formation and the Lower Magnesian Limestone. Sandstone deposits of continental origin formed throughout the Upper Permian at the margin of the Upper Permian Basin.

Generally, the limestones retain only very limited primary porosity although locally this has been enhanced by diagenetic changes. Porosity is primarily due to fractures which are the main channels of fluid movement. This type of porosity is very variable and difficult to predict but values of up to 20% have been recorded where the rock is highly fractured. However, intergranular, vuggy and fracture porosities are commonly plugged at depth by evaporites.

The earliest sediments of Permian age are the Yellow Sands and Basal Breccia of the *Lower Permian* which rest unconformably on the Carboniferous. Contours on the base of these deposits, shown in Fig. 2.3, indicate they attain depths of more than 1800 m in the coastal zone. The Lower Permian displays considerable variations in thickness but in general thickens towards the east and is better developed and more persistent under south-east Yorkshire, Humberside and Lincolnshire. However, it is only in east Lincolnshire that the thickness exceeds 30 m (Fig. 2.4).

The Lower Permian sediments are mainly poorly cemented dune sands although some are probably of fluvial origin. The porosity, deduced mainly from geophysical logs, is between 20 and 25% in Lincolnshire, where the deposit is thickest. Maximum values of between 25 and 30% occur in Yorkshire but there the thickness is only 10 to 15 m. There is an inverse relationship between porosity and depth.

As already mentioned, much of the Lower

Permian sandstones is of aeolian origin and is, therefore, likely to be "clean" sands. Such deposits form good reservoirs and the high porosity values support this view. Although the permeability of the deposit is not known, its nature and porosity implies high values, probably at least several hundred millidarcies and much higher in some zones. Unfortunately, the thickness is limited and the overall transmissivity may be only 10 Dm where the thickness is 30 m. However, it should be appreciated when assessing the value of the Lower Permian reservoir for water production, that where the porosity exceeds 20%, as it can do where maximum thicknesses are attained, the average permeability could be as high as 1000 mD which would give a transmissivity of 30 Dm, if the aquifer is 30 m thick (as it is, for example, below Grimsby).

Temperatures can be expected to exceed 50°C in the Permian limestones along the Holderness and Lincolnshire coastal areas. In south-east Yorkshire and north-east Lincolnshire the temperature at the base of the Lower Permian Sands and Basal Breccia exceeds 60°C and locally is probably more than 70°C (Fig. 2.4).

Assessment of the geothermal potential

The southern part of the East Yorkshire and Lincolnshire Basin is an area of high heat flow (Richardson and Oxburgh, 1979). It lies within a north-west to south-east belt across northern England where values are between 60 and 80 mW/m². The temperature gradient has been calculated at some 80 sites in the basin and twelve measurements, that may be regarded as equilibrium measurements, have been made. North of the Humber the average value of the geothermal gradient derived from these equilibrium measurements was 28°C/km and south of the Humber 34°C/km. The average for the equilibrium measurements made south of the river is influenced by two high values of 46 and 53°C/km (Burley and Edmunds, 1978); if these are omitted the average falls to 29°C/km. Measurements made in "virgin strata" give an average gradient of 30°C/km. Most of the estimates are based on measurements made at the bottom of boreholes. The average for all measurements north of the Humber was 24°C/km and south of the river 29°C/km; the overall mean being 27°C/km. A few drill stem tests gave a mean of 29.7°C/km. Values based on bottom hole temperatures are likely to under-estimate true equilibrium temperatures and, therefore, values of 24°C/km and 29°C/km for the regions north and south of the Humber may be regarded as conservative.

Reviewing these data, it would appear that the thermal gradient in south Yorkshire is likely to be between 20 and 25°C/km and probably nearer the higher value, that is close to the national average. For Lincolnshire, the range is more likely to be between 25 and 30°C/km, again

with the probability that the true value is nearer 30°C/km.

If values are assumed for Yorkshire and Lincolnshire of 25 and 30°C/km respectively, the temperatures at various depths are given below, accepting that the mean surface temperature is 10°C and ignoring any effects caused by local variations in thermal conductivity:

Depth	Yorkshire	Lincolnshire
	°C	°C
500	22.5	25
1000	35	40
1500	47.5	55
2000	60	70
2500	72.5	82.5
3000	85	100

Thus to attain temperatures of more than 55°C it would be necessary to drill to 1800 m in Yorkshire and 1500 m in Lincolnshire.

The aquifers that may be considered to have potential as sources of hot water are within the Permo-Triassic, namely the Sherwood Sandstone, the Permian limestones and the Yellow Sands and Basal Breccia of the Lower Permian.

The depth of the top of the Sherwood Sandstone is always less than 1200 m and the estimated temperature at the top is only slightly above 40°C. The formation attains thicknesses in excess of 350 m in north-east Lincolnshire and Yorkshire and the base of the aquifer lies at 1450 m below Grimsby but only 1300 m below Bridlington, two possible demand centres for energy. The anticipated temperatures would be 53°C below Grimsby but only 42°C below Bridlington.

Thus the temperatures in the Sherwood Sandstone are everywhere below the 55°C minimum and only approach this figure within a limited area of north-east Lincolnshire. This implies that in the coastal area the temperatures of the Permian aquifers exceed the 55°C minimum criterion and with increasing depth the isotherm for 55°C moves westwards.

The problem when contemplating developing water resources in the Permian limestones is the difficulty of predicting the permeability. While this can be very high it can equally well be extremely low, and in any attempt to develop the hot water resources of the basin the Permian carbonates should be regarded as a possible source of additional water rather than the prime target but, nevertheless, a possible source that could make the venture extremely successful if very favourable permeability was encountered.

This discussion is leading to the conclusion that the most favourable target aquifer for development is the Lower Permian. The temperature in these deposits in the coastal zone of north-east Lincoln-

Figure 2.1 Principal localities in the East Yorkshire and Lincolnshire Basin

Figure 2.2 Some major structural units in the East Yorkshire and Lincolnshire Basin

Figure 2.3 Contours on the base of the Permian in East Yorkshire and Lincolnshire

Figure 2.4 Thickness of the Lower Permian with temperatures at the base of the Permian in East Yorkshire and Lincolnshire

shire and east Yorkshire is likely to be more than 60°C. Unfortunately, the thickness only exceeds 30 m within this higher temperature zone in east Lincolnshire (Fig. 2.4) but this constraint is counterbalanced to some extent by the fact that the permeability is likely to be at least 200 to 300 mD and the transmissivity at least 10 Dm. Below Grimsby the estimated thickness of the Lower Permian is 30 m and the temperature at the base is between 60 and 65°C. Along the coast south of Grimsby both the thickness and temperature increase to 60 m and more than 60°C respectively, although in a region where demand for hot water is less obvious.

If the probable regional groundwater flow system in the basin is considered, it is clear that the coastal zone will be a discharge area with the tendency for upward groundwater flow. The Permian is underlain by Carboniferous strata comprising an interbedded sequence of sandstones, mudstones and coals, probably very faulted. Although water movement in these rocks will be slow, preferred flow directions are likely to be upwards, along faults or fracture zones, into the Permian. If a well was fortunately sited above a zone of favourable upward flow in the Carboniferous, the temperature in the Lower Permian may be enhanced. Whether this would persist over an extended period of time would depend upon the rate of flow from the Carboniferous into the Permian in relationship to the extent to which the aquifer is developed. Clearly, the chances of intersecting such a favourable zone are not great and must be speculative but what is not speculative is that the anticipated natural temperature in the aquifer is not so likely to be reduced by groundwater flow.

Under development conditions, where water is being pumped from the Lower Permian, any induced flows of water from the overlying carbonates into the sands would reduce the temperature of the water but again, when this would occur would depend on the location of the leakage in relation to the storage being developed in the Lower Permian.

So far consideration has only been given to the potential for water resources in excess of 55°C. If the effectiveness of heat pumps is improved water with a lower temperature may be suitable as an energy resource. Development of water in the Triassic sandstones would then be an obvious possibility as temperatures are greater than 40°C.

The temperature at the base of the Middle Jurassic exceeds 20°C in the Vale of Pickering and in south-east Yorkshire, east Lincolnshire and north Norfolk. The thickness of the sequence in Lincolnshire is about 50 m and it is greater than this in the Vale of Pickering. From the nature of the deposits, high yields of water cannot be guaranteed and yields from the entire sequence are unlikely to exceed 25 l/s. However, the

sequence comprises a wide range of rock types including limestones. If fractures were intersected in either limestones or sandstones much greater yields could be obtained.

The Chalk should contain water in excess of 20°C in the coastal zone of Yorkshire but, as discussed earlier, the permeability is likely to be very low and exploration would not be worthwhile.

CHAPTER 3. WESSEX BASIN

Introduction

The Wessex Basin is a structural and sedimentary basin, containing rocks ranging in age from Permian to Palaeogene. It flanks the southern side of the London Platform and extends from east Devon eastwards under the Weald. Although the structure extends beneath the English Channel, only the on-shore area is described here.

Most of the data used in this study have been provided by commercial and government organisations exploring for oil. Few boreholes penetrate deeper than 1 km, and of those that do, a high proportion are in a relatively small area to the west of Bournemouth where oil has been discovered. Seismic coverage is extensive, but gives little information below the Lias. The main centres of population lie along the coast in Bournemouth, Southampton and Portsmouth, where the basin is believed to be deep (Fig. 3.1).

The basin is structurally complex, particularly in its lower levels, due mainly to block faulting. Faults which trend roughly in an east-west direction are cut by transcurrent faults trending north-west to south-east. Block movements along faults of both trends affected sedimentation and erosion during a number of intervals in the Permian and Mesozoic. At other times, for example during the deposition of the Cornbrash, sedimentation appears to have continued without interruption across the fault blocks.

The depths and thicknesses of the various formations have been estimated from borehole information and from an interpretation of seismic data. Below the base of the Lias, seismic reflections are poor, however, and provide little useful information, so much of the postulated structure in the Permo-Triassic is speculative.

The principal aquifer in the basin is the Chalk but sandstones and limestones in the Lower Cretaceous and Jurassic are also water-bearing, as well as the Permo-Triassic sandstones (Fig. 3.2). From the geothermal point of view the Permo-Triassic sandstones have the greatest potential although sands in the Upper Lias may be of value in the future if the use of heat pumps means that lower temperatures are acceptable for the development of energy.

Review of the principal aquifers

Cretaceous The *Chalk* does not vary greatly in thickness over the Wessex Basin. It is around 300 m thick in the northern part and attains its maximum development of about 500 m in an apparently north-west to south-east trough across the Isle of Wight. The formation is deepest under the northern half of the Isle of Wight where temperatures of 25 to 40°C can be expected.

The Chalk crops out over an extensive area of

the Wessex Basin but in the south it is overlain by the Tertiary. In the outcrop zone it is a good aquifer, particularly along the lines of valleys where the transmissivity is typically of the order of 1500 to 3000 Dm. The high permeability is due to fissures enlarged by groundwater circulating in the upper 50 to 100 m of the aquifer. The permeability tends to decrease at depths of more than 100 m although some horizons produce water from greater depths. The permeability also decreases in a down-gradient direction where the aquifer is overlain by the Tertiary. Well yields in the outcrop zone commonly exceed 50 l/s but less than 10 l/s would be more typical below the Tertiary.

The permeability of the aquifer at the depths where maximum temperatures occur is likely to be low and the aquifer has little potential as a source of geothermal fluids.

The *Upper Greensand* forms the basal part of the Upper Cretaceous marine transgression and as such it covers an extensive area. Thickness variations are not large, being between 30 and 60 m over most of the basin. The formation consists mainly of fine grained to medium grained silty glauconitic sandstones and sands with some calcareous-cemented sandstone. In the western part of the Weald the sands pass into a compact siliceous sandstone, which is likely to lead to some reduction in permeability. The formation crops out extensively in the north-western and western parts of the basin and also around the Weald. Like the Chalk, it is deepest under the northern part of the Isle of Wight, and temperatures of 40 to 45°C can be expected there.

Because of pre-Upper Cretaceous erosion and overstep, the *Lower Greensand* is limited in extent to an area in the eastern part of the Wessex Basin and to the southern part of the Isle of Wight. Isopachytes show an east-west trending trough with thicknesses of up to 200 m in the east around the Weald, but there the formation is so shallow that temperatures are unlikely to be above 20°C. In the northern part of the Isle of Wight, where it is deepest, it is also thin, so it is unlikely to have geothermal potential. The lithology is mainly arenaceous, although some clay units are present. Typical values for the permeability of the Lower Greensand are between 5 and 20 darcies.

Jurassic The *Portland* is missing over a large part of the west of the Wessex Basin owing to erosion and overstep by the Upper Cretaceous. It is, however, present to the south of the Purbeck-Isle of Wight monocline (owing to pre-Albian downfaulting to the south). The Portland appears to reach its greatest thickness of around 80 m in the vicinity of Winchester and it is 55 m thick to the north-west of Salisbury. It thins towards the north-east and appears to form a west-north-west to east-south-east trending basin.

The formation consists of bioclastic and oolitic limestones with some sandstones and clays and it is likely to have reasonable permeability. It has, however, no large outcrop in the west, being overstepped by the Upper Cretaceous and it is not in hydraulic continuity with overlying beds because of the Gault. Temperatures are likely to be highest under the Weald, where the thickness probably reaches 60 m, but maximum temperatures are probably only 35 to 40°C.

The *Corallian* appears to be thickest in the structurally complex area of the Isle of Purbeck, and in the north-east, where it reaches 137 m. It is a highly variable formation and probably originated on a shelf with a source of sandy detritus to the north-west. In Dorset and west Hampshire particularly, the formation contains a number of sands, but it is quite shallow, with temperatures below 35°C. Oolitic limestones (such as the Osmington Oolite) are other permeable units within the *Corallian*. It is probable, however, that these various sands and limestones are lenticular and they may not be in hydraulic continuity. The formation crops out in the north-west and west but the outcrops are not large because of the Upper Cretaceous overstep. The clayey nature of the basal Upper Cretaceous rocks acts as a confining bed separating it from overlying permeable formations.

The depth of the formation increases eastwards and southwards. Over most of the basin to the east of Salisbury, temperatures are above 35°C and probably reach 50 to 55°C under the southern half of the Isle of Wight, and in a small region in the north-east of the area covered in Fig. 3.1.

The *Cornbrash* shows only small thickness changes throughout most of the Wessex Basin, although it appears to be absent in the extreme north-east and south-east (Fig. 3.1). Elsewhere its thickness does not exceed the 24 m found to the south-west of Salisbury. The formation is a rather rubbly bioclastic limestone and should have good permeability. It will have hydraulic continuity with its outcrop in the west but this outcrop is rather narrow although to the north-west it is wider.

As is the case with the *Corallian*, the depth of the formation increases eastwards and also in the south of the Isle of Wight, where temperatures of up to 60°C can be expected. Over most of the area to the east of Winchester the temperature of the formation is likely to be above 50°C, but unfortunately its thickness may be less than 10 m.

The *Upper Lias Sands* (including the Bridport Sands) appear to be limited to the extreme west and south-west of the Wessex Basin, this being palaeogeographically an area of migrating shallow-water sand bars. Passing north and north-east from this area the clay content rises considerably and most boreholes in the central and eastern part of the Wessex Basin show either muddy sandstones or

mudstones. In Dorset the Bridport Sands are generally 60 to 80 m thick apart from an anomalous thickness of 140 m in one borehole. Temperatures in this area range from 30° to 50°C increasing eastwards to 60°C as the clay content increases. The formation has an extensive outcrop to the west in west Dorset and Somerset. The Bridport Sands are probably in hydraulic continuity with the overlying Inferior Oolite, although this is only a few metres thick in the west.

The transmissivity of the Upper Lias Sands/Inferior Oolite near outcrop is about 500 Dm, but laboratory determinations of the permeability of core material from the Winterborne Kingston Borehole suggested an intrinsic transmissivity of only 1.2 Dm. The Upper Lias sands would only be a potential aquifer in areas where fractures enhanced the intrinsic permeability significantly.

Permo-Triassic The structure of the Permo-Triassic is less well understood than that of the formations above it, partly because fewer boreholes penetrate it, but mainly because it does not contain horizons which behave as good and reliable seismic reflectors; the deepest well-defined traceable reflector lies at the top of the Permo-Triassic. The structure postulated here (Figs. 3.2 and 3.3) is inferred from the limited borehole evidence, from gravity evidence, and from surface fold structures which suggest the presence of basement faults which may have controlled Permo-Triassic deposition.

The Permo-Triassic is perhaps the formation most affected by basement structures and Fig. 3.3 shows the suggested effect of various east-west and north-west to south-east block faults on the thickness. The deposits are missing in the extreme north-east and are thin or missing beneath most of the Weald. Evidence from boreholes indicates a possible thickening towards the south-west and south.

The sedimentation in these basins is likely to have been controlled by movements along the marginal faults, with the coarser more permeable sediments occurring within the grabens and the attenuated tighter more argillaceous formations occurring on tops of the horst blocks. A possible control of the Permo-Triassic sedimentation by the north-west to south-east trending Bembridge—St Valery line might have encouraged the erosion of earlier rocks to the north-east of it, with subsequent deposition in the grabens of the Wessex Basin. This may have brought about an enhancement of the permeability, particularly in the southern graben in the area of south Hampshire and the northern part of the Isle of Wight. It is also possible that some coarser sediment was being derived from upstanding horst blocks of basement in the area of the English Channel.

The temperature contours shown in Fig. 3.3 are for the top of the Permo-Triassic, and are

based mainly on depths interpreted from seismic data. Temperatures in the main aquifer, the Sherwood Sandstone, should be significantly higher than this as it is confined by a thick argillaceous sequence, the Mercia Mudstone. In the Winterborne Kingston Borehole the average temperature of water from the Triassic sandstones measured in drill-stem tests was 85°C at depths between 2306 and 2425 m.

The arrangement of both the basins and their sedimentary facies in an east-west trend makes it probable that north to south hydraulic continuity in the aquifer might be poor, while the continuity in an east-west direction can be expected to be considerably better. Pressure measurements support this inference, indicating that the east-west faults act as impermeable boundaries. Natural recharge would most likely be from the main outcrop area to the west in Devon and Somerset. Natural groundwater flow in the Triassic sandstones is, however, very slow.

Although the transmissivity of the Triassic sandstones at Winterborne Kingston was 11 Dm, the data on which this is based were affected by the proximity of a hydraulic barrier and a more realistic indication of the aquifer transmissivity might be 15 Dm. Laboratory tests indicated that over a thickness of only 3.2 m, at a depth of 2424 m, the average intrinsic permeability was 1695 mD. This gives an overall transmissivity for this short section of 5.4 Dm. It is likely that such discrete zones of high permeability are the main contributors to the overall transmissivity of the aquifer. A transmissivity of 15 Dm, where the formation water is 85°C and has a total mineralisation of 300 g/l, would correspond to a transmissivity of 23 m²/d.

Groundwaters in the Triassic sandstones at depth in the Wessex Basin are brines with salinities ranging up to 200 or 300 g/l. Sodium and chloride are the dominant ions and the brines are characterised by low calcium concentrations and low Br/Cl ratios. The Br/Cl ratios are considered diagnostic of the fact that the bulk brine composition has arisen from the dissolution of halite by groundwaters with initial compositions less saline than that of sea-water. Typical analyses are listed in Table 3.1.

The low piezometric surface at Winterborne Kingston of 200 m below sea level results from the unusually high total mineralisation of the formation water. Although the piezometric surface is almost 250 m below that at outcrop the density difference of the respective formation waters is such that the difference in piezometric head is negligible.

Heat flow and temperature measurements

The most reliable heat flow measurement in the basin was made by Oxburgh and others (1978) in the Winterborne Kingston Borehole. This gave a value of 78 ± 7 mW/m², which is above the average for the U.K. A compilation of temperature measurements in boreholes throughout the Wessex Basin (Burley and Edmunds, 1978) indicated a mean temperature gradient, to a depth of 3 km, of about 30°C/km, which is significantly above the average gradient for the U.K. Thus, for an aquifer to contain water at a temperature of 60°C it needs to be at a depth of about 1650 m.

Table 3.1 Chemical analyses of representative formation waters from the Triassic sandstones (units are mg/l)

IGS Ref. No.	1 77/160	2 77/126	3 77/1448	4 79/981
pH	6.85	6.40	6.8	7.2
Ca	2920	3380	3720	882
Mg	450	515	696	213
Na	114000	110000	75474	92000
K	1820	1400	992	800
SO ₄	2000	2300	1540	5404
Cl	181000	182500	124605	136320
HCO ₃	—	—	62	—
Sr	92	86	—	—
Ba	<0.2	<0.2	—	—
Li	22.4	24.4	—	—
Br	57	29	—	—
Total mineralisation	302360	300230	207030	235620

- 1 Winterborne Kingston Borehole. DST sample from 2380–2402 m
- 2 Winterborne Kingston Borehole. Interstitial water from 2322 m
- 3 Wareham No. 1 Borehole. DST sample from about 1746 m
- 4 Wytch Farm. Oilfield brine produced from about 1576 m

Figure 3.1 Principal towns and deep boreholes in the Wessex Basin

Figure 3.2 Generalised east-west cross section showing main formations in the Wessex Basin

Figure 3.3 Temperature and postulated structure of the Permo-Triassic in the Wessex Basin

Assessment of the geothermal potential

The Cretaceous aquifers (Chalk, Upper and Lower Greensand) reach their greatest depth under the northern half of the Isle of Wight, though temperatures above 45°C are unlikely. Jurassic aquifers are unlikely to reach depths sufficient to give temperatures of more than 55°C, except perhaps for the Cornbrash in the southern part of the Isle of Wight. They are also unlikely to have individual transmissivities of more than 3 Dm. The Upper Lias sands (the Bridport Sands), which is one of the most permeable Jurassic formations, only attain temperatures of about 50°C in Dorset, and their transmissivity is unlikely to exceed 2 Dm.

The only formation likely to have sufficient transmissivity and contain water at temperatures above 60°C is the Sherwood Sandstone in the Permo-Triassic. The permeability of core material from the Sherwood Sandstone in Dorset has been found to be greater than 1000 mD and field testing has shown that a transmissivity of about 15 Dm occurs at one site at a depth of about 2400 m where the aquifer temperature is 85°C. The formation water at depth is a hypersaline brine.

With current knowledge, the delineation of the aquifer and the nature of the facies variation at depth is uncertain. Because of this any borehole drilled to investigate the geothermal potential must be regarded as an exploratory venture, but nevertheless exploratory drilling is worthwhile and the potential of the aquifer as a geothermal resource would seem to be good.

CHAPTER 4. CHESHIRE AND WEST LANCASHIRE BASINS

Introduction

Following the Hercynian earth-movements a major Permo-Triassic basin developed below the northern part of the Irish Sea. The West Lancashire Basin is an on-shore extension of this basin and the Cheshire Basin, although a separate structure, is connected to the Northern Irish Sea Basin along the Wirral peninsula (Fig. 1.1 and Plate 1). The eastern margin of the two basins is marked by the Pennines while the uplands of North Wales and Shropshire form the western and southern limits of the Cheshire Basin. Much of the region underlain by Permo-Triassic rocks is rural but it includes the Liverpool-Manchester conurbation (Fig. 4.1).

Basically the Permo-Triassic rocks in the two basins may be regarded as a thick layer of marl (the Mercia Mudstone Group) overlying an equally thick sandstone unit (the Sherwood Sandstone Group and the Collyhurst Sandstone). Details of the sequence are given in Fig. 4.2 together with the nomenclature adopted in this chapter. The sandstone unit is subdivided by two distinct facies — the Manchester Marl and the Chester Pebble Beds (Fig. 4.2) but neither of these deposits is present throughout both basins. The Manchester Marl represents a marine incursion from the north-west and where it is present the underlying sandstone is recognised as the Collyhurst Sandstone. The Chester Pebble Beds originated from the south and where they occur they serve to separate the Wilmslow Sandstone from the Kinnerton Sandstone. The base of the Pebble Beds is taken as the base of the Triassic. The Wilmslow Sandstone is overlain unconformably by the Helsby Sandstone which, in turn, is succeeded by the transitional Tarporley Siltstone and the Mercia Mudstone, which includes salt deposits. The salt has physical properties of density, seismic velocity and thermal conductivity which are very different from other rocks and consequently the uncertainty over its distribution introduces equal uncertainty into all aspects of the geophysical interpretation.

The Penarth Group and Jurassic rocks are preserved in the outlier at Prees in the Cheshire Basin.

Geology of the Permo-Triassic sandstones

The Collyhurst and Kinnerton sandstones are aeolian sands with dune bedding and "millet seed" grains. The Collyhurst Sandstone ranges in thickness from a few metres to over 250 m in the Manchester area and up to 750 m near Formby. This variation is due to deposition on a very dissected land surface and also to the influence of contemporaneous faulting.

The Chester Pebble Beds are considered to be fluvial deposits formed in a large sub-aerial

alluvial fan (Fitch and others, 1966). They have been silicified and the base can be recognised on sonic logs by the marked difference in porosity between them and the underlying Kinnerton Sandstone (Colter and Barr, 1975).

The silicification extends up into the overlying Wilmslow Sandstone which is considered to be a fluvatile and lacustrine deposit (Audley-Charles, 1970) although including some aeolian deposits. The uniformity in the thickness of the silicified zone has been commented upon by Colter and Barr (1975). In the Prees No. 1 Borehole it is 505 m thick, in Knutsford No. 1, 459 m and in Formby No. 6, 305 m.

Three lithofacies have been recognised (Thompson, 1970a and b) in the Helsby Sandstone. The lower Thurstaston Member, which is comparable with the underlying Wilmslow Sandstone, is partly of aeolian and partly of fluvatile origin. The middle Delamere Member is a fluvatile deposit of red pebbly sandstones with silts and shales, while the upper Frodsham Member is predominantly an aeolian sandstone.

In the Cheshire and West Lancashire basins there is a total thickness of some 1300 to 2000 m of arenaceous deposits much of which have very favourable lithological characteristics from the point of view of water development projects.

The major structural control in the basins is believed to be faulting although contemporaneous subsidence has probably affected the thickness of the strata significantly. Few deep boreholes have been drilled in the Cheshire Basin so that the interpretation of the regional structure has been based on geophysical data particularly seismic reflection surveys and gravity data. Geophysical logs run in three deep commercial boreholes (Prees, Knutsford and Milton Green) were interpreted to identify possible seismic reflectors and these were correlated with reflection events on seismic sections adjacent to the borehole sites. Thus from the boreholes at Prees and Knutsford it was possible to identify and follow a number of reflections within the Permo-Triassic along interconnected seismic lines and to relate the data between the two boreholes. The objective was to define the top and bottom of the sandstone unit. The base of the Permo-Triassic is difficult to trace, probably because of variability in the lithology of the underlying rocks and the considerable relief of the pre-Permian land surface. Gravity data were interpreted as a general test of the validity of the seismic interpretation. The gravity anomalies are reasonably explained in terms of density units defined by seismic mapping.

The end product of the seismic study is a map of contours on the base of the principal geological horizons. Contours of the depths to the top of the sandstone unit, that is the Helsby Sandstone, and the base of the Permo-Triassic, are shown in Figs. 4.3 and 4.4. The regional dip is to the south-east

and the bases of the Mercia Mudstone and the Manchester Marl are 2.0 and 3.4 km deep respectively in the south-east of the Cheshire Basin. Although the same tendency is apparent with regard to the base of the Permo-Triassic, with a depth of 4.7 km in the south-east of the basin, the greatest depth is probably in the centre and north-east because of the marked relief of the pre-Permian topography.

In the West Lancashire Basin only two boreholes, at Formby and Scarisbrick, completely penetrate the Permian. Data from these boreholes and a shallow borehole at Kirkham have been used to deduce the physical properties of the geological units. There were no seismic data available in this basin at the time of this study; therefore, structural interpretation has been based on gravity data.

At Formby, in the south of the area, the proven depth to the base of the Permo-Triassic is 1788 m and at Scarisbrick, 8 km north-east of Formby, it is 1653 m. Maximum depths of 3 km may be attained in the Fylde between Blackpool and Kirkham; depths of about 2 km may be found in an area between Southport, Preston and Fleetwood. It should be realised that the choice of regional Bouguer gravity anomaly is critical when interpreting the gravity data and as it is impossible to model more than one density uniquely, the depth forecasts are speculative.

Aquifer properties

The basin-wide variation of the aquifer properties of the Permo-Triassic sandstones is known only incompletely. Whereas the typical values for porosity and permeability are available for the outcrop zones and for some distance downdip, few deep boreholes penetrate the sequence. In the deeper parts of the basins reliance has, therefore, been placed on the interpretation of a limited number of down-hole geophysical logs together with detailed studies made in connection with hydrocarbon exploration in the Northern Irish Sea Basin.

Some logs run in the Prees Borehole revealed that the Collyhurst and Kinnerton sandstones have low porosities, generally only between 10 and 12%, occasionally as low as 6% and never exceeding 14%. Neutron and formation density logs support this interpretation. Qualitative indications of permeability, derived from the separation of the deep and shallow traces of the dual induction-log, suggest that the Kinnerton Sandstone in the Prees Borehole is for the most part impermeable. However, over two intervals with a total thickness of more than 250 m, the permeability appears to be more favourable and may approximate to 100 mD. A transmissivity of 19 Dm has been estimated for this vertical interval.

The mean intergranular permeability of the Kinnerton Sandstone at outcrop is about 2000 mD

and the reduction at depth is probably due to cementation and the formation of secondary clay minerals but the evidence from the Prees Borehole may not be representative of the situation in the deeper parts of the basins. However, the sedimentary processes that gave rise to the Collyhurst and Kinnerton sandstones tend to result in rocks with good primary permeabilities.

At outcrop the porosity of the Chester Pebble Beds ranges from 20 to 30%. The bulk field permeability is generally between 800 and 8000 mD and the mean intergranular permeability is about 650 mD (Lovelock, 1977). Geophysical logs run in the Prees Borehole show porosity variations between 10 and 20% and thus, despite cementation and the presence of secondary clay minerals, the porosity can still be significant. From the dual induction-laterolog, permeable horizons at the top of the sequence can be recognised. These become less frequent and/or less permeable towards the base. A minimum thickness of 100 m with a permeability of 100 mD would be a reasonable assumption for this unit and this would give a transmissivity of 10 Dm.

The Wilmslow Sandstone is a fine-grained red sandstone with argillaceous laminae and varying degrees of cementation. This varied nature results in a wide range of physical properties. The permeability ranges from more than 10 000 mD to less than 10 mD, the respective porosities being 30 and 13%.

Laboratory tests on core samples taken from the "St Bees Sandstone" of the Northern Irish Sea (where the Kinnerton and Wilmslow sandstones cannot be separated because of the absence of the intervening Chester Pebble Beds), show that a combination of quartz overgrowth, calcite cementation and the formation of platy clay minerals reduces the intergranular permeability to less than 10 mD even when the porosity is 20% (Colter and Ebburn, 1978).

Downhole geophysical logs run in the Prees Borehole show correspondingly unfavourable results for the Wilmslow Sandstone. The best available data are from the sonic log which indicates the porosity is less than 10%. The dual induction-laterolog supports the suggestion of very low porosity. The separation between the deep and shallow investigation responses is small, and the few permeable zones are thin with only low permeability.

In the Helsby Sandstone the more porous horizons appear to be restricted to the upper and lower members — the Frodsham and Thurstaston — presumably because they originated as aeolian sands. The middle, less porous, Delamere Member, thins southwards and is absent in the Prees Borehole and at outcrop on the southern margin of the Cheshire Basin. In mid-Cheshire, where again the Delamere Member is absent, the permeability and porosity are both greatest in the middle of the

Helsby Sandstone sequence with values reaching 4000 mD and 30% respectively. More data are available in north Cheshire, from both outcrop and shallow boreholes, where the permeability ranges up to 15 000 mD although the porosity can be reduced, by suture contact pressure solution, to 25–30%.

The sonic log for the Prees Borehole suggests a primary porosity for the Helsby Sandstone of 14 to 21%; values are consistently high in the top few metres and average about 17%. The same order of magnitude is interpreted from the neutron and formation density logs, the top 67 m showing an average porosity of 16% and the bottom 46 m an average of 15%. The dual induction-laterolog indicates the Helsby Sandstone section is consistently permeable, especially near its base.

Cores from the Helsby Sandstone of the Northern Irish Sea Basin have been tested in the laboratory and examined petrographically (Colter and Ebburn, 1978) to investigate the relationship between the porosity, permeability and lithology. It is only in the highest Frodsham Member that permeabilities of more than 100 mD could be expected in sandstones with greater than 15% porosity. The transmissivity of the Helsby Sandstone in the Knutsford and Prees boreholes is estimated to be about 2 and 8 Dm respectively.

The Tarporley Siltstone which rests on the Helsby Sandstone is not generally regarded as an aquifer but laboratory tests on cores from the Northern Irish Sea Basin (Colter and Ebburn, 1978) have indicated porosities of up to 20% and intergranular permeabilities of up to 400 mD. Cementation has, however, reduced the permeability to less than 10 mD in many samples and the significance of this formation as an aquifer still remains to be proved.

When the Permo-Triassic sandstones are considered as a whole they clearly have considerable potential as a source of warm water. They are good aquifers at and near outcrop where fissure flow contributes significantly to the permeability. At depth in the Cheshire and West Lancashire basins fissures will be of less importance and greater reliance must be placed on intergranular permeability. Cementation of the sandstone has reduced this over parts of the sequence but, even bearing this in mind, a total transmissivity of 40 Dm may be anticipated.

Heat flow and temperature measurements

Heat flow has been calculated in five boreholes in the northern part of the Cheshire Basin and in one borehole (at Kirkham) in the West Lancashire Basin. The values for the Cheshire Basin tend to be low and the mean was 34 mW/m². The single value for the West Lancashire Basin of 71 mW/m² is higher than the average for the U.K. The site has been included in a high heat flow belt that has been postulated across northern England

Figure 4.1 General geology and principal localities in the Cheshire and West Lancashire basins

Figure 4.3 Depth to the top of the Permo-Triassic sandstones and temperature at this horizon in the Cheshire Basin

Figure 4.4 Depths to the base of the Permo-Triassic in the Cheshire and West Lancashire basins

Figure 4.5 Temperature-depth relationship in the Cheshire Basin.

Figure 4.6 Estimated temperatures at the base of the Permo-Triassic in the Cheshire Basin

(Richardson and Oxburgh, 1979).

The plot of measured temperatures against depth for the Cheshire Basin (Fig. 4.5) based on data given by Burley and Edmunds (1978) indicates that temperatures at depth are relatively low as would be expected from the low heat flow values. All measurements below 1000 m are 'bottom hole temperatures' not corrected for the effects of mud circulation in the boreholes, and they will, therefore, tend to under-estimate the 'equilibrium' formation temperatures. If data from boreholes close to, but outside, the margins of the basin are included in this plot, the distribution of points remains substantially the same, suggesting that low temperature gradients might be expected for the whole area and do not result from local disturbances due to the distribution of highly conductive salt formations.

The temperatures expected at the top and bottom of the Permo-Triassic sandstone unit in the Cheshire Basin are shown in Figs 4.3 and 4.6 respectively. These values were obtained from Fig. 4.5 assuming mean gradients of 23°C/km for the Mercia Mudstone and 12°C/km for the Sherwood Sandstone. Thus temperatures correspond to depths and a maximum temperature of 56°C at the top of the Sherwood Sandstone occurs near the south-east margin of the Cheshire Basin; temperatures at the base of the Permo-Triassic reach 80°C in the same area.

The temperature measured at the bottom of the Prees Borehole (80°C at a depth of 3828 m) is likely to underestimate the equilibrium temperature. Assuming that the vertical thermal conductivity profile is not greatly different in the deepest part of the Cheshire Basin, it is likely that an equilibrium temperature of at least 90°C will occur at the deepest point which is over 4.5 km. The sandstone occurs at a depth of 4.5 km over an area of about 150 km². A temperature of 73°C was measured at 3600 m in the Prees Borehole and again this is probably an underestimate of the equilibrium temperature. At this depth the sandstone unit covers an area of about 830 km², or about one third of the total area of the basin.

If it is assumed that the heat flow measurement made in the Kirkham Borehole is representative of the West Lancashire Basin then higher temperatures than were estimated for the Cheshire Basin could be expected at all depths. However, if there is salt below the 'low' at Kirkham (as is possible), then this could account for the high heat flow in the borehole, and would mean that the heat flow and hence temperatures in the rest of the basin would be much lower.

Assessment of the geothermal potential

The sandstones at the base of the Permo-Triassic sequence have the following proven depths below datum and thicknesses:

Basin	Borehole	Depth (m)	Thickness (m)
Cheshire	Prees	3540	1600
Cheshire	Knutsford	2775	2068
W. Lancashire	Formby	1788	1715

Interpretation of seismic and gravity data for the Cheshire Basin suggests that the base of the sandstone unit attains a depth of at least 4.5 km and is about 2.3 km thick.

Analysis of residual Bouguer gravity anomalies indicates that the maximum depth to the base of the sandstone in the West Lancashire Basin may be about 3 km.

Heat flow and temperature measurements suggest the Cheshire Basin may be a region of low average gradient. A single value for the West Lancashire Basin was high and while this may be anomalous, the site is near the southern boundary of a proposed belt of high heat flow. The average thermal gradient in the Cheshire Basin is 23°C/km in the Mercia Mudstone and 12°C/km in the underlying sandstones, and if this is maintained over the basin as a whole temperatures of at least 90°C may be expected in the deepest parts. The same gradient would give a temperature of 70°C in the deepest parts of the West Lancashire Basin. If, however, the single high heat flow value in West Lancashire is representative of that area, then temperatures of about 100°C would be found at the same depth.

Estimates of the permeability and porosity of the sandstone from geophysical logs together with laboratory and field permeability studies of both shallow and off-shore boreholes indicates the sandstone contains zones of favourable permeability and porosity. An overall transmissivity of 35 Dm is possible.

The most favourable location for developing low enthalpy geothermal fluids would be in the south-east of the Cheshire Basin. The high heat flow in West Lancashire may be an encouraging feature and, if the value is not anomalous, a site in this basin would also have considerable potential.

A point to bear in mind is that it may be advisable to penetrate only a short distance into the sandstone as further deepening may not give the expected return of increased temperatures because a low thermal gradient may exist in the sandstone due to high thermal conductivity and circulation.

CHAPTER 5. NORTHERN IRELAND

Introduction

The only approach to exploiting geothermal energy, which could be explored in Northern Ireland at the present time, is that of using hot groundwater from deeply buried permeable strata in sedimentary basins, to provide a source of low enthalpy heat. Knowledge of the distribution of rock permeabilities within the sedimentary basins in the province is limited, but two groups of strata are prospective targets:

- 1 Carboniferous rocks of various types; and
- 2 Permo-Triassic sandstones.

The Carboniferous strata comprise a very variable sequence of limestones, sandstones and shales occurring mainly in the west of the province. Exploratory wells for hydrocarbons at Big Dog, Owengarr, and Glenoo (Fig. 5.1) revealed thicknesses for the Carboniferous basin of more than 2002 m, 2024 m, and 2091 m respectively but no information about permeability at depth is available. At Owengarr and Glenoo, Old Red Sandstone sediments were encountered beneath the Carboniferous but rocks of this age are not regarded as having a geothermal potential in Northern Ireland, because of their poor hydraulic properties where they occur at the surface. However, considerable parts of the Carboniferous sequence are known from water supply boreholes to have good permeability, albeit usually secondary, near the surface. No heat flow data or even stabilised temperatures are available from this western area, the only temperature measurements having been made in the deep wells not more than two to three hours after circulation of drilling mud had ceased. These measurements indicated gradients in the range 21 to 24°C/km which are significantly lower than values obtained under similar circumstances in boreholes in the Permo-Triassic basins further east. The geothermal potential of the Carboniferous basins does not, therefore, appear to warrant active investigation at the present time; especially since the area in question is sparsely populated, being largely agricultural with very little manufacturing industry, so that demand for a low grade heat source would be very limited at present.

This report, therefore, concentrates on the Permo-Triassic sandstones as hot water aquifers. They not only occur in the more densely populated and industrialised east of the province but appear to have a greater geothermal potential on the basis of their aquifer properties, geological situation, and the local heat flow and temperature gradient.

Geology of the Permo-Triassic basins

The igneous activity which occurred in the north-western parts of the British Isles in Tertiary times was very extensive in Northern Ireland. Central intrusion complexes were emplaced in Lower Palaeozoic greywackes in Counties Down and Armagh, while a thick pile of plateau basalt lavas was built up over most of County Antrim as well as over parts of Counties Londonderry, Tyrone and Armagh (Plate 1). Erosion, including glaciation, has reduced the basalt sheet to a total area of some 3975 km² and a maximum known thickness of almost 800 m, although this figure could well be exceeded under Lough Neagh. However, the basalts have protected the underlying Cretaceous, Jurassic, Triassic and Permian sediments from erosion.

Strata of these ages crop out around most of the periphery of the basalt area. The relatively small outcrop areas of the Permo-Triassic rocks are shown in Fig. 5.1, but the basalts conceal deep sedimentary basins which are infilled mainly with Triassic sediments, extending to depths of about 3000 m below sea level and underlying a total area of about 4000 km². The main centres of deposition extend from beneath Lough Neagh north-eastwards into the North Channel (Fig. 5.2) lying more or less astride the continuation of the Midland Valley of Scotland. A narrower trough with an identical trend occurs further north-west reaching the north coast around the Port More Borehole, and is probably connected with the main basin along a NNW trending axis which breaches a NE to SW structural high connecting Dalradian basement rocks on either side of the basalt outcrop. Further north-west again the basin appears to be over-deepened along another NE to SW axis in Lough Foyle.

Along their western boundary and in the Belfast Harbour area, the Permo-Triassic rocks rest mainly on Carboniferous sediments, but basement rocks form the south-eastern and north-eastern margins, where Triassic sandstones rest directly on Lower Palaeozoic greywackes and Dalradian schists respectively. Neither of the two boreholes which have penetrated the Permo-Triassic strata in the central area, at Langford Lodge and Ballymacilroy, encountered Carboniferous strata, although the latter probably occur beneath the basin further east and also beneath the northern trough. They were encountered in the Magilligan hole (Fig. 5.2) beneath 977 m of Jurassic and Triassic sediments.

The sediments in the deeper parts of the basins are generally arenaceous. Permian sandstones, which are often coarse-grained and uncemented, and breccias are overlain by the Triassic Sherwood Sandstone formation. The latter is a predominantly medium-grained sandstone, often with a calcareous cement, and with marl and mudstone intercalations. In the deeper

parts of the basins the thickness of the Permo-Triassic sandstones exceeds 1000 m. The argillaceous component of the Sherwood Sandstone increases upwards until the formation passes into the Mercia Mudstone, which is predominantly marls and mudstones with sandstone intercalations and including thick halite deposits in the south-east of the main basin. The Triassic succession is completed by sediments of the Penarth Group but these are not always present. They comprise both argillaceous and arenaceous materials but never exceed a few tens of metres in thickness. The Triassic strata are usually, but not always, overlain by Jurassic argillaceous sediments, the Lias, which can be up to about 100 m thick. In the basalt covered parts of the basins a layer of Chalk (the Ulster White Limestone) up to 50 m thick usually occurs immediately beneath the basalt sheet. Around Lough Neagh, and presumably beneath much of the lough, basins of Tertiary sediments, the Lough Neagh Clays (Fig. 5.1), and Quaternary sediments rest on the basalt sheet. They are predominantly argillaceous, attaining thicknesses of almost 400 m on land and probably much more beneath the lough.

Aquifer properties of the Permo-Triassic sandstones

The Permian and Sherwood sandstones constitute useful aquifers yielding potable water supplies in various areas around the margins of the basins where they occur at shallow depth. In these areas the porosity of the sandstones is usually in the range 20 to 30%, and groundwater flows through them as a result of a combination of primary (intergranular) and secondary (fissure) permeability. Fissure flow is dominant in the Sherwood Sandstone but is less so in the Permian aquifers where the lesser degree of induration permits greater intergranular flow. Relatively little is known about the permeability of these aquifers at depth in the basins, where they usually comprise at least 50% of the total thickness of fill: in the deepest areas the sandstone sequence appears to be overthickened relative to the argillaceous component of the fill and to approach 70% of the total thickness.

Although porous, permeable, fluviatile sandstones of Triassic age appear to occur throughout all the basins this is certainly not true of the Permian deposits. In any of the supposed Permian sequences the open sandstones, probably of aeolian origin, comprise only a small proportion of the generally tight arenaceous material of mainly terrestrial origin, which are usually overlain by fluviatile marls. The open sandstones, therefore, tend to be impersistent laterally. Therefore, as far as this report is concerned the Triassic and Permian sandstones are grouped together and regarded as a single aquifer sequence in terms of their geothermal potential.

The porosity and transmissivity of the sandstones at outcrop generally increases from west to east. This appears to be related to grain size and an associated increase in permeability, because no changes in thickness are evident.

The aquifer properties of the sandstones have been examined in some detail in the Newmill, Port More and Ballymacilroy boreholes, which are all sited in the deeper parts of the Permo-Triassic basins.

Horizontal and vertical intergranular permeabilities were measured on samples from the Newmill Borehole collected at 0.3 m intervals between depths of 803 to 812 m and 1574 to 1583 m. Although the permeability ranged up to more than 800 mD, it was only over relatively limited thicknesses, of the order of 1 to 3 m, that it consistently exceeded 100 mD. However, the average permeability was about 200 mD. The porosity ranged from 10 to 25% and the majority of values exceeded 15%.

A smaller suite of samples was examined from the Sherwood Sandstone Group in the Port More Borehole. The porosity clearly declined with depth from more than 20% at less than 1375 m, to generally less than 16% at greater depths, although with some exceptions. The intergranular permeability was very low — less than 5 mD — for samples with low porosity. At shallower depths of between 1250 and 1550 m, values generally exceeded 100 mD and several were greater than 500 mD; the average being 320 mD. If this reflects the true average, the transmissivity over 300 m would be very encouraging.

The permeability of the various sandstone horizons is closely related to grain-size distribution and cementation. The higher permeabilities were found in samples with a uniform grain size and which were not cemented, whereas low values of both permeability and porosity reflected a very wide range of grain size and poor sorting.

Two favourable aquifers were identified within the Triassic and Permian sandstones in the Ballymacilroy Borehole by using lithological and geophysical logs, in situ hydraulic testing and laboratory analysis. The details of the aquifers are:

Triassic sandstone	210 m thick, from 1450 to 1660 m
Permian sandstone	45 m thick, from 1902 to 1935 m and 1983 to 1995 m.

The effective horizontal intergranular permeability of core taken from the Triassic sandstone was 212 mD and the mean inter-connected porosity was 18%. On the basis of in situ hydraulic tests, it is considered that 72 mD is a more reasonable estimate of the bulk field permeability. Therefore, the transmissivity of the Triassic aquifer is about 15 Dm.

In situ tests of the Permian sandstone gave a similar bulk permeability to that of the Triassic

Figure 5.1 Simplified geological map of Northern Ireland

Figure 5.2 Permo-Triassic basins in Northern Ireland

aquifer, rather greater than might have been anticipated from the geophysical logs. On this basis the transmissivity of the Permian aquifer is about 3 Dm.

The formation waters from both aquifers were sodium-chloride brines with total mineralisation of some 120 g/l.

Heat flow and temperature measurements

The Permo-Triassic sandstones are overlain by argillaceous rocks with low thermal conductivity but as there is also an additional "blanket" of low thermal conductivity in the form of a basalt sheet with in places more argillaceous sediments on top of the basalt. This greatly enhances the prospects of locating hot water at shallower depths than may be the case in other basins in Britain.

Four heat flow measurements (Table 5.1) are available for Northern Ireland (Wheildon pers. comm.).

Table 5.1. Heat flow measurements in Northern Ireland

Location	Interval (m)	Heat flow (mW/m ²)	
		Uncorrected	Corrected
Port More	422-580	80	87
Killary Glebe	1158	74	-
Annalong Valley	40-66	80	109
Seefin Quarry	40-150	69	187

The Annalong Valley and Seefin Quarry locations are in the Mourne Mountains and the corrected value for the Annalong Valley site is approximate as the conductivity data for the Seefin Quarry site was used. All the values are appreciably higher than the U.K. average of 60 mW/m².

A temperature of 57°C was recorded in the Port More Borehole at the top of the Sherwood Sandstone Group (at 1090 m below sea level) and at a depth of 1482 m, within the sandstone, it was 63.3°C indicating a mean geothermal gradient of 36°C/km.

In the Ballymacilroy Borehole the temperature of the brine in the Triassic aquifer was 62°C at a depth of 1529 m. This corresponds to an average geothermal gradient of 34°C/km from ground level across the thick Tertiary basalt sequence, the Jurassic clays and the Triassic marls overlying the aquifer.

The temperature of the Permian brine, 240 m deeper and separated from the upper aquifer by over 30 m of mudstone, was only 65°C. The lower geothermal gradient to the top of the Permian sandstone suggests that either natural groundwater flow is occurring in the upper aquifer or there is some degree of hydraulic connection between the two.

Geothermal gradients derived from measurements in other boreholes are:

Location	Temperature °C	Depth m	Formation	Gradient °C/km
Killary Glebe	52.5	1157	Carboniferous	37
Langford Lodge	47.8	1020	Triassic	37
Newmill	50.0	1969	?Permian	20

Considered overall these results imply that the geothermal gradient in the area underlain by Permo-Triassic sandstones is appreciably above the national average.

Assessment of the geothermal potential

The thick sequence of basalt and argillaceous sediments above the Permo-Triassic sediments has an appreciable insulating effect which increases the geothermal gradient to values in excess of 30°/km. In the Port More Borehole at a depth of 1480 m the temperature was over 60°C and this was also the case in the Ballymacilroy Borehole at a depth of 1500 m.

If a gradient of 33°C/km is assumed, the temperature at a depth of 2 km would be about 75°C and at 3 km over 100°C. The base of the Permo-Triassic is more than 3 km below the surface north-west of Larne and over extensive areas it is greater than 2 km below ground (Fig. 5.2). Relatively high permeabilities are only encountered in the sandstones over limited thicknesses but nevertheless the very small sample of data currently available encourages the view that the transmissivity of the sandstones would be high enough to provide an adequate yield of hot water.

Geology

The Worcester Basin is a north-south trending downwarp which probably passes into a graben-type structure at depth. It is bounded to the west by the Precambrian and Lower Palaeozoic rocks of the Malvern Hills, to the north by the Midland Coalfields, to the south by a conjectural extension of the Mendip axis and to the east by the Vale of Moreton Axis (Fig. 6.1). Permo-Triassic and Jurassic sediments are preserved in this downfolded and downfaulted region. The floor of the basin is in Palaeozoic rocks and these are overlain by the Permo-Triassic sequence.

Six boreholes, which penetrate the base of the Permo-Triassic, have been drilled in the basin but many more exist in the surrounding area. In the Worcester Basin itself, four have sonic velocity and formation density logs from which the physical properties of individual geological units have been assessed.

Of the six boreholes referred to above only one is sited near the centre of the basin, the remainder being on the periphery. In view of this the form of the base of the Permo-Triassic and the areal variation in the thickness of the sandstone unit at the base of the sequence, have been derived from geophysical interpretations.

The Permo-Triassic sequence is shown in Table 6.1. The Bridgnorth Sandstone, the conglomeratic Kidderminster Formation and the Wildmoor Sandstone are good aquifers; the overlying Bromsgrove Sandstone is also water-bearing but less important than the underlying sandstones. The outcrops of the Permo-Triassic are very limited around the margins of the Worcester Basin and few data are available about the aquifer properties. By analogy with other regions in Britain the permeability and porosity would be expected to be good. The porosity derived from geophysical logs run in boreholes is about 20%.

Table 6.1. Permo-Triassic sequence in the Worcester Basin

Triassic	Penarth Group
	Mercia Mudstone with
	Arden Sandstone
	Bromsgrove Sandstone
	Wildmoor Sandstone
	Kidderminster Formation
Permian	Bridgnorth Sandstone

The combined thickness of the Permo-Triassic sandstones is shown in Figure 6.1. It increases towards the centre of the basin and attains a maximum thickness of more than 1500 m.

Depths to the base of the Permo-Triassic (Fig. 6.2) are based mainly on the interpretation of geophysical data. The Bouguer anomaly maps indicate that the Worcester Basin is a closed low area containing two subsidiary lows, one near Winchcombe and the other near Worcester. The inference from "highs" on both gravity and magnetic maps is that the basin is separated from the Wessex Basin by a pre-Permian sill and this is supported by evidence from boreholes. The maximum depth in the centre of the basin is considered to be about 2300 m. Different interpretations are possible depending upon whether or not Coal Measures occur below the Permo-Triassic. If they do, sandstones within them may prove to be aquifers.

Heat flow and temperature measurements

A single heat flow measurement in the basin has a relatively low value of 33 mW/m². The average temperature gradient in the area (based mainly on "bottom hole" temperature measurements to a depth of 3 km) is only 23°C/km, which is the gradient used to calculate the temperatures in Fig. 6.2. However, there is considerable variation with lithology; in the poorly conducting argillaceous material above and below the Permo-Triassic sandstones, gradients are generally higher than in the sandstones themselves.

Assessment of the geothermal potential

The Permo-Triassic sandstones in the basin probably attain a maximum thickness of at least 2000 m and reach depths of more than 2.3 km. The average temperature gradient is about 23°C/km which would lead to temperatures at 2 km in the region of 55°C. Little is known about the aquifer properties of the sandstones at depth.

Figure 6.1 Estimated thickness of the Permo-Triassic sandstones in the Worcester Basin.

Figure 6.2 Depth to the base of the Permo-Triassic sandstones in the Worcester Basin.

Figure 6.3 Temperature-depth relationship in the Worcester and north Wessex basins and surrounding areas

CHAPTER 7. CARLISLE BASIN AND ADJACENT AREAS

Introduction

The low-lying, drift covered Solway Plain, which is the surface expression of the Carlisle Basin, is bordered by the Lower Palaeozoic rocks of the Southern Uplands and the Lake District to the north-west and south respectively, and by the Carboniferous of the Pennines to the east. Interest in the geothermal potential of the region arose from the presence of permeable and porous Permo-Triassic sandstones particularly in the deep Mesozoic Carlisle Basin. A further factor was the unexpectedly high temperatures measured in the Silloth and Archerbeck boreholes (Fig. 7.1).

Only one deep borehole that penetrates the Permo-Triassic succession has been drilled near the centre of the Plain, and the structural history of the area is a matter for conjecture based on the evidence provided by outcrops around the margin of the basin. In particular the nature and extent of Carboniferous strata beneath the Permo-Triassic is unknown. The interpretation of the structure is, therefore, based on geophysical information derived from regional aeromagnetic coverage and gravity surveys, compiled by the Institute of Geological Sciences, together with a detailed gravity and about 35 line-km of seismic reflection data.

The post-Carboniferous geological sequence in the Solway region, including the Vale of Eden is given in Table 7.1.

Table 7.1 Geological sequence in the Carlisle Basin and adjacent areas

Lower Lias
Stanwix Shales
Kirklington Sandstone
St Bees Sandstone
St Bees Shales
Penrith Sandstone and Brockrams

The Lower Lias forms the higher ground to the west of Carlisle and this represents the only known occurrence of post-Triassic rocks in the region.

The most productive aquifers are the sandstones in the Permo-Triassic of which the Penrith Sandstone in the most promising source of geothermal energy as it occurs near the base of the succession and includes horizons with high porosity. Aquifers within the Carboniferous are probably confined to the sandstones of the Upper Carboniferous. The Upper Old Red Sandstone crops out on the northern margin of the Carlisle Basin and, if it extends southwards beneath the Carboniferous, could represent a geothermal

reservoir, although its permeability may be low; the geophysical data currently available cannot be used to confirm its occurrence in this region.

The most extensive area of Permo-Triassic rocks is in the Carlisle Basin but three other basins contain Permo-Triassic sediments in the surrounding region. These are the Vale of Eden, the Dumfries Basin and the Lochmaben Basin (Fig. 7.1 and Plate 1).

Carlisle Basin

The Permo-Triassic sequence in the Carlisle Basin is known from outcrops and was proved by the Silloth Borehole which reached a total depth of 1342 m in what was believed to be Lower Carboniferous rocks. The sequence penetrated above the Carboniferous was:

	Thickness (m)	Depth (m)
Quaternary	55	55
Stanwix Shales	325	380
Kirklington Sandstone	94	474
St Bees Sandstone	396	870
St Bees Shales	63	933
Penrith Sandstone and Brockrams	379	1312

It had been thought that both the Kirklington and Penrith sandstones reduced in thickness and eventually died out to the west, but the presence of a significant thickness of Permian sandstone at Silloth indicates that conditions of deposition varied appreciably within the area and increases the possibility that aquifers might exist at depth elsewhere. The absence of Upper Carboniferous is perhaps surprising but is consistent with the interpretation of the gravity and seismic data. The borehole was located on a small local uplift identified from the gravity data and land seismic and sparker surveys, with the primary intention of testing the stratigraphy of the Permo-Triassic. Schlumberger logs suggested that all the sandstones were water-bearing. Effective porosity values were up to 25% with the highest porosities recorded in the Kirklington and Penrith sandstones. Temperature measurements suggested a relatively high thermal gradient and the bottom hole temperature at 1335 m was 68°C, recorded only 6 hours after mud circulation had ceased.

The maximum thickness of the Permo-Triassic in the Carlisle Basin probably occurs beneath a Bouguer anomaly low (Ag in Fig. 7.1), 9 km to the east of the Silloth Borehole. The increase in depth of the base of the Permo-Triassic towards the centre of the basin, where salt may overlie the Penrith Sandstone, is considered to be less than 400 m so that it is unlikely that Penrith Sandstone will be found below 1700 m.

The Silloth Borehole was sited 9 km west of

the centre of the Bouguer anomaly low just referred to. Values have increased by nearly 5 mGal from the centre of the low to the borehole. A density contrast of 0.25–0.35 g/cm³ between the Permo-Triassic and Lower Palaeozoics could imply an additional 325–450 m of Permo-Triassic at the centre of the basin, while the seismic evidence indicates a thickening of at least 200 m. A range 1500–1900 m is, therefore, given for the depth to the base of the Permo-Triassic north-east of Abbeytown where the basin is likely to be thickest. The use of a higher density contrast to reduce the thickening required to explain the change in Bouguer anomaly, would be justified if salt occurred beneath the gravity low. Slight increases in both salinity and drilling rate were detected at a depth of around 915 m in the borehole but no further evidence of salt was found.

To the north-east of the basin the Permian thins as the pre-Permian floor rises to within 650 m of the surface. A series of strong seismic reflections are developed at about 1 second two-way travel time (approx. 1800 m depth) which are provisionally attributed to the Carboniferous Limestone Series. If this is the case there may be up to 1 km of Upper Carboniferous to the east of Kirkbride. As a mean density contrast of no more than 0.15 g/cm³ at the base of the Permo-Triassic would account for the observed rise in Bouguer anomaly across this part of the basin, the gravity data support the idea of a change in Carboniferous lithology to lower density formations, which probably include Coal Measures to the east, unless there is a steep regional gravity gradient.

Although the thickest part of the Permo-Triassic basin would be expected to coincide with the youngest Mesozoic outcrop in the Great Orton outlier, the sequence is almost certainly thicker near the Bouguer anomaly low, some 10 km further west along the direction of elongation of the Lias outcrop. From the seismic evidence it appears that lateral variations are also occurring in this direction so that the thickness of Permo-Triassic beneath the outlier may be significantly reduced, with little or no Permian sandstone, while the Upper Carboniferous is more fully developed. The origin of the basin attributed to the gravity low may be explained by the intersection of north-north-westerly trending Hercynian fault lines with a broad Caledonian synclinal structure. In view of the lack of control with which to define the deposition of the Carboniferous formations, no detailed models are put forward on the basis of the geophysical data. The presence of a variable thickness of Coal Measures cannot be distinguished from changes in the thickness of the Permo-Triassic by the gravity data, and the seismic coverage is open and too restricted in area. Furthermore, there are no magnetic rocks within the younger formations to enable depth estimates to be made. Bouguer anomaly profiles across the low indicate a residual

amplitude of 6½–10 mGal, depending upon the regional trend which is adopted, and an approximately elliptical shape. If the mean density contrast between the Permo-Triassic and underlying rocks is 0.2 g/cm³, there would be a thickness of no more than 1200 m to the base of the Permian. In order to account for the thickness found in the Silloth borehole, on the edge of the gravity low, without invoking a steep regional gradient, it is necessary to assume either that variations occur within the Carboniferous subcrop, as mentioned above, or that the mean density of the Permo-Triassic increases to the west, implying a higher proportion of shales and breccia relative to porous sandstone, or that salt occurs beneath the centre of the low.

Around and to the east of Carlisle the Bouguer anomaly contours show a regional decrease in value to the north, and there is no indication that the thickness of Permo-Triassic varies significantly except for a tendency to thin towards the east (in view of the lack of a gradient across the Triassic-Lower Carboniferous contact). North-west of Carlisle a small but well defined anomaly maximum at [National Grid Reference NY 329 560] coincides with the main aeromagnetic anomaly (Bm in Fig. 7.1) although, as it apparently originates from a much shallower depth, there is no obvious connection between the two.

Other Permo-Triassic basins

Of the five Bouguer anomaly lows shown in Fig. 7.1 associated with steep gradients, two can be attributed to the Criffel granodiorite (Fg in Fig. 7.1) and Skiddaw granite (Gg) intrusions, while the other three (Bg, Cg and Dg) have been related to Permo-Triassic basins. In the Vale of Eden a maximum Permo-Triassic thickness of 800 m has been estimated from gravity data (Collar, 1978, personal communication) and values of about 1100 m were derived for the Lochmaben and Dumfries anomalies (Bott and Masson Smith, 1960), the former being set within a known Carboniferous basin while the latter two are surrounded by Lower Palaeozoics; breccias tend to be thicker along the south-west margins of these basins. The thicknesses of Upper Carboniferous underlying the Permo-Triassic are not known and their presence would lead to a reduction in the estimated Permo-Triassic thickness but a greater total thickness for the basins. Minimum Bouguer anomaly values of less than zero mGal are found over each basin (compared with 3½ mGal over the Carlisle basin) and the associated gradients are relatively steep. In the case of the Scottish basins it seems likely that deposition occurred over a relatively short time-scale, while the Solway plain region was subject to subsidence over a longer period and wider area. The lower anomaly values found in the Vale of Eden probably reflect a thicker development of Carbon-

iferous as well as density variations within the underlying rocks. The three basins are all extended along a north-north-west axis and, by analogy, the Permo-Triassic within the Solway Plain may be affected by the same trend. The seismic data offer some evidence for this as do the gravity anomaly contours (although subordinate to the north-east trend).

Another gravity low 15 km north of Carlisle (Eg in Fig. 7.1) is similar in form to that east of Silloth but probably represents a concealed extension of the Canonbie Coalfield and a thickening of the Upper Carboniferous rather than a significant Permo-Triassic basin.

Temperature measurements

Bottom hole temperatures were recorded at two levels in the Silloth Borehole. At 727 m the temperature was 28°C when measured only 3 hours after mud circulation had ceased. At 1335 m a bottom-hole temperature of 68°C was measured 6 hours after circulation had stopped; using an approximate, empirical, correction to allow for the cooling effects of the circulated fluid gives an estimate for the equilibrium temperature of 80°C and a corresponding mean temperature gradient of 52°C/km to this depth. One other deep temperature measurement at the Archerbeck Borehole [NY 4157 7815], 23 km north of Carlisle, gave a logged temperature of 61.2°C at a depth of 1365 m within the Carboniferous Limestone Series; the time since mud circulation ceased was not recorded. The temperature at the depth recorded implies a temperature gradient of 37.9°C/km.

Although too much reliance cannot be placed on these isolated measurements the temperature gradients within both the Permo-Triassic and Carboniferous formations appear to be above average. There is no reason to suppose that the thermal conductivity of these rocks is lower than for similar rocks elsewhere but heat flow information would be needed to resolve this point.

Assessment of the geothermal potential

Geophysical evidence suggests the Permo-Triassic sequence is about 1700 m thick in the deepest part of the Carlisle Basin and over 1000 m in the Dumfries and Lochmaben basins. This is in a region where bottom hole temperatures in two boreholes gave above average temperature gradients. This is not entirely unexpected as the region is within the high heat flow belt postulated by Richardson and Oxburgh (1979). The thermal gradient of 52°C/km in the Silloth Borehole is particularly high. This would give a temperature of over 60°C at 1000 m and nearly 90°C at 1500 m. If the more conservative figure of 38°C/km for the Archerbeck Borehole is taken, then the temperatures at 1000 and 1500 m would be rather less than 50°C and about 67°C

respectively.

The temperature of the Permo-Triassic sandstones may be expected to exceed 60°C over an appreciable area (Fig. 7.1). Whether or not the rock properties are appropriate for water development would require testing by drilling, but the prospects must be encouraging. Certainly the Permo-Triassic sandstones would be a potential source of heat if the temperature requirements were relaxed in the event of heat pumps being an economic proposition.

Figure 7.1 Principal geophysical anomalies in the Carlisle Basin and adjacent areas

CHAPTER 8. THERMAL WATERS IN THE BATH-BRISTOL BASIN

Introduction

Thermal waters discharge naturally at the surface at two localities in the Bath-Bristol basin, and historical records also refer to the interception of tepid water in boreholes. In the city of Bath (Fig. 8.1) three thermal springs have been used for balneological purposes at least since Roman times. The principal spring discharges from the Lias at a rate of nearly 15 l/s and a temperature of 46.5°C. At Hotwells, Bristol, a thermal spring discharges from the Carboniferous Limestone at a temperature of 24.3°C and an approximate flow rate of 2 l/s. Boreholes made in Kingsmead Street, Bath (Pinch's Well) and at Batheaston also intercepted thermal water. The high temperature of all these waters is considered to be due to the deep circulation of meteoric water, probably in the Carboniferous Limestone but also possibly in the Old Red Sandstone.

The Bath-Bristol basin is the broad synclinal structure which is limited to the south by the Mendip axis, to the west by the Carboniferous Limestone ridge extending from Clevedon through Bristol and to the north, and to the east by the eastern limb of the Bristol Coalfield (Fig. 8.1). More precisely, the groundwater divide along these ridges forms the boundary and thereby encompasses the hydrogeological unit possibly contributing to the thermal springs.

The structure of the basin is complex but basically the synclinal structure is in Carboniferous rocks which are overlain unconformably by Triassic sediments. The Carboniferous was folded by the Hercynian movements and major east-west folds associated with thrust faults affect the sequence and are believed to influence the circulation of groundwater.

The entire sequence embraces rocks from the Lower Palaeozoic to the Jurassic (Table 8.1). Lower Palaeozoic rocks and the Old Red Sandstone occur around the margin of the basin (Fig. 8.1).

The shape of the basin is well defined by the Carboniferous Limestone outcrop and sub-crop. The limestone, which is about 500 m thick, has a considerable bearing on the hydrology of the basin particularly the circulation of the thermal waters. It is a compact limestone with virtually no primary porosity. Water movement is through fissures and solution cavities.

The overlying Millstone Grit and Coal Measures form an alternating sequence of sandstones and shales. The main sandstone developments are the Brandon Hill Grit (which is diachronous and equivalent to the Upper Carboniferous Limestone Series in the north) and the Pennant Sandstone of the Upper Coal Measures.

The overlying Triassic was deposited on an irregular Carboniferous land surface. The Dolomitic Conglomerate, at the base, is a scree deposit restricted to the margins of the high ground. Towards the centre of the basin it passes laterally into a sandstone, about 20 m thick, overlain by the Mercia Mudstone. The Triassic is succeeded by the Jurassic which is restricted to the eastern part of the basin.

Characteristics of the thermal waters

The temperature of the King's Spring at Bath is remarkably constant at 46.5°C. The discharge rate varies from about 13 to 15 l/s. Two other thermal springs, the Old Royal and Cross Bath springs, are very close to the King's Spring and their temperatures and chemical qualities are very similar but the flow rates are much smaller, only about 1.5 l/s from the Old Royal and 1.0 l/s from Cross Bath. The Hotwells Spring in Bristol discharges from the Hotwells Limestone of the Carboniferous Limestone Series on the north bank of the River Avon. As already mentioned, the temperature is 24.3°C and the flow rate 2 l/s.

The total mineralisation of all the thermal waters is low. The value for the King's Spring is about 2100 mg/l, the dominant ions being calcium and sulphate. The tritium content is negligible thereby indicating the absence of post-1953 recharge in the water.

The Hotwells Spring also has a low mineralisation (about 900 mg/l) but it is a Ca, HCO₃ - SO₄ water. The tritium content is greater than 34 T.U. and the nitrate content about 25 mg/l, indicating considerable dilution of the thermal component by recent near-surface groundwater. The discharge also has a high positive redox potential of +350 mV. A mixing model involving shallow Carboniferous Limestone groundwater and a deep component, similar to that at Bath, would explain the hydrochemical characteristics.

The water from the springs at Bath is relatively enriched in strontium, lithium and fluoride compared with non-thermal waters in the basin. The higher concentrations of both strontium and lithium are consistent with circulation and mineralisation of the thermal waters in the Carboniferous (or another Upper Palaeozoic aquifer). Levels of dissolved metals are enhanced in the thermal springs, relative to regional groundwaters in the sequence Fe > Mn > Ni > Cu. The presence of variable traces of oxygen in the thermal waters at Bath implies a small contribution from a relatively shallow source, possibly the Triassic, although the residence time must exceed 30 years because of the low tritium content.

Chemical data for the Bath thermal water show that Ca, Mg, Sr, Ba, SO₄, HCO₃ and F can be explained on the basis of chemical equilibrium with calcite, dolomite, gypsum, barite and fluorite respectively. However, the evidence cannot be

Table 8.1. Summary of the main geological formations in the Bath–Bristol Basin and their characteristics

<i>System</i>	<i>Formation</i>	<i>Thickness (m)</i>	<i>Lithology</i>	<i>Classification</i>	<i>Permeability</i>
JURASSIC	Toarcian (Midford) Sands	30–56	Sands, silts	Aquifer	Primary
	Lower Lias	6–60	Clay, calcilutites, limestones	Aquiclude	—
TRIASSIC	“Keuper”	<250	Mudstone with impersistent sandstone	Local aquifer/ Aquiclude	Primary
	Dolomitic Conglomerate		Well cemented conglomerate	Local aquifer	Secondary
CARBONIFEROUS	Coal Measures	(Pennant Sst: 244–742)	Coarse cemented sandstone	Aquifer	Secondary
	‘Millstone Grit’	30–275	Grit, sandstones, sandy limestones and mudstones	Aquitard	—
	Carboniferous Limestone	550–915	Massive crinoidal limestones, dolomites, calcilutites and oolites	Aquifer	Secondary
	Lower Limestone Shales	16–152	Calcareous shales and thin crinoidal limestones	Aquiclude	—
DEVONIAN	Old Red Sandstone	67–134	Shales, cemented sandstones and conglomerates	Aquifer	Secondary
SILURIAN	Ludlow, Wenlock and Llandovery Series	<290	Cemented sandstones and shales predominant with some volcanics	Aquiclude	—

used quantitatively to indicate residence times or origin. The inferences to be drawn from these facts are:

1. large scale mixing with water from intermediate depths, which would disturb the equilibrium, has not occurred;
2. extensive contact with secondary mineral deposits in either Mesozoic or Palaeozoic aquifers has not occurred because of under-saturation with respect to celestite. The strontium levels at Bath are consistent with prolonged dissolution from the Carboniferous Limestone.

A noteworthy feature arising from the chemical studies is the similarity of the Bath thermal waters and groundwater in the Triassic near Bath. This, together with the historical record of the presence of warm waters at Batheaston, suggests that thermal waters may be recharging the Triassic.

In addition to studies of the inorganic chemical composition of the thermal waters and their comparison with the non-thermal groundwaters of the basin, the isotope ratios δD , $\delta^{18}O$, $\delta^{13}C$ and $\delta^{14}C$ were determined and also the uranium content, $^{234}U/^{238}U$ activity ratio, and the ^{226}Ra and ^{222}Rn contents. The object was to assess the age of the water and to generate possible mixing models, leading to an indication of the residence time and the proportion of deep-seated thermal water in the thermal springs.

The inert gases, helium and argon, were also analysed to obtain information about the temperature at the time the groundwaters actually entered the ground and also assist in the determination of age and residence time.

Chemical geothermometry methods, particularly those based on dissolved silica, were also applied to the data for all groundwaters sampled.

The results of these studies were integrated in an attempt to understand the nature of the thermal flow system. The conclusions are discussed in the following section and in more detail in a comprehensive report on the Bath-Bristol basin which is being prepared. They are summarised in Table 8.2.

Thermal flow system

The study has confirmed the view that the thermal water is of meteoric origin. It probably enters the basin as infiltration into the Carboniferous Limestone around the periphery and gravitates to considerable depths in the aquifer, and possibly the Old Red Sandstone, before rising to the surface along deep-seated fractures.

The dissolved inert gas contents of the thermal waters indicate that they have been equilibrated with air at the time of recharge and are, therefore, of meteoric origin. This is supported by the stable isotope results; the δ^2H and $\delta^{18}O$ values of water from the King's Spring at Bath and Hotwells at Bristol lie close to the meteoric water line defined by:

$$\delta D = 8 \delta^{18}O + 10$$

The temperatures at which air equilibration took place in the soil zone, at the time the thermal waters were being recharged, have been estimated from their dissolved inert gas contents as 8.7 and 9.7°C for the Bath and Bristol waters respectively, thus indicating that they were recharged during climatic conditions similar to the present. They are, therefore, likely to be younger than 10 000 years, the end of the Devensian glaciation in Britain, or, less likely, older than 70 000 years, the start of the last stage of the Pleistocene.

Chemical geothermometry based on the dissolved silica content of the thermal water sources at Bath suggest the most probable temperature of silica equilibration is 80°C. The minimum temperature of the thermal reservoir, derived using chalcedony as the controlling silica polymorph, is 64°C. The most likely temperature of silica equilibration for the thermal component of the Hotwells Spring at Bristol is slightly lower at 60°C.

As the source of the thermal water is rain falling on the basin, the high temperature is considered to be due to groundwater circulating to a depth of between 2700 and 3500 m in the Carboniferous Limestone and/or the Old Red Sandstone under the prevailing geothermal gradient of 20°C/km.

The low tritium content of the King's Spring indicates that no significant contribution is derived from the Jurassic aquifers overlying the Lower Lias clays at Bath. The Carboniferous Limestone and Old Red Sandstone outcrops in the anticlinal cores of the Mendips are the only areas likely to furnish sufficient piezometric head to drive the hydrothermal system and an evolution solely within the Triassic sequence must be discounted by the piezometric evidence alone. The relatively high SO_4^{2-} content of the thermal water at Hotwells could be generated deep within the Carboniferous Limestone/Old Red Sandstone aquifers, rather than by contact with evaporite deposits in the overlying Triassic. The $^{87}Sr/^{86}Sr$ ratios, whilst indicating a Triassic origin for the strontium, are consistent with a derivation of the strontium from secondary mineralisation in the Carboniferous Limestone. The lithium content is comparable with other groundwaters of deep origin within the Carboniferous Limestone in the U.K. rather than with groundwaters from Triassic sandstones.

Consideration of the discharge temperature, the probable chemical equilibration temperature of the thermal water, and the possible sources for the thermal energy of the water, also suggest that the Carboniferous Limestone and possibly the Old Red Sandstone are the source aquifers at depth. The enrichment in ^{13}C , however, is one of the strongest lines of evidence that the thermal water has evolved within the marine Carboniferous

Limestone rather than the largely non-marine Old Red Sandstone. Even so, a small proportion is considered to have circulated deep within the Old Red Sandstone, prior to storage and transmission within the Carboniferous Limestone.

Although it is not possible to make an exact estimate of the age or residence time of the thermal water, various lines of evidence — for example $\delta^{14}\text{C}$, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $\delta^2\text{H}$, inert gases, ^3H , and ^4He — taken together allow a strong case to be made, for the bulk of the water to be less than 10 000 years old.

The $\delta^{18}\text{O}$ data and estimated recharge temperatures imply that the thermal water originated as precipitation during a temperate climate similar to that of the present day. The low negative $\delta^{13}\text{C}$ values indicate that the most likely source aquifer is the Carboniferous Limestone and also that considerable equilibration of HCO_3^- with the source rock has occurred. This means in turn that a reliable model for correcting the ^{14}C ages cannot be established except that a *maximum* age for the bulk of the water is most likely to be about 19 000 years, if one assumes that mixing with any younger or older water is below 10%. Furthermore, in view of the supporting evidence for the temperature of recharge, the age of the bulk of the thermal water must be less than 10 000 years.

The exact proportion of water older than 10 000 years in the mixture cannot be easily assessed. Although it is possible to assign an age, using ^4He , to intergranular flow aquifers with known radioelement contents, it is more difficult in fissure flow formations such as the Carboniferous Limestone or Old Red Sandstone. The ^4He levels at Bath are unusually high and it is difficult to envisage a mechanism for generation of the observed amount within a residence time of 10 000 years using known models. This aspect requires further study, but the conclusion at present is inescapable that a small proportion of the discharge at Bath (and at Bristol) is older and is derived from a deeper aquifer.

The results of periodic ^3H determinations on water from the King's Spring suggest that any contribution from the Jurassic aquifers which overlie the Lower Lias clays at Bath is small. However, the occasional presence of small concentrations of ^3H and fluctuations in the Eh and radioelement content of the thermal water are probably caused by some leakage of water from these aquifers at a rate not exceeding 3 per cent of the thermal discharge.

The major element characteristics demonstrate the hydrochemical similarity between the thermal water source and groundwater from the Triassic sequence near Bath. The probable piezometric distribution implies that thermal water from a deep source not only discharges at Bath but also recharges the Triassic in the vicinity of the thermal spring and that it may then flow radially

away from the spring in the Triassic. Groundwater at 13.2°C is pumped from the Triassic at Weston (1.9 km west of the King's Spring) and tepid groundwater (16.7°C) has been reported in the Triassic at Batheaston, 4 km NE of the King's Spring.

Further evidence for this flow into the Triassic comes from a similarity between the excess ^4He contents of the Bath thermal water and the groundwater at Weston and also from the similarity of the $\delta^{13}\text{C}$ values for the dissolved carbonate in these two sources. The SO_4^{2-} of the thermal water declines during flow in the Triassic to Weston and Batheaston. The ^{226}Ra content at Weston is much lower than for the King's Spring and is likely to have been removed by cation exchange and/or during sulphate precipitation. The uranium geochemistry also changes from the King's Spring to Weston, the uranium content increasing and the $^{234}\text{U}/^{238}\text{U}$ activity ratio decreasing slightly. This would be expected to occur if minor mixing with relatively recent and more oxidising water occurred.

The excess ^4He levels at Weston are in fact higher than at Bath, and it is possible that accumulation of ^4He in the Triassic has been facilitated by diffusion from depth up the nearby Pennyquick fault.

It can be assumed, due to its short half-life, that the ^{222}Rn content of groundwater is derived very close to the discharge point except in the case of fissure flow. The ^{222}Rn contents of the King's Spring and Weston groundwaters are similar but are not likely to be linked by rapid fissure flow because of the large temperature difference between them. Thus the Weston source must derive its ^{222}Rn locally in the Triassic and laboratory tests have demonstrated that considerable ^{222}Rn contents accumulate in pore waters in the Mercia Mudstone. It is, therefore, probable that much of the ^{222}Rn content of the thermal water is also derived from this formation.

Further work on the piezometric levels and hydraulic characteristics of the Triassic close to Bath, and on the major and radioelement geochemistry is necessary to confirm the interpretation and to establish the flow pattern of the thermal water in the Triassic more completely.

At Bath, the King's Spring, the various minor thermal discharges and the Kingsmead Street borehole (Pinch's Well) are aligned east to west. Historical records show that the discharges from the Old Royal and Cross Baths were reduced considerably and immediately by the artesian flow from Pinch's Well. This may illustrate the local importance of an E-W fault at Bath in controlling the flow and distribution of the thermal water at intermediate depths both within the Triassic sequence and through the Lower Lias to the surface.

On a larger scale the thermal springs at

Bath and Hotwells, Bristol, occur on opposite limbs of the Bristol Coalfield syncline but along a WNW-ESE alignment parallel to the major Armorican structures of the Mendip periclinal axis and the strike of the major thrust fault systems. This relationship between the thermal springs and major tectonic structures may reflect the importance of deep southerly dipping thrust planes in controlling upward flow of the deeply circulating groundwater.

The cumulative evidence points to the Carboniferous Limestone as the key component of the thermal system although the Old Red Sandstone possibly plays a role. Indirect flow into the limestone from the Lias, Mercia Mudstone, Coal Measures or Millstone Grit is improbable but this could only be clarified following further hydrological investigations. However, mixing of the thermal waters and shallow groundwater does occur, probably as the hot water rises to the surface, as shown at Hotwells, for example. Direct recharge of the Carboniferous Limestone and Old Red Sandstone along their outcrops is probably the input point for the thermal cycle which is depicted conceptually in Fig. 8.2.

Thermal water as a potential resource

The thermal water is believed to be stored at depths of between 2700 and 3500 m in the fracture system of the Carboniferous Limestone and any attempt at exploitation would need to be directed at this aquifer.

In the vicinity of Bath a relatively rapid ascent of thermal water probably occurs up a southerly dipping thrust and through younger, near-vertical, faults to the surface. At least one fifth of this ascending thermal water recharges the Triassic siltstones, but the larger proportion is discharged at the Bath thermal springs. At Bristol the thermal water mixes with a considerable amount of shallow, cold groundwater prior to discharge. The thermal component is believed to flow up a fault system in the Carboniferous Limestone which is related to the Avon Thrust.

The low effective bulk permeability of the Carboniferous Limestone at depth is unlikely to allow a flow of thermal water much greater than the observed discharge at Bath, that is approximately $1000 \text{ m}^3/\text{d}$, and there could, therefore, be no exploitation of thermal water within a radius of several kilometres of Bath without the serious risk of affecting the spring discharge. The sensitivity of the thermal flow to reduction of pressure in nearby boreholes verifies this.

It is possible that the Carboniferous Limestone stores thermal water along its 15 km strike between Bath and Bristol, but at present this is speculation and would have to be proved by drilling. Any exploration borehole should be located towards the Bristol end of the thrust fault system, believed to control the flow, to minimise the

danger of affecting the Bath Springs.

At Bath a discharge of almost $50 \text{ m}^3/\text{hr}$ of water at 46°C results from a natural head loss of 10 m. A drawdown of 30 m in a borehole tapping the resource at depth might, therefore, furnish a supply of 100 to $110 \text{ m}^3/\text{hr}$. Should the actual discharge be at 70°C and the water be rejected from a heat exchanger at 25°C , this would furnish a thermal yield of about 5 MW.

The fact that the reservoir would be essentially a fracture system in a massive limestone has important implications. Firstly, the siting of a successful borehole, on the evidence available, would be largely a matter of chance; secondary permeability systems show marked heterogeneity in their hydraulic characteristics and the interception of open, interconnected fissures at any particular site cannot be predicted. Artificial stimulation of the natural permeability might have to be considered, to effect communication with the fracture system. Secondly, it would be wise to assume that hydraulic communication via fractures could exist between any production borehole and the Bath thermal spring system over considerable distances.

As a means of protecting the existing thermal springs it is important to examine the hydraulic regime in the basin in more detail by drilling before any geothermal development is considered. The hydraulic characteristics of the Carboniferous Limestone at depth within the basin also require in-situ testing. A thorough testing programme should, therefore, be planned for any borehole designed to investigate the Carboniferous Limestone and preferably it should be sited in the vicinity of Bristol.

The disadvantage of exploration nearer Bristol than Bath is that the depth of groundwater circulation in the Carboniferous Limestone is thought to be less, and the maximum temperature of the deep thermal water would be lower, at around 60°C , as suggested by the thermal component of the Hotwells Spring.

Table 8.2. Summary of conclusions from the geochemical indicators.

Parameter	Aspect of study	Conclusions relevant to Bath/Bristol thermal springs
Na K Ca Mg HCO ₃ , pH SO ₄	Cation ratio geothermometry + Mineral equilibria + Definition of major hydrochemical type	Na/K/Ca geothermometer invalid in the sedimentary aquifers of the region. Major ion chemistry constant at Bath over 12 months and calcite, dolomite and gypsum equilibria established. Thermal water at Bristol mixed 1:2.3 with shallow limestone groundwater. Geochemical relationship between Weston and Bath denotes that thermal water is leaking into the Triassic
SiO ₂	Dissolved silica geothermometry	Chalcedony gives 64°C and quartz 96°C max equilibration temperature. 64°C used as minimum reservoir temperature
NO ₃	Indication of near surface (pollutant) contamination	Nitrate (1.2 ± 0.1 mg/l) remains constant during monitoring period and shallow pollution can be ruled out
Sr, Li Ba, F Ni, Cu Fe, Mn	Possible indication of source aquifer	Li supports theory of leakage into Triassic. Fluorite equilibrium attained. High Sr consistent with evolution within Carboniferous Limestone, but ⁸⁷ Sr/ ⁸⁶ Sr (0.71075 ± 6) suggests Triassic origin and derivation of Sr from secondary mineralisation
pH, Temperature Eh, dissolved O ₂	Definition of controlling mineral equilibria and redox system	Temperature constant (46.5 ± 0.1°C) but pH, Eh and O ₂ varied during monitoring period. Sulphide absent. Possibility of contribution of small amount of groundwater at intermediate depth
Tritium, ³ H	Indication of post-1953 recharge to source	No contribution of recent (post 1950's) groundwater at Bath
δ ¹⁴ C, δ ¹³ C	Indication of groundwater age and carbon isotope evolution	δ ¹³ C (-1.6 ‰) diagnostic of marine carbonate equilibration/evolution suggesting the Carboniferous Limestone is the main thermal reservoir. Radiocarbon results (mean 4.5% modern) denote <i>maximum</i> age of 19 000 years
δ ¹⁸ O, δ ² H	Indication of origin of groundwaters (juvenile; meteoric; marine)	Meteoric origin indicated at Bath with δ values similar to local present day groundwaters (-7.4 ‰, -46 ‰). Recharge during glacial or periglacial conditions therefore ruled out.
²³⁴ U/ ²³⁶ U ²³⁸ U content	Investigation of systems' potential to indicate source aquifer and evidence for mobilization of uranium	²³⁸ U content at Bath (0.06 ± 0.002) extremely low, but activity ratio (2.62 ± 0.23) varied during monitoring implies up to 10% mixing with intermediate depth groundwater
²²⁶ Ra ²²² Rn ⁴ He	Indication of residence time, flow history and radiochemical characteristics	²²² Rn and ⁴ He levels varied during monitoring reflecting a) 1976 drought, b) possible seasonal head change in confining strata. Anomalously high ⁴ He content (1432 cm ³ STP/cm ³ H ₂ O) at Bath implies a long residence time or an enriched radiogenic source
Inert Gases Ne, Ar, Kr, Xe	Estimation of recharge temperature	Recharge temperature of Bath thermal water (8.7°C) comparable with that of modern regional groundwaters; rules out periglacial recharge

Figure 8.1 Solid geology map of the Bath-Bristol region

B: Broadfield Down D: Dundry Down M: Mendip Hill

Figure 8.2 Conceptual model of the flow path of thermal water in the Bath–Bristol Basin

1. Recharge on the Carboniferous Limestone/Old Red Sandstone outcrop of the Mendip Hills.
2. Down dip (and down gradient) flow.
3. Possible gain from Lower Palaeozoic and leakage to Upper Carboniferous via Farnborough Compression zone.
4. Some leakage of very old ^4He bearing groundwater from Old Red Sandstone and possibly Lower Palaeozoic.
5. Storage and chemical equilibration with the Carboniferous Limestone.
6. Relatively rapid flow up thrust fault system associated with Hercynian tectonism.
7. Recharge of Keuper siltstone by thermal water.
8. Discharge at the surface.

CHAPTER 9. THE MIDLAND VALLEY OF SCOTLAND – A GEOPHYSICAL APPRAISAL

Introduction

The Midland Valley of Scotland is a lowland tract about 80 km wide which stretches 200 km across Scotland with a north-easterly trend (Plate 1 and Fig. 9.1). It lies between the rugged terrain of the Grampian Highlands to the north and the softer hills of the Southern Uplands to the south. The two largest cities, Glasgow and Edinburgh, and most of the main industrial centres of Scotland are all situated in the Midland Valley, constituting a potential consumer area for geothermal energy supplies. The possibility that arenaceous rocks of Upper Palaeozoic age may occur at sufficient depth in the Midland Valley and contain geothermal resources led to an appraisal of the available geophysical data with a view to assessing the geothermal potential.

Geology

The Midland Valley is an elongate basin containing sedimentary and igneous rocks, mainly of Devonian and Carboniferous age, bounded to the north-west and south-east by major parallel structural lines, namely the Highland Boundary Fault and the Southern Upland Fault respectively (Fig. 9.1). Other north-easterly trending structures are common but there are also some with north-westerly trends, such as the Permian-filled Mauchline Basin, and northerly trending folds such as the Clackmannan Syncline.

Dalradian metamorphic rocks occur to the north of the Highland Boundary Fault while to the south of the Southern Upland Fault, greywackes and shales of Lower Palaeozoic age are found. Either of these rock assemblages may underlie the Midland Valley and there is a possibility that in parts, strata of Silurian age may rest upon continental basement of Lewisian type.

Geological opinion remains divided on the early structural evolution of northern Britain, but it seems likely that the Midland Valley came into being in middle to late Silurian times during the penultimate phase of the Caledonian orogeny. A sequence of up to 9 km of terrestrial sediments and volcanic rocks of Upper Silurian and Lower Devonian age accumulated in a subsiding basin flanked to north and south by upland areas. An episode of folding and erosion during the Middle Devonian was followed by the deposition of up to 1.5 km of Upper Devonian sandstones and conglomerates. These are overlain, usually conformably, by the Lower Carboniferous Calciferous Sandstone Measures, which in the west contain large thicknesses of lava, but are predominantly represented by sandstones and mudstones in the east. Above these rocks the deposition of the Lower Limestone Group, the

Limestone Coal Group, the Upper Limestone Group, the Passage Group and the Coal Measures was locally influenced by folding and fault movements. Finally, Permo-Triassic sandstones were deposited following an episode of gentle folding with local volcanic activity. Surviving deposits are not common and do not extend to significant depths.

Although there is no information about deep aquifers, some general observations can be made about the potential of some of the arenaceous horizons based on local hydrogeological surveys. The Lower Devonian sandstones contain some supplies of water but are locally cemented. There are suggestions that the permeability may decrease regionally to the west. The Upper Devonian sandstones are generally less well cemented. Abundant groundwater has been obtained from the Upper Devonian Knox Pulpit Formation in central Fife, in the north-east of the Midland Valley, but this formation has not been found elsewhere in the Midland Valley. The Calciferous Sandstone Measures locally contain appreciable amounts of water and there are also considerable quantities in the Passage Group.

Geophysical data

Regional Bouguer gravity anomaly maps covering the area from 220–390 km E and 650–800 km N (British National Grid) have been produced by IGS. This area encompasses much of the Highlands and all but the south-west corner of the Midland Valley. Data are available for the missing portion and for the bordering area in the Southern Uplands and hence the position has now been reached where a detailed interpretation of the anomaly field could be attempted.

A number of papers has been published on the interpretation of detailed gravity surveys in local areas and it is evident that considerable success can be achieved in terms of near surface geology. The main problem remains of separating the regional effects from these near surface effects and interpreting the regional in terms of a further separation of deep crustal and shallow effects. This intractable problem is unlikely to be solved by consideration of the gravity field on its own but comprehensive studies including magnetic, seismic and geological data may enable the construction of a realistic model of the Midland Valley.

The Aeromagnetic Map of Great Britain (Sheet 1) shows a complex pattern of anomalies in keeping with the complex geology of the Midland Valley. Separation of anomalies due to shallow and deep causative structures has been effected by filtering but interpretation has not yet been detailed.

The Lithospheric Seismic Profile of Britain (LISPB) crossed the eastern end of the Midland

Valley. The results show a layer at a depth of 2.5 km with a seismic velocity of 5.8 km/s, which has been interpreted as Lower Palaeozoic. Geological evidence predicts a much thicker sequence of Upper Palaeozoic rocks and a further examination of the LISPB data is indicated. The National Coal Board reflection seismic surveys in the Clackmannan coalfield were aimed at shallow reflectors and are unlikely to yield data relevant to geothermal prospecting. A reflection survey south-west of Glasgow demonstrated that reflections could be detected from beneath the Clyde Plateau lavas but again the depth of investigation was too shallow to be of use in geothermal prospecting. As part of the present geothermal programme, IGS detected reflections at two experimental sites, one on the Devonian lavas of the Ochil Hills and one on the Lower Devonian sediments west of Kippen (see Fig. 9.1). At the former a reflection was detected from a depth of about 6 km but the results were generally so poor that it is impossible to say anything about the reflector or whether there are any deeper reflectors. At Kippen a short profile was measured and reflections were detected down to 4 seconds two-way time. A necessarily speculative interpretation suggests that the base of the Upper Silurian here lies at about 8 km depth.

Heat flow and temperature measurements

Heat flow values in the Midland Valley range from 37 to 72 mW/m². Two sites (NS 10, NS 12, see Fig. 9.1) are near Glasgow and have high values (68 and 55 mW/m²) but these are not considered very reliable. Other sites (NO 9 and NT 15) on the north side of the Firth of Forth, are more reliable but have lower heat flow values (37 and 40 mW/m²).

Average temperature gradients have been calculated from measurements made at sites more than 500 m below ground level and the values range between 9 and 39°C/km. The most reliable measurements, totalling about eight, give mean gradients ranging between 20 and 27°C/km to a maximum depth of 1200 m.

Assessment of the geothermal potential

The requirements for the exploitation of geothermal energy are the existence of an aquifer of adequate permeability buried at a depth sufficient to yield water at the required temperature. Permeable strata have been studied near the surface in both Devonian and Carboniferous successions but nothing is known about the permeability at depth. The temperature measurements indicate that a useful aquifer would have to be at a depth of over 2 km to give a temperature of 60°C. It is unlikely that an extensive Carboniferous aquifer would be found at depths of that order and therefore attention must be concentrated on the Devonian. The Knox Pulpit Formation may be

present and permeable at such depths below Upper Carboniferous in a belt that extends from Dunfermline to Leven. Geological and some geophysical evidence both indicate that at least in the north-east quarter of the Midland Valley adequate thicknesses of Devonian sediments exist, the complication being the lack of knowledge of the precise position and thickness of the Devonian lavas within the succession. At the western end of the Midland Valley, interpretations of some geophysical surveys have suggested the basement is less than 3 km deep but geological evidence is against this. The positive values of the Bouguer gravity anomaly, particularly over the south-east quarter, still lack an adequate explanation.

CHAPTER 10. POTENTIAL OF HOT CRYSTALLINE ROCK

Introduction

Energy in the form of heat within the earth's crust represents an almost unlimited source but its development is restricted by its inaccessibility. In sedimentary basins the objective is to bring heat energy to the surface by developing a natural fluid — hot water — but because rock permeability decreases with depth while temperature increases, this approach is practicable only under appropriate geological conditions. Exploitation of the major part of the heat stored in the crust requires new techniques applicable in hot impermeable rocks. This has led to the Hot Dry Rock concept which involves creating an artificial fracture system between two boreholes; water is pumped down one, heated by the hot rock and recovered from the second for energy extraction.

The feasibility of the concept has been proved by the Los Alamos Scientific Laboratory at their Fenton Hill Site in New Mexico. Two wells were drilled to depths of about 3000 m, where the temperature was 200°C, and successfully interconnected. Water was circulated through the system over a 75 day period (Tester and Albright, 1979). The programme is continuing and currently two further boreholes are being drilled to about 4000 m in an attempt to repeat the experiment under more exacting conditions with a larger man-made fracture system.

Initially, at least, any application of the hot dry rock concept is likely to be applied in igneous rocks which exhibit anomalous heat flow. In the U.K. heat flow values are available for only three major crystalline bodies. This general absence of data together with the obvious need to be able to identify areas where the hot dry rock concept may be applied in the U.K. led to a programme of work with the following objectives:

1. Define some preliminary exploration criteria by which bodies or regions likely to have above average heat flow associated with hot crystalline rock may be identified in the absence of actual heat flow measurements.
2. In the light of (1) review all relevant geo-physical, geochemical and geological data for all major crystalline bodies.
3. Recommend hot rock target areas for further study.
4. Establish a framework within which the future direction of exploration and exploitation of hot rock in the U.K. may be discussed.

The minimum temperature required for hot rock exploitation is generally considered to be 150°C but it should be in excess of 200°C for power generation (ERDA, 1977). The average geo-thermal gradient in the U.K. is approximately

25°C/km and the average heat flow is close to the world mean of 60 mW/m². Temperature of about 200°C should, therefore, be attainable at depths of about 8 km over most of Britain.

It is uneconomic at present to drill to such depths to exploit geothermal energy, but the cost can be considerably reduced where suitable temperatures can be reached at shallower depths. Thus the overall objectives of the study were to consider factors affecting the temperature-depth relationship in Britain and bring together all the available data with the aim of identifying areas of crystalline rock where anomalous temperatures may be found at accessible depths. The results of the work programme are given in detail by Lee (1978).

Assessment of hot rock potential

The heat flow at any point has three major components:

1. heat from magma bodies;
2. heat transferred by conduction from the earth's interior;
3. heat generated by radioactive decay of uranium, thorium and potassium isotopes in the crust.

Heat flow in Britain is dominated by factors 2 and 3. There has been no recent volcanic activity and individual crystalline bodies of Tertiary age, and certainly those of greater age, are likely to have cooled to equilibrium temperatures. A more regional thermal effect persisting from the Tertiary period (that is a regional variation in factor 2) is a possibility which still requires investigation.

It has been shown that heat flow generally increases linearly with increasing heat production, within a particular heat flow province. The paucity of heat flow data in Britain has meant that the characteristics of the British heat flow province (or provinces) are not well defined and are still the subject of discussion.

Heat flow and heat production data are available for only three of the major crystalline bodies in the U.K. The Cornubian granite batholith (of Hercynian age) and the concealed Weardale granite (Caledonian) have above average values of both, while the concealed Wensleydale granite (also Caledonian) is normal (see summary of prospects below and Fig. 1.1).

Setting aside any regional variations (as yet undefined) in the heat conducted from depth, any heat flow anomalies over other crystalline bodies are likely to be associated with above average heat production.

In addition to heat flow, two other factors are important in the selection of suitable targets.

1. The thermal conductivity of both the crystalline rock and any sedimentary cover. The steepest temperature gradient occurs when high heat flow is associated with low thermal conductivity.

2. Large intrusive volume.

Most of the major British crystalline bodies are shown in Fig. 1.1. They were emplaced during the last three major phases of igneous activity in the U.K. (Caledonian, Hercynian and Tertiary). The prospects for hot rock in each area have been provisionally assessed from a summary of relevant data. Where no heat flow data are available possible targets have been selected mainly on the basis of:

1. Heat production data (uranium, thorium and potassium concentrations). Where these are not available the potential for high heat production has been assessed qualitatively from suggested correlations between uranium enrichment, age, origin and geophysical expression.

2. Large intrusive volume as indicated by gravity data.

The available data are given in detail by Lee (1978). They suggest that the best prospects for hot rock in the U.K. lie in above average heat production in the larger Caledonian or Hercynian granites, enhanced locally by the insulating effect of low conductivity sedimentary cover.

Summary of main prospects

The Cairngorm 'batholith' The high uranium concentration of the Cairngorm granite makes it a possible hot rock target (Brown, 1978). The gravity data suggest that the entire line of granites from Hill of Fare, Mount Battock and Bennachie in the east, through Lochnagar and Glen Gairn to Cairngorm and possibly Monadhlaith in the west, are linked at depth to form one large batholith. The gravity anomaly over most of the batholith (about -30 mgal) is of the same order as that at Weardale which indicates that it probably extends to a depth of several kilometres.

Uranium concentrations across the batholith, apart from at Cairngorm, are not particularly high. Thorium concentrations are above average at Monadhlaith and Mount Battock. These differences in enrichment may be real, reflecting differences in character between the granites and the multiple intrusion history of the batholith, or they may simply be a result of the small number of samples on which the values were based. The existence of a high uranium concentration at Cairngorm is sufficient to justify further study of the whole batholith.

The Etive granite is a ring complex consisting of four or five successive intrusions. The gravity anomaly (about -30 mgal) indicates that the granite extends to a depth of several kilometres and is probably about 20 km in diameter. The uranium concentration (17.29 ppm) is probably high but this view is based on only three samples.

The Loch Doon and Fleet granites The Loch Doon intrusion is a composite body varying from norite at the northern and southern tips through tonolite to an elongated central unit of biotite granite. The Fleet granite, to the south of the Loch Doon complex, consists mainly of muscovite-biotite granite.

The uranium concentration of the Loch Doon intrusion increases from 3 ppm at the edge to 8 ppm over the acid central core (Brown and others, in press). This compares with 1.5 to 3 ppm for the country rock. A similar gradational increase from 11 to 23 ppm is observed in the thorium distribution. The enrichment of heat producing elements associated with the granite centre would result in heat production significantly above average ($4.1 \mu\text{W/m}^3$) if maintained at depth.

Uranium concentration in the Fleet granite is not particularly high (4.87 ppm) but the thorium concentration is above average (29.13 ppm).

An interpretation of gravity data shows that the Loch Doon and Fleet intrusions are connected at depth to form a single body which also includes the minor Carsphairn intrusion (Allsop, in Dawson and others, 1977). The composite batholith covers approximately 45 by 30 km². It extends to a depth of 12 km beneath the Fleet granite and 7 km beneath Loch Doon. The model shows the existence of a substantial granitic platform at a depth of 3 to 4.5 km to the east of Loch Doon. If a significant volume of the Doon/Fleet mass is enriched in heat producing elements then above average heat flow may be expected.

The Newry granodiorite is in a similar structural setting to the intrusions of the Southern Uplands of Scotland. A strong positive Bouguer anomaly associated with a basic mass beneath the Tertiary centre partially obscures the negative anomaly due to the granodiorite, but it is believed to extend to a depth of 13 km (Cook and Murphy, 1952).

The Weardale granite A granite beneath the stable Alston Block in the northern Pennines was postulated by Bott and Masson Smith (1957) from interpretation of the large negative gravity anomaly, and the existence of a granite of Caledonian age at a depth of 390 m directly beneath the Carboniferous succession was subsequently proved by the Rookhope Borehole.

Heat flow determinations in the Rookhope Borehole were carried out by Bott and others (1972). They reported a value of 91.7 mW/m² (corrected for topography only) which is significantly above average. The excess heat flow can probably all be accounted for by high heat production ($4.65 \mu\text{W/m}^3$) due to above average concentrations of uranium, thorium and potassium. Above average heat flow of 95.8 mW/m² was also reported in the Woodland Borehole and hydro-

thermal water ascending the nearby Butterknowle Faults has been proposed as a possible explanation (Bott and others, 1972). Whatever the reason for high heat flow at Woodland it appears that heat flow within the Weardale granite itself is genuinely high due to above average radioactive heat production.

The Lake District batholith An east-west trending gravity 'low', which reaches individual minima over the exposed Eskdale, Shap and Skiddaw granites, has been interpreted as a granite batholith (Fig. 1.1) of Caledonian age connecting the exposed granites at depth (Bott, 1974).

The exposed granites vary in character but both the Skiddaw and Shap granites show significant uranium enrichment. The average heat production over these outcrops is $4.75 \mu\text{W}/\text{m}^3$ which is slightly higher than the Weardale value.

The evidence suggests that heat production (and consequently heat flow) within the Lake District batholith may be as high as that observed at Weardale. It must, therefore, be considered to be a potential hot rock target area.

The Cheviot granite The Cheviot granite (Fig. 1.1) is characterised by a Bouguer gravity anomaly of about -20 mgal. Available data suggest that heat production may possibly be above average ($4.3 \mu\text{W}/\text{m}^3$) but this figure is a result of the high thorium concentration based on only two samples.

Eastern England Negative gravity anomalies at Market Weighton and in the East Midlands west of Lincoln possibly indicate the location of other buried granites although the anomalies may also be explained in terms of thick low density sediments.

The Cornubian granite batholith is the only major crystalline body of Hercynian age in the U.K. Heat production ($4.68 \mu\text{W}/\text{m}^3$) is uniformly high over the whole batholith (Tammemagi and Smith, 1975). The general character of the batholith, a radioactive granite with a large negative gravity anomaly, is similar to that of the Caledonian Weardale granite.

Provisional heat flow results from a series of boreholes across the Bodmin granite give an average of $119.4 \text{ mW}/\text{m}^2$, after correction for topography and palaeoclimate (Francis and Wheildon, 1978). This work showed that the thermal anomaly is not confined only to the Lands End and Carnmenellis outcrops where all previous measurements were taken.

The heat flow measurements at unmineralised sites are probably representative of the heat flow in the bulk of the batholith. The mean corrected heat flow over the Carnmenellis and Bodmin outcrops is

$121 \text{ mW}/\text{m}^2$ and the average conductivity is $3.27 \text{ W}/\text{m}/^\circ\text{C}$.

The latest results suggest that a borehole in excess of 5 km would be required to reach a temperature of 200°C , but it may be possible to attain this temperature at a shallower depth between the major outcrops where the granite is overlain by low conductivity sediments.

Conclusions

Measured heat flow is the most important factor for the initial assessment of geothermal potential but unfortunately measurements have only been made in three major crystalline bodies. In the absence of such data the prospects for hot dry rock have been assessed by considering the characteristics of crystalline bodies formed during the last three major phases of igneous activity, that is the Caledonian, Hercynian and Tertiary.

The best prospects among the Caledonian granites are those which have high radioactive heat production, particularly where this is enhanced by the insulating effect of low conductivity sedimentary cover. Where no heat flow data exist suitable intrusions have been identified mainly on the basis of their size and their potential for high heat production. Where heat production values are sparse or non-existent the potential for high heat production has been assessed from the suggested correlation between uranium enrichment and age, origin and geophysical expression.

The Cornubian batholith of south-west England is the only major crystalline body of Hercynian age in the U.K. Because of its high heat flow it has been recognised as a potential hot rock target and is currently being investigated with this objective in mind.

All the major Tertiary volcanic centres are underlain by large basic to ultra-basic plutons which should have cooled to equilibrium temperatures and their heat production should be low. Above average heat flow due to a more regional effect persisting from the Tertiary period is a possibility.

Overall it is unlikely that dry rock at 200°C exists shallower than about 4 to 5 km anywhere in the U.K.

The present desk study has concentrated on the more obvious hot rock targets. Buried crystalline bodies have been postulated in other areas, from gravity and magnetic data. They have not been considered in the absence of other evidence for the presence of shallow hot rock, but their existence should not be overlooked in future studies.

Proven technology for large-scale, long-term production of high enthalpy heat from hot dry rocks does not yet exist. However, it is well

advanced and it is essential that the data should now be collected from which rational assessments can be made of national and local prospects when development becomes economic and practicable. That will necessitate completion of the inventory of the hot rock potential in the U.K. It must also be borne in mind that the exploitation of low permeability non-crystalline rocks has also been suggested and the potential of such geological occurrences has not yet been attempted for the U.K.

CHAPTER 11. GEOCHEMISTRY OF GROUND-WATER IN THE CORNISH GRANITE

Introduction

Anomalously high heat flows of about 120 mW/m² have been measured across the Carnmenellis granite of S.W. England (Francis and Wheildon, 1978) and the anomaly is now known to extend across the Bodmin granite as well. Early suggestions that convecting thermal groundwater might in part be responsible for this anomaly were prompted by the known occurrence of thermal inflows in the mine-workings. With this background and in the light of the history of research at Marysville, U.S.A. (E.R.D.A., 1977), the groundwaters associated with the Carnmenellis granite have been studied to investigate the significance of their flow pattern with regard to the assessment and exploitation of hot dry rock geothermal energy in the granite.

Groundwater has been encountered in shallow boreholes, less than 100 m deep, across the surface outcrop of the granite and in mines between depths of 200 m and 700 m below ground level within the mineralised belt on the northern edge of the outcrop. In general the shallow groundwaters have a low total mineralisation: of less than 250 mg/l. The deeper groundwaters are much more highly mineralised, the most saline reaching 19 000 mg/l and discharging at a depth of 690 m at a temperature of 42°C.

Hydrochemical characterisation of the groundwaters
The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values for the deep and shallow groundwaters and surface waters indicate that all the groundwaters are meteoric. There is no evidence either for a marine component or a magmatic component in the deep brines.

A general trend is observed of higher mineralisation, lower tritium content and higher temperature with greater depth. Also with depth the relative proportion of Mg^{2+} , SO_4^{2-} and HCO_3^- decrease as the groundwaters become essentially $\text{Na}^+ + \text{Ca}^{2+}$, Cl^- brines (Fig. 11.1). These trends in major component composition are paralleled by increasing concentrations of minor components such as Sr^{2+} and Li^+ . The concentration and $^{234}\text{U}/^{238}\text{U}$ activity ratio of dissolved uranium similarly show the shallow groundwater evolves as it percolates downwards. Oxidising groundwater at shallow depths dissolves uranium with relatively low $^{234}\text{U}/^{238}\text{U}$ activity ratios. At the deeper levels uranium is deposited under the prevailing reducing conditions and the activity ratios consequently increase.

In more detail, however, at any particular depth in the mines a range of total mineralisation and temperature is encountered in the groundwaters (Fig. 11.2). The prevailing geothermal gradient (38°C/km at South Crofty) suggests that groundwaters at any particular depth

Table 11.1. The range of properties of mine-waters encountered at the Wheal Jane and South Crofty mines.

Sample	Tritium T.U. (±2)	Li	Sr mg/l	TDS	Temp °C
Shallow Groundwater	50	<0.01	<0.5	150	10
<i>Wheal Jane</i> †					
77/775	6.2	35	9.7	4300	29.5
77/776	6.6	26	12.8	5600	39.5
78/415*	33	2.9	2.4	1400	24.8
78/416*	—	3.5	1.8	1140	26.4
78/417	6.5	27	11.2	4800	29.9
78/418*	25.6	1.5	0.9	440	23.9
<i>South Crofty</i> †					
78/408*	7.4	13	5.4	2590	37.0
78/409*	13.0	11.8	14.3	5410	36.8
78/410	12.0	54	33.4	11260	43.0
“Hot Dry” (77/774, 78/407)	4.7	120	40	19100	41.5

* waters inferred to be percolating downwards

† Wheal Jane samples are from a depth of 300 m
South Crofty samples are from a depth of 690 m

LOCATION MAP

- x Pendarves 230-260m
- o Mt. Wellington 210-240m
- Wheal Jane 300m
- ▲ South Crofty 690m

Figure 11.1 The chemical composition of groundwaters encountered at depth in mines in Cornwall

Figure 11.2 Depth against temperature of samples with hydrochemically mature convecting groundwater samples indicated

comprise either 'percolation' water moving downwards or 'convecting' thermal water moving upwards. These two types may be distinguished by reference to a variety of hydrochemical and radiochemical parameters. The upward moving groundwaters have had a longer residence time in the granite. Their chemical nature has been determined at higher temperatures and they have developed hydrochemical characteristics by which they may be distinguished from the younger cooler percolation groundwaters. The range of groundwaters encountered at depths of 300 m in Wheal Jane and 690 m in South Crofty are compared with a typical shallow groundwater in Table 11.1. Out of ten separate discharges studied at these depths, the five considered to represent percolation groundwaters have a relatively higher tritium content and lower mineralisation than those interpreted as representing older groundwaters, which have evolved at higher temperatures and at deeper levels.

On this basis five inflows representing thermal, hydrochemically more mature, groundwater have been identified in the deepest levels of the South Crofty and Wheal Jane mines. These 'thermal' groundwaters have been studied in further detail to determine as fully as possible their flow history, in particular their depth of circulation and their residence time.

Residence time

Tritium concentration suggests that the bulk of the mature thermal groundwater has a residence time of less than twenty-five years. It is considered justified to assume that no significant dilution has taken place because the deeper percolation waters themselves have tritium contents approaching those of the thermal waters.

Other indicators of groundwater age have been studied, in particular ^{14}C , radiogenic ^4He and radiogenic ^{40}Ar . Although qualitatively the activity of ^{14}C is much lower in the deeper 'thermal' groundwaters it is not possible to determine their age by this method without more knowledge of the source of the dissolved carbonate and the solution mechanism. Radiogenic ^4He is in general enhanced in the minewaters and the enhancement is approximately proportional to the discharge temperatures, but insufficient is known about the water/rock reaction surfaces and the controlling uranium concentrations to be able to estimate a residence time from the helium data.

The $^{40}\text{Ar}/^{36}\text{Ar}$ activity ratio is enhanced only in the most saline thermal discharge at the deepest level in South Crofty mine. The ratio of $^{40}\text{Ar}/^{36}\text{Ar}$ in atmosphere equilibrated water is 1:295 and in rock of average potassium content a detectable increase could only develop over periods longer than 10^6 years. For example the thermal water discharging at Bath, in Avon, derived from the

Carboniferous Limestone, does not have any enhancement over atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratios although the thermal spring at Buxton, Derbyshire, has a $^{40}\text{Ar}/^{36}\text{Ar}$ activity ratio of 1:306. In the case of the deep brine in the South Crofty mine from the Carnmenellis granite, it must be said that although the bulk was recharged within 25 years, a very small proportion may be extremely old, possibly older than one million years.

Geothermometry and depth of circulation

By identifying the percolation groundwaters at different depths and temperatures and assuming that they represent groundwaters whose hydrochemistry has been determined by geochemical equilibration at their sampling temperature, they can be used as indicators of the reliability of the cation and dissolved silica geothermometers. Of the cation geothermometry methods, that including a correction for pCO_2 is considered most appropriate (Paces, 1975). Of the dissolved silica geothermometers, closest agreement was attained by assuming chalcedony to be the controlling silica mineral phase. Application of these methods to the thermal brines (Table 11.2) results in a maximum estimated equilibration temperature of 67°C . On this basis it is estimated that equilibration of the thermal brine takes place no deeper than 2000 m.

Conclusions

Recent measurements across both the Carnmenellis and the Bodmin granites have given substantially identical heat flow results to depths of 150 m. These indicate that the thermal flows within the mineralised belt at the north of the Carnmenellis granite do not represent the upward limb of a circulation cell restricted to that granite. Rather, the scale of groundwater circulation observed in the mineralised belt probably exists across the entire batholith.

The circulating groundwater is entirely of meteoric origin and the residence time for the bulk of the circulation is less than 25 years. It is unlikely to have reached depths greater than 2000 m. Below 2000 m the thermal gradient may increase, but in view of the very uniform gradients measured across the granite it appears unlikely that the rate of groundwater circulation is sufficient to disturb appreciably the observed heat flow pattern.

To reach beyond the limit of natural meteoric groundwater circulation future boreholes drilled into the Cornubian granite of south-west England should be deeper than 2000 m.

Table 11.2. Geothermometry results for the thermal 'mature' groundwaters

Sample	SiO ₂		Na/K/Ca (Paces)	Collection Temp. °C
	Quartz	Chalcedony		
{ 77/774 78/407 } S. Crofty	87	54	67	} 41.5
	86	53	61	
	74	40	21	43.0
{ 77/775 77/776 78/417 } Wheal Jane	61	27	47	29.5
	78	44	50	39.5
	62	28	29	29.9

CHAPTER 12. REVIEW OF GEOTHERMAL POTENTIAL IN THE UNITED KINGDOM

The prospects of developing geothermal resources in the United Kingdom depend upon either the presence of permeable rocks in deep sedimentary basins or the successful development in economic terms of the hot dry rock concept. The sedimentary basins can be conveniently divided into those formed in Mesozoic and those in Palaeozoic rocks. The Mesozoic sequence, together with the underlying Permian, includes the principal aquifers in the U.K. As a whole, this sequence contains deposits with higher permeabilities and porosities, whereas the Palaeozoic sequence includes a greater proportion of hard, indurated, compact rocks; storage in them is more limited and groundwater flow is almost entirely through fissures. For this reason the studies to date have concentrated on Mesozoic basins.

In the Mesozoic basins the sandstones at the base of the Permo-Triassic lie at depths sufficient to provide fluids at a useful temperature and are likely to have hydraulic properties that would be favourable for the development of any hot water they may contain. The mean geothermal gradient in the Mesozoic basins is over $30^{\circ}\text{C}/\text{km}$ at a depth of at least 2 km over large areas of Lincolnshire, Wessex, Northern Ireland and possibly in West Lancashire and in the Carlisle Basin. Substantially lower mean gradients are found in the Cheshire and Worcester basins.

In the coastal zone of Lincolnshire the Lower Permian occurs at depths where the temperature exceeds 60°C but the sediments are only 30 to 60 m thick. Permo-Triassic sediments probably occur in the Wessex Basin over appreciable areas at depths where the temperature again exceeds 60°C .

A high heat flow together with the insulating effect of the Tertiary basalts and underlying sediments is responsible for the geothermal gradient of more than $30^{\circ}\text{C}/\text{km}$ in Northern Ireland. Temperatures above 60°C have been recorded at depths of 1500 m and the Permo-Triassic sandstones are more than 2 km deep over an extensive area. In the Carlisle Basin there are indications that 60°C is exceeded at depths of 1000 to 1500 m.

Although the gradient is low in the Cheshire Basin, the Permo-Triassic sandstones are believed to lie at the appreciable depth of more than 3.5 km over an area of 800 km^2 , at which depth the temperature in the sandstones should be over 75°C . Limited data for the West Lancashire Basin imply that the gradient could be high but, even if it is similar to that in Cheshire, 70°C should be attained in the sandstones and as much as 100°C is possible.

It is clear that most of the Mesozoic basins contain Permo-Triassic sediments at depths where temperatures of more than 60°C can be expected. Considered overall, the Cheshire and Northern Ireland basins offer the best immediate prospects of developing a geothermal resource in these sediments, for they have already been proved at appropriate depths and thicknesses. If thick Permo-Triassic sandstones are proven in the Wessex Basin the prospects in the southern part, where the depth and thermal gradient are both appropriate, will also be good. In Lincolnshire the Lower Permian is relatively thin but this may be off-set by high permeabilities. Prospects are also encouraging but less certain in the West Lancashire and Carlisle basins.

The main question remaining is whether the permeability is adequate to provide the required flow of hot water. This can only be determined by drilling. A transmissivity of 20 Dm would make a venture economic and this would require an average permeability of 100 mD over a thickness of 200 m. These requirements are possible in the Permo-Triassic sandstones at depth in certain parts of the Mesozoic basins and exploratory boreholes to test the anticipated conditions would be worthwhile in a number of areas.

Further improvements in the design of heat pumps would lead to the use of waters at temperatures significantly less than 60°C — possibly as low as 20°C . Relaxation of the temperature constraint introduces other aquifers and larger areas to the potential geothermal resource base. However, despite the introduction of other aquifers — such as arenaceous horizons in the Jurassic — the Permo-Triassic sandstones would still have the greatest potential. They remain the most favourable aquifer both with regard to thickness and hydraulic properties.

Although the programme has concentrated on Mesozoic basins, some preliminary studies have been made of Palaeozoic sequences. Yields of water from Palaeozoic aquifers would, in general, be much smaller than from the Mesozoic and hence the cost of producing a given amount of energy would be greater. Upper Coal Measures sandstones and the Old Red Sandstone (Devonian) are the most likely source rocks. A preliminary appraisal has been made of the structure of Carboniferous and Devonian rocks in the Midland Valley of Scotland. This suggests that the Devonian may exist at depths where temperatures would be suitable for energy purposes, but little is known about its permeability.

The investigation of the thermal waters in the Bath-Bristol Basin confirmed they are of meteoric origin having been recharged at a temperature of 9°C during climatic conditions similar to the present day. Dissolved silica geothermometry indicated the maximum temperature of geo-

chemical equilibration is 80°C for the Bath thermal water and 60°C for the Bristol water, the discharge temperatures are 46.5°C and 24.3°C respectively. The geothermal gradient implies circulation to depths of between 2700 and 3500 m in the Carboniferous Limestone and possibly the Old Red Sandstone. The bulk of the thermal water is less than 10 000 years old but the concentration of radiogenic ⁴He implies that a small proportion of much older water is rising from greater depth and mixing with the Carboniferous Limestone groundwater. Significant levels of tritium in the Bristol thermal water reveal that it is a mixed source and the most likely mixing model incorporates a thermal component identical to the Bath water.

A valuable conclusion arising from a regional study of the chemistry of shallow groundwater in the basin is that thermal waters are rising and recharging the Triassic near Bath. Recognition of further geochemical anomalies in the Triassic could lead to the identification of other thermal flows in the underlying Carboniferous.

As the Carboniferous Limestone is the main reservoir of the thermal water and as flow is along relatively infrequent fractures, it would be impossible to recognise, in advance of drilling, the relative merits of any individual site. Any exploratory drilling would have to be away from the vicinity of Bath to avoid intercepting the fissure system that provides for the thermal discharge in the city.

The thermal waters in the Cornubian granite are also believed to be of meteoric origin and the residence time of most of the water is less than 25 years. The flow paths are unlikely to have extended to more than 2000 m, the maximum equilibration temperature being 67°C.

If current experiments in America prove that the hot dry rock concept is economic, the best prospects for its application in the U.K. would appear to be in Caledonian and Hercynian granites which have high radioactive heat production, particularly if this is enhanced by the insulating effect of poorly conductive sedimentary cover. High heat flows are known to be associated with the Cornubian granite and the concealed Weardale granite. On the basis of geochemical and geophysical characteristics the following intrusions have also been recognised as having some potential for hot dry rock development:

- Cairngorm and Etive granites in north Scotland.
- Loch Doon and Fleet granites in the Southern Uplands.
- Cheviot and Lake District granites in northern England.
- Newry granite in Northern Ireland.

It is, however, unlikely that there is dry rock at 200°C at less than 4 to 5 km below the surface anywhere in the U.K.

The preliminary assessment of the geothermal potential of the U.K. is promising but indicates that further studies are necessary before a programme of exploitation can be considered. The predictions of the potential in the Mesozoic basins should be tested by drilling. Field investigations are necessary to improve the basis for the conclusions about hot crystalline rock and further studies, similar to those made of the Mesozoic basins, are required to look more closely at the potential of Palaeozoic basins.

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