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Assessment of BGS data for ground source heat pump installations in the UK.

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Assessment of BGS data for ground source heat pump installations in the UK

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Summary

This report describes an assessment of data held by the British Geological Survey (BGS) in relation to the identification of barriers to the development of the ground source heat pump (GSHP) market in the UK. It forms part of the BGS Partnership Programme where projects are co-funded by industry and BGS. In this case the work was done as part of a project funded by Building Research Establishment (BRE) and the NIFES Consulting Group (Agreement F10/9/1027/7490) as part of the Future Practice R&D call from the UK Government Energy Efficiency Best Practise programme.

Ground source heat pumps (GSHP) are one of the most energy efficient environmentally clean and cost effective space conditioning systems available. A heat pump is a device that takes up heat at a certain temperature and releases it at a higher temperature. Ground coupled heat pumps work by utilising the heat stored in groundwater or the ground. At a relatively shallow depth (15m), the ground temperature will be approximately equal (±0.1°C) to the average mean air temperature throughout the year. In winter the ground temperature is generally higher than the air temperature, and in summer lower than the air temperature thereby providing capability for both heating and cooling modes. Generally thermal energy is transferred from the earth to fluid in a closed loop and is upgraded by passing through a water source heat pump. Typically the closed loop is configured in a vertical borehole or horizontal loop system in a shallow trench (1-2m). In the UK borehole depths are usually in the range 50-100m, in other EU countries depths of up to 150m are common.

GSHP are common in Europe and North America but there are only about 300 systems in UK homes and a few larger systems in commercial buildings. One of the factors identified as a barrier to uptake is the expense and uncertainty associated with installation of the external ground loop. Typically this can be 30-60% of the installation cost. This contributes to the capital cost premium on GSHP and can be a market barrier. Reduction in design uncertainty may help to reduce this cost.

Geological parameters impact directly on many aspects of the uncertainty: site temperature, performance prognosis, drilling costs. In addition the variety of the UK geology means that site-specific solutions need to be identified. The near-surface temperature profile includes components due to heat conduction, fluid flow, antecedent climate and the effects of diurnal and seasonal change in solar radiation. The British Geological Survey (BGS) has a unique spatial geothermal database of observed equilibrium sub-surface temperature. These data indicate that some areas have stable ground temperatures of 15°C at depths of 100m whereas other sites have temperatures of only 7°C. The GSHP performance for a 100m borehole is therefore likely to vary significantly with location. Existing models of shallow (0-100m) temperatures in the UK are inadequate and relevant properties are not readily available.

BGS holds a large amount of geoscience data with potential use to the GSHP industry. The main classes of data relate to geological formations, attributes of those formations especially thermal properties and state of the formations especially temperature and water saturation. Currently these data are not easily accessible to GSHP users and installers. The existing BGS GeoReports facility provides detailed geological reports and water borehole prognosis reports, both of which are useful for GSHP but key information on thermal state and properties is not provided. Residential GSHP installations may not require detailed geological assessments but confirmation of temperature and thermal properties together with some indication of ground conditions would be useful. Current use of the BGS Georeports facility by GSHP installers is limited.

Key points relative to the design process for GSHP in the UK

- Observed stable ground temperatures at 100m depth vary between 7-11 °C in Scotland and 11-15 °C in Southwest England
- The range of local mean annual air temperatures is strongly affected by elevation, site and aspect
- Thermal conductivity of UK rocks varies from about 1.5 - 3.5 W m^{-1} K^{-1}
- Site-specific GSHP design for depths of up to 200m requires
  -temperature, thermal conductivity and hydrogeology
  -nature and thickness of drift or made ground in relation to drilling costs

1 Introduction

A heat pump is a device which takes up heat at a certain temperature and releases it at a higher temperature. Ground source heat pumps (GSHP) are one of the most energy efficient, environmentally clean, and cost effective space conditioning systems available. They work by utilising the thermal store of the earth in either a closed or open loop heat exchange system. Despite perceptions, the energy store in water at 5 °C is only 11% less than the energy in water at 40 °C. The thermal energy output is not generated so that typically GHSP systems have a coefficient of performance (thermal output/electrical inout) of about 3.5. Typically the output is 3-20 KW so that GSHP systems are well suited to domestic and small commercial heating (cooling) requirements.

In the UK approximately 30% of final energy consumption is in domestic premises with about 82% of this for space and water heating. GSHP systems are widespread in Sweden and other EC countries but have not yet developed in the UK market for a variety of reasons, including the maritime temperate climate and low prices for primary energy. Typically, total installation costs may be 3-5 times conventional space heating and external installations are up to 30-60% of the capital costs of a GSHP system. However, running costs for a GSHP system can be about 50% of conventional electric space heating and carbon saving can be about 40%. In addition GSHP can reduce primary energy consumption by up to 50%. Payback periods depend primarily of fuel cost savings and can be 5-10 years.

Most GSHP systems use vertical-loop (VL) indirect circulation heat exchange systems coupled to electrically powered vapour compression cycle heat pumps. Geological factors impact directly on the site characterisation and therefore the design and cost of the system. The UK has an extremely varied solid geology and the Quaternary cover is extensive and variable. The geological prognosis of the site and rock properties will influence the drilling methods and system costs. Other very important aspects are the predicted subsurface temperatures, the thermal properties of the strata, the water saturation level and the natural or induced hydraulic flow.

The characteristics of the site are affected by the mean annual air temperature, the conductive heat flux, fluid flow and heat transport effects, rock thermal conductivity and diffusivity, terrain effects and palaeoclimate. Existing models used for site temperature prediction and system design are very approximate and increase uncertainty in the output and performance of the system. Measured equilibrium temperatures at a depth of 100m show a variation across the UK between about 7-15 °C. The actual range of variation may exceed this. This variation needs to be predicted, verified and incorporated into a new model.

In many countries, geological conditions are generally more uniform than in the UK. GSHP designers and installers can use past experience and can often assume a simple geological model with overburden material over a crystalline rock formation with favourable thermal properties. The UK geology is extremely varied with many formations and lithological types recognised.

2 GSHP summary

Ground source heat pumps (GSHP) have been identified as the most energy efficient technology for space heating and cooling (Rawlings 1999). A heat pump is a device for moving thermal energy from a lower temperature to a higher temperature. Ground source heat pumps using either vertical-loop (VL) or horizontal-loop (HL) ground collectors, have the potential to reduce primary energy consumption and associated greenhouse gas emissions. The stable ground temperatures mean that ground source heat pumps are inherently more efficient than air source systems. For heating, air source heat pumps are less efficient when ambient air temperatures are low. GSHP systems are either direct circulation of the refrigerant or indirect. Efficiencies of GSHP for low-temperature (<40 °C) distributed hot water systems are high, with coefficients of performance (COP) typically 3.5 for indirect systems and up to 5 for direct systems.

The closed loop portion of an indirect ground source heat pump (GSHP) system consists of polyethylene pipe buried in the ground and charged with a water/antifreeze solution. Thermal energy is transferred from the earth to the fluid in the pipe, and is upgraded by passing to a water source heat pump. A typical sizing guideline for vertical loops (based on USA) is 11-26 m of vertical borehole for each installed 1 kW of heating capacity (Rawlings 1999). In Sweden a general sizing guideline for indirect horizontal loops is 50W/m of pipe (Rawlings 1999). In Scandinavia many GSHP systems are sized to meet 50-70% of the design heating load. In the UK a 100-metre vertical closed loop borehole will typically deliver 14000 kWh of useful heating energy and 11000 kWh of useful cooling energy every year for life, although this is dependent on site characteristics. Direct ciculation systems can reduce external loop design lengths by up to 50%.

- Low energy consumption has the potential to deliver associated lower CO_2 emissions compared with conventional fossil fuel or electric space heating systems. In commercial applications, energy savings of 40% compared with air source heat pumps and over 70% compared to electric resistance heating can be achieved, and CO_2 emissions can be reduced to less than half that associated with typical heating ventilation and cooling (HVAC) design. Each domestic GSHP installation has potential to save 1.5-2 tonnes of CO_2 annually.
- With the heat source buried in the ground, the system is both invisible and quiet. There is no need for boiler, flue, cooling tower, water treatment or associated plant rooms, and the total building resource content is reduced.
- For indirect horizontal-loop GSHP systems in domestic applications trenches are normally about 1-2m deep and up to 40m long. In favourable ground conditions approximately, 150m of pipe are required for each 3 kW of heat pump capacity. A well insulated, 200 m^2 home might need about a 9 kW system.
- Closed indirect vertical-loop GSHP systems can use a smaller footprint. U-shaped loops of pipe are inserted into the well and backfilled with a high-thermal conductivity grout sealing solution. In Scandinavia the boreholes are generally not grouted. Typically, boreholes to depths of about 100m are used although there is a current trend towards deeper drilling (200m). A general guideline is 100m per 3.5 kW of heat pump capacity although this varies with thermal properties.
- Closed-loop indirect systems use high-density geothermal rated polyethylene pipe. Properly installed, these pipes will last many years. This pipe material is inert to chemicals normally found in soil and has reasonable heat conducting properties.
- Direct circulation collectors, using refrigerant in copper tube, can be more effective at extracting heat. A 2.75 kW system with 65m of copper collector can deliver 42W/m compared with 20W/m for an indirect circulation with 200m of polyethylene pipe. Currently, direct circulation is only available for small systems , less than 3 kW.
- An environmental benefit is that ground source heat pumps typically use 25% less refrigerant than split-system air-source heat pumps or air-conditioning systems.
- GSHP are ideal for new-build schemes using wet underfloor heating. Estimated annual energy heating-cooling savings of the order of 50-60% are possible.

A variety of related geological parameters directly affect the installation of the external loop in terms of cost and performance (Figure 1, Table 1)

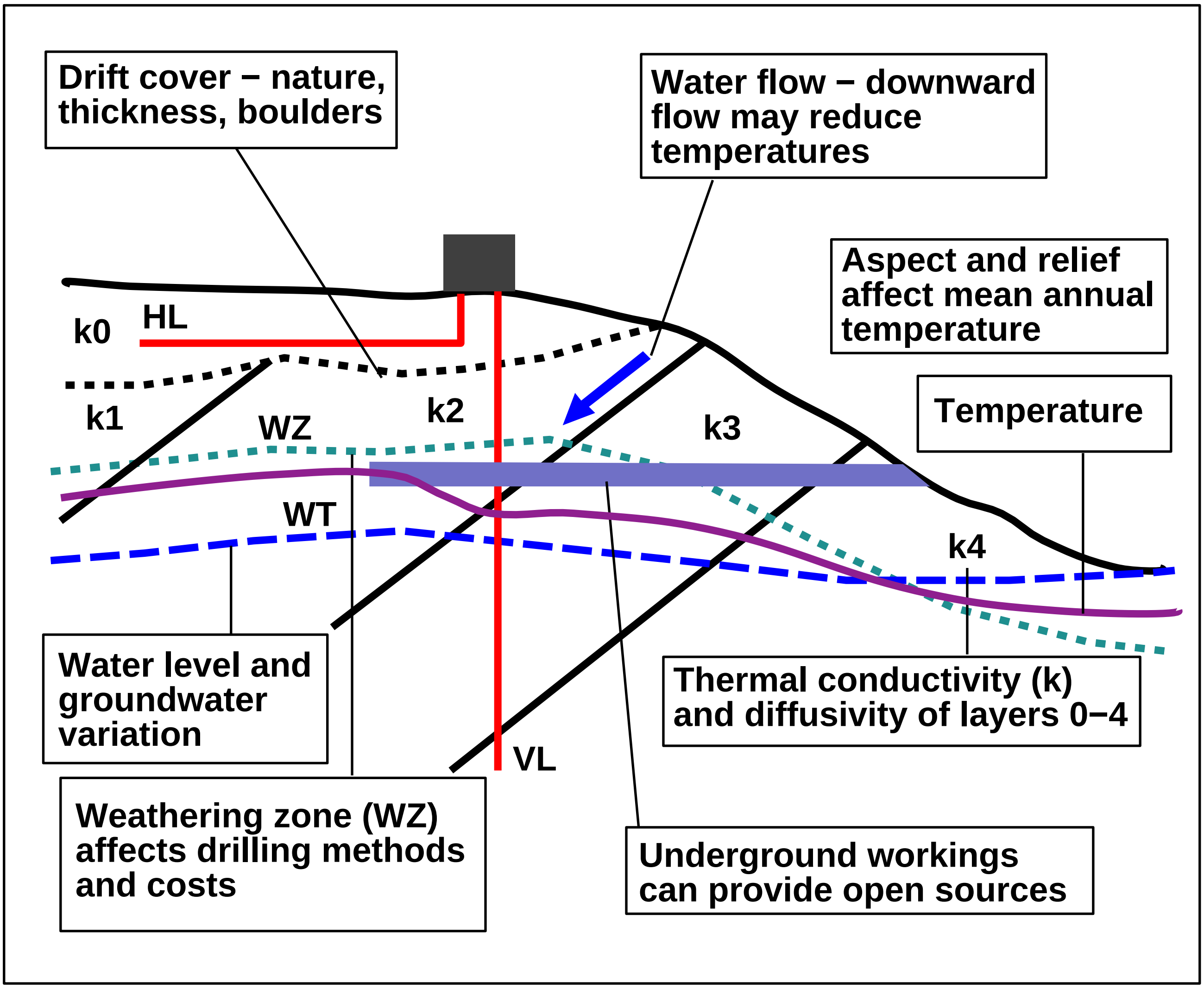

Figure 1 Geological factors which might affect installation of a ground source heat pump

Table 1 Some geological factors with responses that impact GSHP systems

	Geological factor	Response impact
1	Rock formation	rock properties, drilling/trenching methods
1	Cover sequence	cover properties, trenching, drilling methods
1	Weathered layer	drilling methods and costs
1	Mine workings	drilling methods, open source systems
2	Temperature	heating and cooling performance
3	Rock thermal conductivity	heat exchange performance
3	Rock diffusivity	heat exchange performance
4	Rock strength	drilling methods and costs
5	Water Saturation	thermal properties, performance
5	Groundwater transport	heating and cooling performance

The geological parameters can be considered in terms of five main groups (1-5): geology, temperature, thermal properties, geotechnical properties and hydrogeology. The main aspects of BGS data relating to these groups are discussed below.

3 Data

3.1 GEOLOGY

In relation to the land area, the geology of the UK is extremely complex. This is not just a reflection of a long history of geological mapping but a real variety of rock formations, ages and lithologies. As part of its mission, the British Geological Survey is responsible for geological maps of the UK land and continental shelf.
As part of the national survey the UK has published geological maps at scales of 1:625000, 1:250000 and 1:50000. Much of the primary geological mapping has been done at 1:10000 and geological standards are available as reference for much of the country at this scale.
In a broad sense, the geology of the UK shows a general increase in age from southeast to northwest. This feature is associated with a corresponding change in rock properties including thermal and geotechnical properties. East of a line from the Bristol Channel to the Humber estuary, strata at the surface are mostly Triassic and younger in age.

3.1.1 DiGMapGB

A major project, DiGMapGB (Digital Geological Map of Great Britain) is currently preparing 1: 50 000 scale data for England, Wales and Scotland. Many existing 'paper-only' maps have been digitised, and the nomenclature, particularly of older maps, updated to current usage. Each polygon is attributed with lithostratigraphical and lithological information which can be referenced to other data tables.

Most onshore geological surveying is carried out on large-scale maps at 1: 10 000 scale (formerly six inch to one mile) and paper copies of this detailed work are available if required. This geology is then usually published in less detailed form on smaller-scale maps at 1: 50 000, 1: 250 000 and 1: 625 000 scales at later dates by a process of successive generalisation and simplification.

Thus, a particular rock unit may be mapped originally to bed detail at 1: 10 000 scale. When published at 1:50 000 it may only be possible to show it to member level. On later compilation at 1: 250 000 and 1: 625 000 it may have to be further simplified to formation then group level respectively.

The 1: 250 000 and 1: 625 000 scale DiGMapGB data reflect the date of compilation of the paper source maps; 1977-92 and onwards for 1: 250 000 scale and 1979 for 1: 625 000 scale. In the intervening years many of the component 1: 50 000 maps have been re-surveyed or revised but most of this new information has not yet been incorporated into the small-scale maps.

Considering the Artificial Ground and Mass Movement themes, these deposits are recorded at 1: 10 000 scale and may be published at 1: 50 000 scale with the usual cartographic selection and simplification of small areas; and perhaps exaggeration in size if particularly important. Artificial and Mass Movement themes are not normally shown on 1: 250 000 and 1: 625 000 scale maps.

1:625000 Scale

The four 1:625 000 scale United Kingdom Geological Maps (Solid UK north, Solid UK south, Quaternary UK north and Quaternary UK south) have been digitised and information made available as the DiGMapGB-625 dataset.

1:250000 Scale.

The onshore areas of the solid geology 1:250 000 scale series maps are available digitally as part of the DiGMapGB-250 dataset. Each rock unit is attributed with lithostratigraphical and lithological codes and the information is available in standard 100 x 100km tiles.

1:50000 Scale

Most of the 1:50 000 scale geological maps for England & Wales and for Scotland are now available digitally as part of the DiGMapGB-50 dataset. Up to four themes of information are available: solid geology; drift deposits; mass movement and artificial ground.

1:10000 Scale

Some 1: 10 000 scale geological maps are available digitally as part of the DiGMapGB-10 dataset. Older detailed mapping such as that on 'County' maps at a scale of six inches to one mile may not have recorded mass movement deposits and artificial ground. Many new 1: 10 000 maps are prepared digitally. In the near future BGS will move to digital capture of linework in the field (pending successful hardware and software trials) and it is hoped to digitise retrospectively many more existing paper maps, especially those of high priority urban areas

3.1.2 DiGMapGB-50 themes

Artificial ground

Artificial ground is a term used by BGS for those areas where the ground surface has been significantly modified by human activity. Whilst artificial or man-made ground is not part of the 'real geology' of solid and drift deposits it does affect them and needs recording because the near surface ground conditions are so important to human activities and economic development.

For DiGMapGB and related purposes, artificial ground information is placed in a separate theme. It may be regarded, in other uses in BGS and elsewhere, as part of the superficial geology that includes both man-made and natural deposits. The Artificial ground theme includes:

- Made ground — man-made deposits such as embankments and spoil heaps on the natural ground surface.
- Worked ground — areas where the ground has been cut away such as quarries and road cuttings.
- Infilled ground — areas where the ground has been cut away then wholly or partially backfilled.
- Landscaped ground — areas where the surface has been reshaped.
- Disturbed ground — areas of ill-defined shallow or near surface mineral workings where it is impracticable to map made and worked ground separately.

Artificial ground was not formerly mapped by BGS. It became a common requirement of the applied geological mapping projects in the 1980s and is now routinely recorded but information is only available for parts of the country. It is classified primarily on its mode of origin, which is usually apparent from the landform or the changes made to the topography.

Infilled ground can also be classified by its composition into types of fill such as inert waste, ash or slag. This is not usually practicable in routine mapping as many landfills are mixed deposits with inadequate records of their actual content.

Caution must be exercised using the artificial theme, as it may become dated very rapidly. BGS cannot monitor every pit and landfill site in the country recording changes from day to day. It is inevitable that many maps of artificial ground will be out-of-date. Also, many urban areas are built on artificial ground but it is impracticable to unravel the details in routine mapping.

Mass Movement Theme

Mass movement deposits on BGS geological maps are primarily superficial deposits that have moved down slope under gravity to form landslips. These affect older deposits including drift, solid rocks and artificial ground. Various landslip types are recognised but they are rarely classified on BGS maps apart from specialised maps for applied geology.

For DiGMapGB and related purposes, mass movement information is placed in a separate theme. Here it also includes foundered strata, where the ground has collapsed due to subsidence.

Caution must be exercised using the mass movement theme because of the potential hazard caused by ground instability. BGS has not always mapped mass movement deposits and they may occur in places where none are mapped. Even on maps where landslips are recorded it is impossible to be sure that all occurrences were found. It is therefore useful to know the location of potential landslip areas such as determined in some applied geological mapping projects. GIS techniques, integrating geological and topographical information, can be used to give an indication of likely slippage by finding, for example, the incidence of clays on steep slopes

Drift deposits

Drift deposits is a term used by the BGS for natural superficial deposits formed during the most recent period of geological time, the Quaternary, which extends 1.8 million years back from the present.

For DiGMapGB and related purposes all natural superficial deposits, in place, are placed in a separate drift deposits theme.

For some uses, in BGS and elsewhere, drift includes all superficial strata whether natural or artificial, and whether in place or affected by mass movement. Drift deposits are the youngest geological deposits and rest on older deposits or rocks referred to as the Solid geology.

Drift geology maps originally showed only onshore deposits formed by various processes such as action by ice, water and wind. More recently offshore drift has been mapped.

Most of these drift deposits are unconsolidated sediments such as gravel, sand, silt and clay, and onshore they form relatively thin, often discontinuous patches or larger spreads. Almost all of these deposits were formerly classified on the basis of mode of origin with names such as, 'glacial deposits', 'river terrace deposits' or 'blown sand'; or on their composition such as 'peat'. Recently some of these drift deposits have been given formal lithostratigraphic names.

Solid geology

Solid geology is a term used for the main mass of rocks forming the Earth's bedrock and present everywhere, whether exposed at the surface in outcrops or concealed beneath superficial deposits or water. They have formed over vast lengths of geological time ranging from ancient and highly altered rocks of the Proterozoic, some 2500 million years ago, or older, up to the relatively young Pliocene, 1.8 million years ago.

For DiGMapGB and related purposes all these rocks are placed in a separate solid theme of information. Wherever possible, they are referred to by their current lithostratigraphic name.

Geological maps usually show all the solid strata onshore, apart perhaps from beneath the coastal plain and extensive alluvium. For DiGMapGB-50 the solid theme has been extended, where necessary, to the coast. On some recently published geological maps Solid is mapped offshore on the Continental Shelf.

The solid geology includes many lithologies, often classified into three types based on origin: igneous, metamorphic and sedimentary. Igneous rocks are derived from molten magma in the Earth's crust. They may, for example, be extruded at the surface by volcanic activity, to form lavas and tuffs (ash); or intruded into other rocks to form large masses of granite and gabbro at depth or minor crosscutting basalt dykes near the surface. Metamorphic rocks such as schist and gneiss are those that have been changed from one rock type to another in the solid state by the recrystallisation of minerals, often at high temperatures and pressures when buried deep in the Earth's crust. Sedimentary rocks are formed when grains and fragments of existing rocks are eroded away by ice, water and wind action, transported elsewhere and redeposited as a sediment. These sediments are often laid down in layers or strata of loose particles of gravel, sand, silt and clay. Over time they may be buried by later sediments and consolidated or cemented to form stratified or bedded rocks such as conglomerate, sandstone, siltstone and claystone. Other sedimentary rocks such as ironstone and limestone are created by chemical or biogenic (life) action.

The geological sequence of rocks preserved varies from place to place but packages of strata with similar characteristics may be recognisable over considerable distances. Such study has developed into the science of stratigraphy, of which lithostratigraphy is but one type

3.1.3 DiGMapGB LEXRock Codes

The main attributes of the digital polygons in DiGMapGB are the Lexicon code and the Rock code. The Lexicon describes the actual rock unit, whereas the rock code relates to the lithology or rock type. Merged together, these two attributes form the LEXRock code. The table of attributes of polygons for the merged UK 1:50000 scale solid geology has over 23,000 LEXRock codes. Many of these are not unique, as the same code such as SSG_SDST (Sherwood Sandstone Group – sandstone) will occur for many of the 1:50000 map sheets. However there are over 9900 unique LEXRock codes for the 1:50000 solid geology theme. This is based on about 1080 Rock codes and about 4520 LEX codes. This suggests that attribution of digital geology by rock lithology would be simpler than attribution by rock Lexicon.

The situation is less onerous if the attribute tables of the digital 1:250,000 solid geology is examined. Geological mapping is often down to the Member level, occasionally the bed level. The basic unit mapped shown on the 1:50000 geological map is the Member, while on the 1:250000 scale map the basic unit is likely to be the Formation or Group. In the 1:250000 series solid geology there are approximately 1270 LEXRock codes and 118 Rock codes. However for site specific enquiries it would be preferable to use the 1:50000 LEXRock codes.

3.2 HEAT FLOW

Heat flux (q) through the earth is determined by the product of the thermal conductivity (λ) and the local temperature gradient and has an average value in the UK of about 58 mWm^{-2}. Subsurface temperature tends to increase with depth, on average at about 26 °C/km, but locally at a very different rate dependant on heat flow and thermal conductivity. In areas where a large part of the upper crust contains radiogenic granite with a high heat production (> 5 μWm^{-3}) the heat flow are increased. Values are locally above 130 mWm^{-2} in parts of Devon and Cornwall. In some parts of the UK geothermal gradients are in excess of 35 °C/km. Heat flow and thermal conductivity structure are the main factors affecting the deeper temperatures across the UK.

Although sub-surface temperatures generally increase with depth (z), this is not a simple function. For the one-dimensional (vertical) case the general equations which govern the variation of temperature (T) are:

$$q = \lambda \delta T / \delta z \qquad [1]$$

$$\delta q / \delta z = -A - \rho f c f v \delta T / \delta z + \rho c \delta T / \delta t \qquad [2]$$

The terms on the right represent the main factors: the heat production of crustal rocks (A), the transfer of heat by fluids and gases (*cf, pf*, *v* specific heat, density and velocity of fluid) and the change of heat store (*c, p* specific heat and density of rock mass) with time (*t*). Often steady state conduction is assumed with no heat transfer so that the second equation simplifies to:

$$\delta q / \delta z = -A \qquad [3]$$

In many cases heat production is assumed to be negligible and the temperature dependence of thermal conductivity is not significant so that for a horizontally layered earth with n layers of thickness h_i and conductivity λ_i the temperature (T_z) at depth z can be approximated by:

$$Tz = To + q\sum_{i=1}^{n} hi / \lambda i \qquad [4]$$

This sort of equation is generally used in GSHP system design, and assumes an average heat flow and thermal conductivity produce an average temperature gradient. There are several software design tools available for GSHP design (Rawlings 1999) although there is no common format or established package for UK design. (For a recent review of GSHP collector design see www.heatpumpcentre.org). Although the estimated temperature at 100m depth is not especially sensitive to temperature gradient, because z is small, the combined effects of heat flow and thermal conductivity can in some cases be important.

A list of heat flow observations in the UK is given in the UK Geothermal Catalogue (UKGC, Rollin 1987). This gives basic location data, elevation, depth interval of the heat flow determinations and an indication of the temperature and thermal conductivity sampling. Arithmetic mean thermal conductivities and bottom-interval equilibrium temperatures are included where available. Each heat flow site has geological codes (001-115) based on the 1:625000 geological map and can be used to give an indication of the thermal conductivity of particular formations.

The BGS 1984-87 geothermal programme added 22 new heat flow observations to the existing dataset of 188 sites (Appendix 2 of Downing and Gray 1986). All these data were collected by the Imperial College Heat Flow Group under contract to BGS. In addition two heat flow measurements were made in the deep wells (RH11, RH12) at the Camborne School of Mines geothermal site at Rosemanowes. The criteria for siting the new heat flow boreholes included geophysical anomalies which might be caused by a buried granite (Market Weighton); basement terrains (Llantwrtyd Wells, Rhiw, Church Stretton); targets in the urban HDR study (Rowlands Gill) and gaps in the existing data distribution (Selkirk). In addition two boreholes were specifically drilled to test the zone of high heat flow in the Bowland Forest area (Clitheroe 2, Wray). Eleven of the 22 new sites were in specially drilled holes 100-300m deep. The remaining observations were made in exploration boreholes at sites which satisfied one or more of the sampling criteria.

Heat production measurements have been made at 4 boreholes on basement rocks in the English Midlands: - Morley Quarry (0.7 μWm^{-3}), Bardon Hill (0.3 μWm^{-3}), Church Stretton (0.7 μWm^{-3}) and Wyche (1.6 μWm^{-3}). In Morley Quarry, on Charnian rocks, measurements of radioactive U, Th and K appeared to show good correlation with downhole gamma ray spectrographic logs suggesting that leaching of U and Th from the borehole chippings was probably not significant.

Estimates of heat flow from deep boreholes were used in the compilation of the Geothermal Map of the UK (BGS 1985). The method involves combining bottom hole temperature (BHT) observations with a mean thermal resistance (the Σ term in equation 4) at each depth, derived from the borehole geology and a databank of mean thermal conductivity. Revision of the temperature catalogue and the databank of thermal conductivity has allowed heat flow estimates to be made at over 500 deep (>1000m) boreholes. These data have been used in the compilation of the UK heat flow map (Figure 2). Digital grids of the UK heat flow data have also been used in the calculation of deep temperatures and low enthalpy geothermal resources for the main UK Mesozoic basins (Rollin et al 1995).

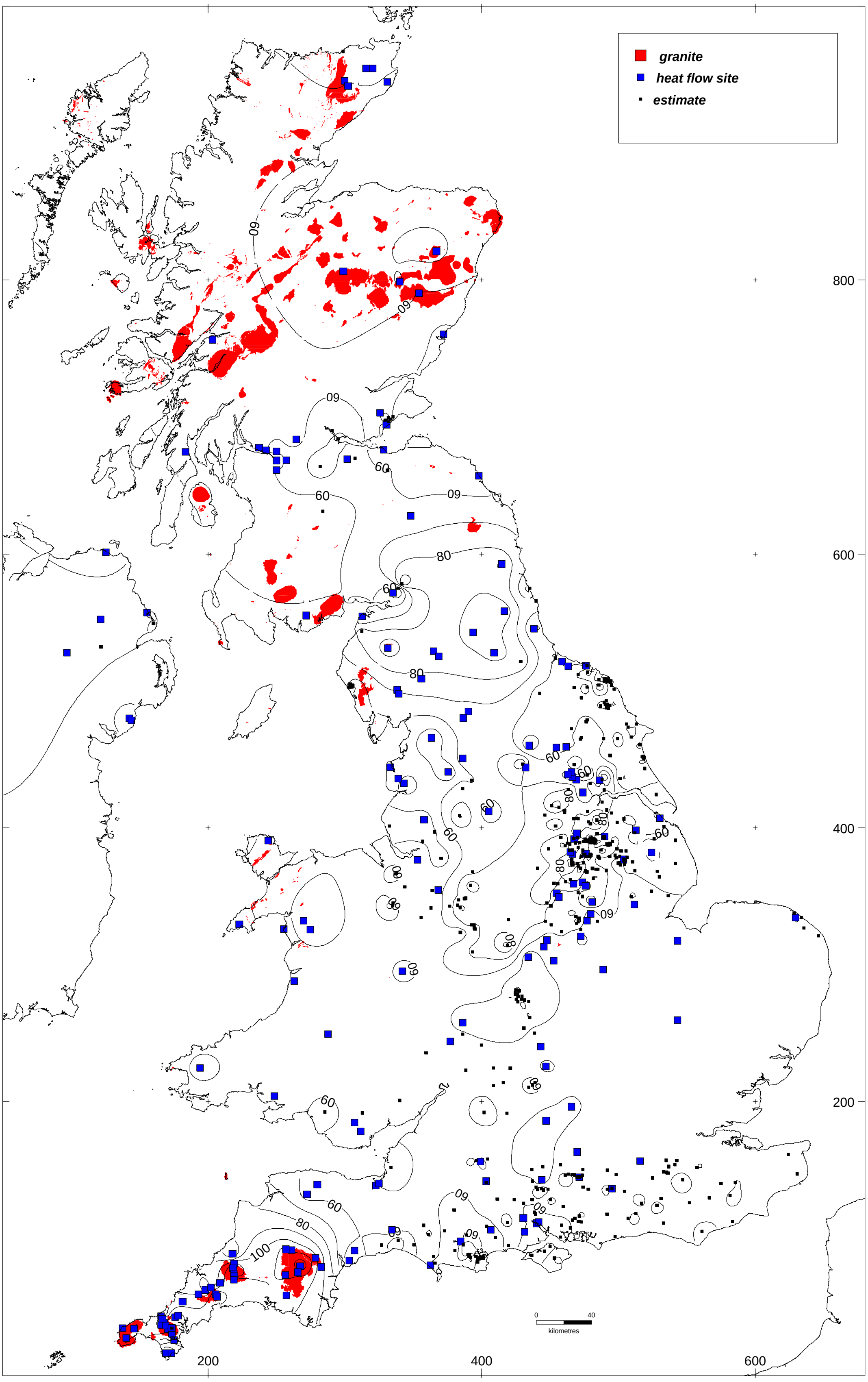

Figure 2 UK heat flow map based on observed and estimated values (mWm^{-2}).

The heat flow map shows some significant changes from that presented by Downing and Gray (1986) and shown on the published Geothermal Map (BGS 1985), largely as a consequence of the strategic siting of the 22 new heat flow boreholes. Most of the new estimates of heat flow are in areas where data already exist and the new data merely reinforce the pattern in these localities.

Noticeable changes are the disappearance of the positive, anomalous heat flow zone in Lancashire associated with only one heat flow observation in the previous compilation. The large area of low heat flow over central and mid-Wales has also been constrained by the observations of heat flows close to the UK mean at Church Stretton and Llanwrtyd Wells. The highest of the new heat flow observations, at Rowlands Gills above a supposed shallow cupola of the buried Weardale granite, was 99 mWm^{-2}. This confirms the Weardale granite as a significant and extensive heat source; previously, the only thermal data for the granite was from the discovery borehole at Rookhope. In addition the commercial boreholes at Dufton and Newbiggin, both with heat flows above 80 mWm^{-2} suggest some continuity of the Weardale heat flow anomaly with that of the Lake District.

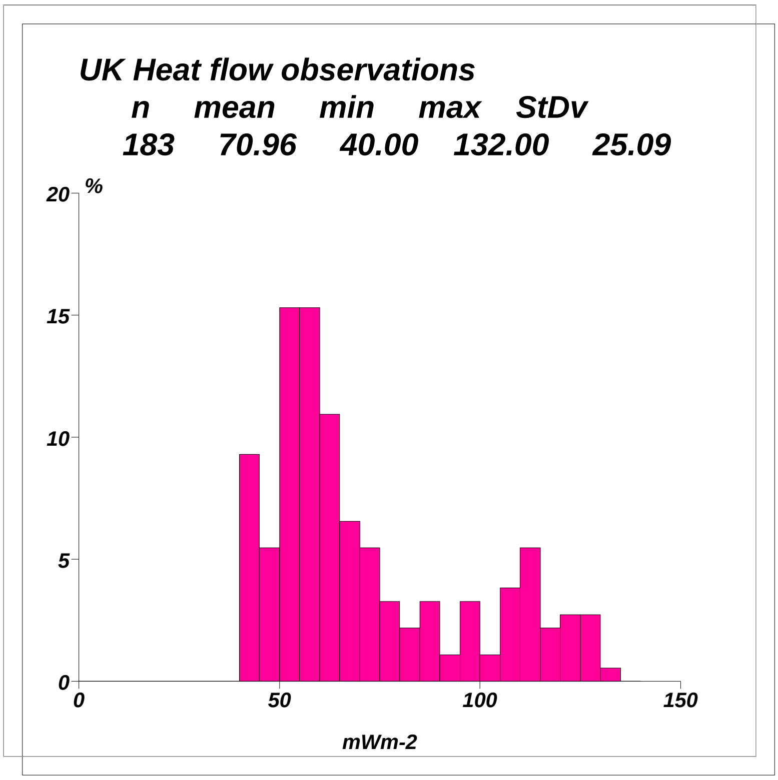

Figure 3 Histogram of UK heat flow data observations

Frequency analysis of the UK heat flow observations (Figure 3), indicates a bimodal distribution with a mean value of 68 ±26 mWm^{-2}. About 25% of the data are from sites above radioactive granites, although these rocks outcrop over less than 10% of the area. About 20% of the data are in southwest England. If these data are excluded the distribution becomes normal with a mean value close to 58 ±16 mWm^{-2} (Figure 4). This can be considered the mean value for the sedimentary crust of the UK. It should be emphasised that individual observations of heat flow in the sedimentary crust can only be considered as providing the apparent conductive heat flow, modified to some unknown extent by convective flow. Local anomalies in the heat flow field can be useful indicators of hydrodynamics, but are generally only identified where data is especially concentrated.

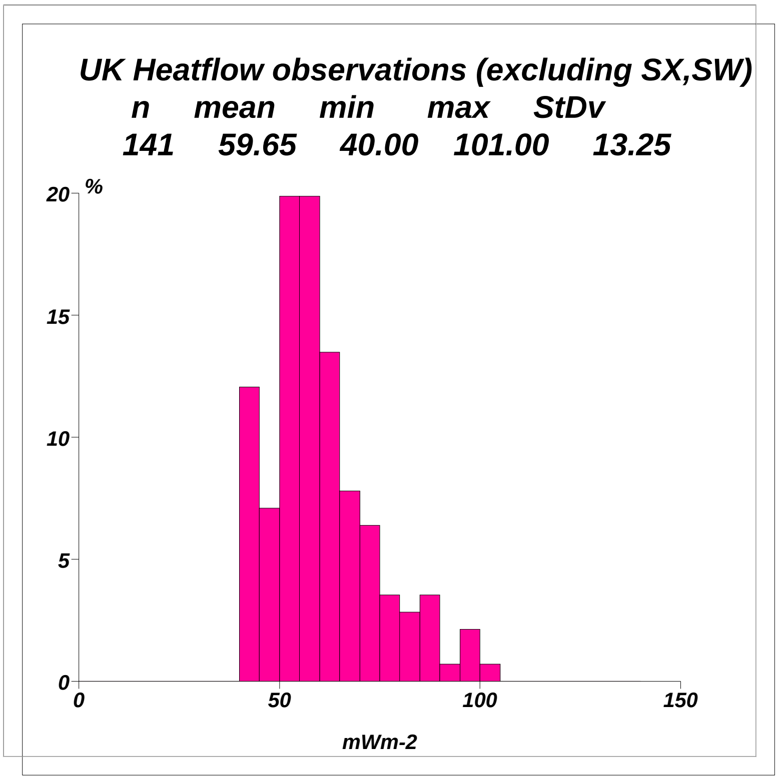

Figure 4 Histogram of UK heat flow observations excluding data in SW England

3.3 TEMPERATURE DATA

The surface temperature of the earth is determined predominantly by the radiant energy from the sun since the earth solidified about 4.5 10^9 years BP. The solar radiation received at the outer atmosphere has an average intensity of about 1400 Wm^{-2}. About 46% reaches the earth surface, 19% is absorbed by the atmosphere and 35% is reflected back into space. The total solar energy reaching the earth surface is about 2.34 10^{24} J yr^{-1}, amounting to about 500 times the annual global energy need. The earth also conducts a small amount of heat from the hot interior but this contributes only about 0.02 °C to the surface temperature of the earth. The mean annual surface temperature is controlled by climate and shows a variation of about 45 °C between the poles and equator.

The near surface temperature profile is complicated by the effects of diurnal and seasonal change in solar radiation. However at depths of about 15m the magnitude of the annual temperature variation is less than ±0.1°C. The effects of past climatic variations are also preserved in the sub-surface temperature profile. Antecedent periods of relative warming and cooling have been transmitted down through the earth and can be observed in detailed temperature profiles. Palaeoclimatic effects tend to vary with local aspect and microclimate but general features can be recognised and have been used to determine the past climatic trends and to highlight the recent global warming. Heat transfer by fluid flow can also complicate the sub-surface temperature profile at any depth. In general, flows of water through the section with any downward component of flow will reduce the temperature locally whereas upward flows tend to increase the local temperature.

Table 2 Summary of main factors affecting sub-surface ground temperature

Parameter	Comments
Heat flow	UK mean 58 mWm^{-2} range 40-135
Thermal conductivity	Range of 1.5 - 4.0 $Wm^{-1}k^{-1}$ Sensitive to porosity
Heat production	Low for sedimentary rocks 3-5 μWm^{-3} for granites
Depth	Mean gradient in top 4 km 25°C/km
Topography	Temperature enhanced at valley sites
Palaeoclimate	Past surface temperature preserved in upper 200m
Tectonic history	Rapid uplift/erosion can enhance temperatures
Groundwater flow	Small fluid movement can transport significant thermal energy

3.3.1 Mean annual air temperature

Changes in climate have been due to changes in the rate of solar radiation received at the surface. Climate change over geological time can be related to change of position relative to the poles or to global changes in the solar constant caused by radiant output variation from the sun or to variations in distance in the sun-earth system. Changes in atmospheric absorption also cause changes in solar energy at the surface. The geological record indicates repeated climate change in the past with a normal warm climate with mean global air temperatures of about 22°C and shorter periods with mean global temperatures close to 2°C at the times of maximum extent of glaciation. Current global mean temperature is about 14°C approximately 10^3 years after the last glacial maximum.

Mean annual air temperature at sea level in mainland UK varies from about 8-12 °C. These data show a general decrease eastwards and northwards from highest values in the SW of England. Since the contribution to surface temperature from terrestrial heat flux is very small the mean annual ground surface temperature should be close to the mean annual air temperature although often shows a variation of ± 1 °C. The most important local factors affecting mean annual air temperature are site elevation and aspect.

3.3.2 Sub-surface temperatures

Past ground surface temperature (GST) is preserved in the equilibrium temperature profile in boreholes. Many studies of borehole temperatures allow reconstruction of the GST history. The penetration of periodic GST fluctuations is largely determined by the soil or rock thermal diffusivity. As an approximate guide, the estimated change in a geothermal gradient of 3°C/100m due to the last glaciation suggests a gradient decrease of about 20% at 100m depth and 10% at 1000m depth. This assumes a thermal diffusivity of 30 m^2 yr^{-1} and approximates the last glaciation as a long period (36 10^3 yr) harmonic of amplitude 13 °C. Generally palaeoclimate has little direct effect on temperature prediction for GSHP but is important when shallow temperature gradients are used to measure heat flow.

Since average soil temperatures and average air temperatures are in equilibrium the mean surface temperature should equal the mean air temperature although generally the surface temperature is about 1°C higher than the mean air temperature.

The temperature profile in the subsurface is affected by thermal conductivity, heat flux, fluid flow and heat transport, heat production, adjacent terrain, palaeoclimate and past geological events such as uplift and erosion (Table 2). In many regions the effects of many of these factors are considered small so that GSHP design tools frequently use a very simple formula to estimate source temperature:

$$Tz = To + gz \qquad [5]$$

Where T_z is the temperature at depth z, T_o is the mean annual ground surface temperature, g is the geothermal gradient and z is the depth. Typically design tools use a value of 20 °C/km for g, assuming a 2 °C increase for every 100 m depth. It may be useful to consider how accurate this model is for prediction of shallow sub-surface temperature.

BGS has measured ground temperatures from several sources.

3.3.2.1 UK GEOTHERMAL CATALOGUE (UKGC)

Measurements of temperatures in the subsurface have been made in mines, wells and boreholes and the British Geological Survey (BGS) has compiled over 3000 of these temperature observations for the UK (Rollin, 1987). These data indicate an average temperature gradient for the upper 4 km of the UK close to 25 °C/km (Figure 5). However many of these temperature observations are bottom hole temperature (BHT) measurements recorded on logging tools during breaks in drilling. Drilling disturbs the thermal conditions in the sub-surface by circulating relatively cool drilling fluid downwards and by transferring heat from the deeper sections. Consequently drilling typically produces a positive component in the upper part of a transient temperature log and a negative component in the lower part of the log. Consequently, BHT observations are commonly less than equilibrium values. The BHT temperatures generally require correction to provide estimates of the equilibrium temperature generally using some function of the drilling time and the time since circulation of fluids during drilling ceased. Despite the general suppression of BHT values these data may actually overestimate the average temperature gradient for the UK since much of the data is from hydrocarbon exploration wells drilled in strata with relatively low thermal conductivity. Furthermore hydrocarbon drilling is often over structural highs which can be associated with positive (upward) hydraulic flow leading to an local positive temperature anomaly. In many areas of the Uk the average geothermal gradient is likely to be closer to 20 °C/km

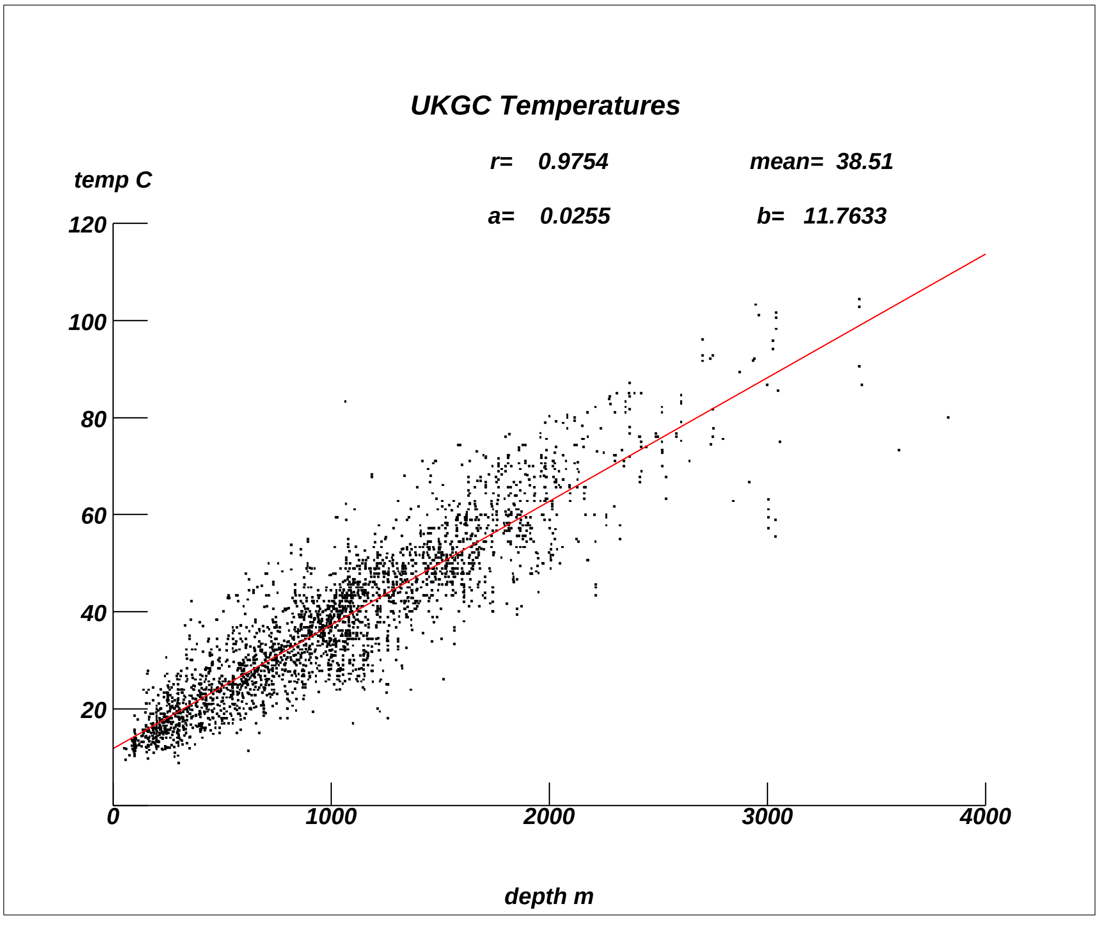

Figure 5 Temperature-depth plot for data in the UK Geothermal Catalogue

Many of the temperature observations in the UKGC are much deeper than the depths of interest to GSHP. Of the 3050 temperatures extracted at 1216 sites (Figure 5) only 126 are at depths less than 200m below ground surface. However the data can be used in conjunction with one-dimensional temperature field models to provide an idea of the temperatures at deep levels. The temperature model for 500m depth (Figure 7) gives a general picture of the variation of the shallow sub-surface temperature pattern across the UK.

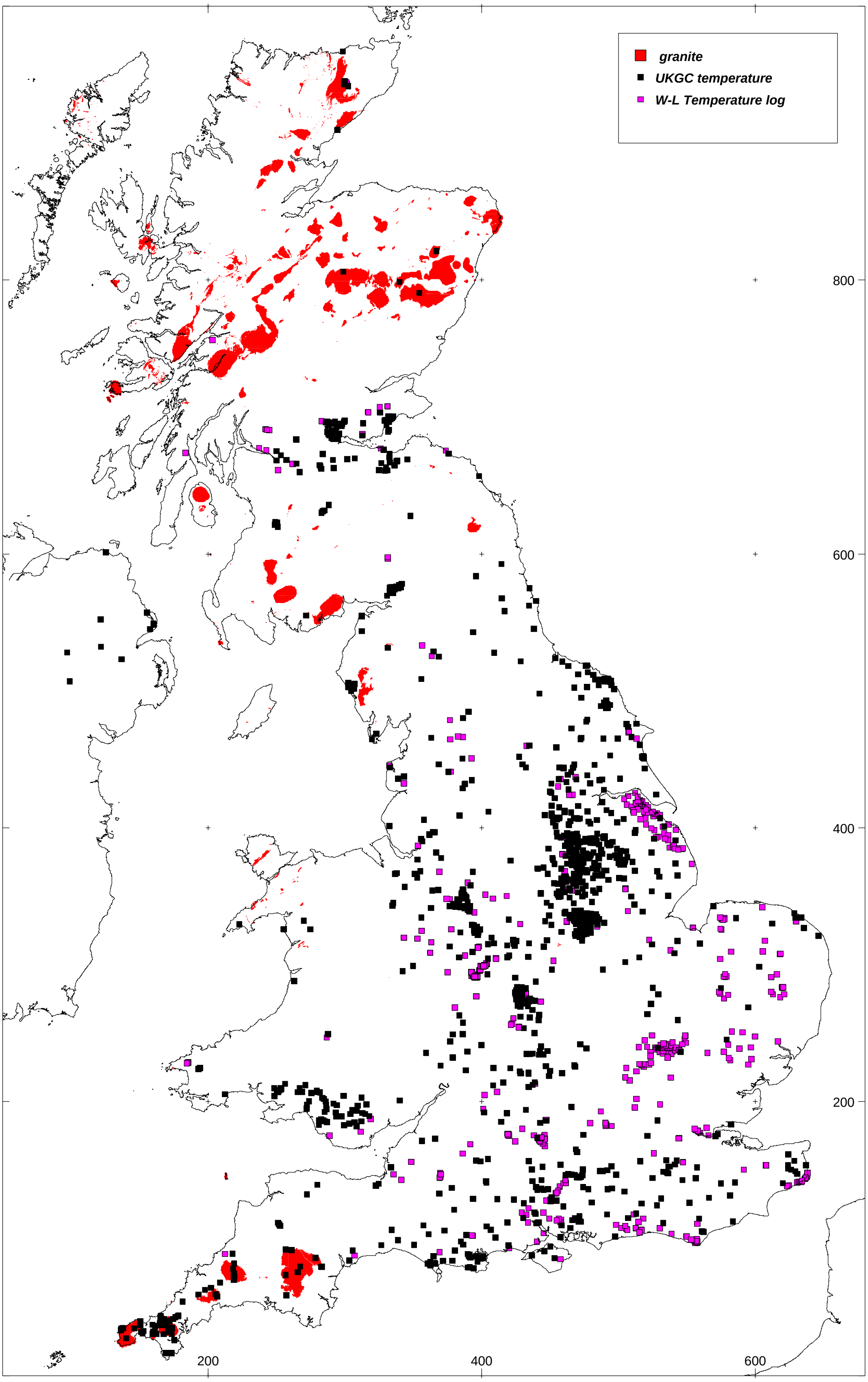

Figure 6 Location of sites with sub surface temperatures in the UK Geothermal Catalogue.

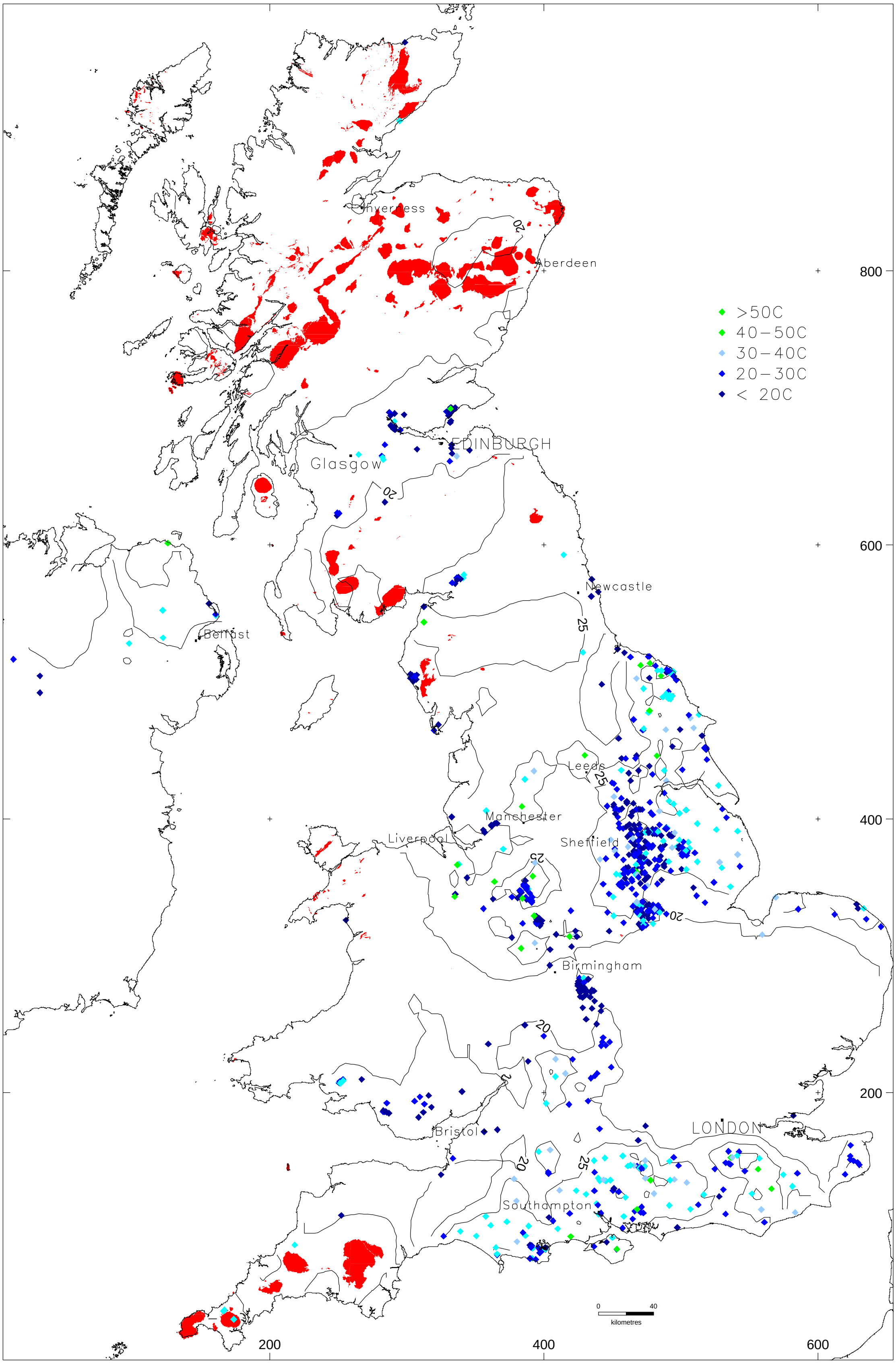

Figure 7 Model of the temperature field at 500m depth based on the UK Geothermal catalogue.

3.3.2.2 Equilibrium temperature logs

The BGS has a spatial database of observed equilibrium sub-surface temperature and thermal conductivity measurements collected in boreholes drilled to observe heat flux. These data are a subset of the heat flow observation population (shown in Figure 2). The data have been collected in boreholes that have been kept open for many months after drilling and repeatedly logged until equilibrium temperatures have returned. These data indicate that some areas have stable ground temperatures of 15 °C at depths of only 100m. Conversely other regions show stable temperatures at 100m depth of only 7 °C.

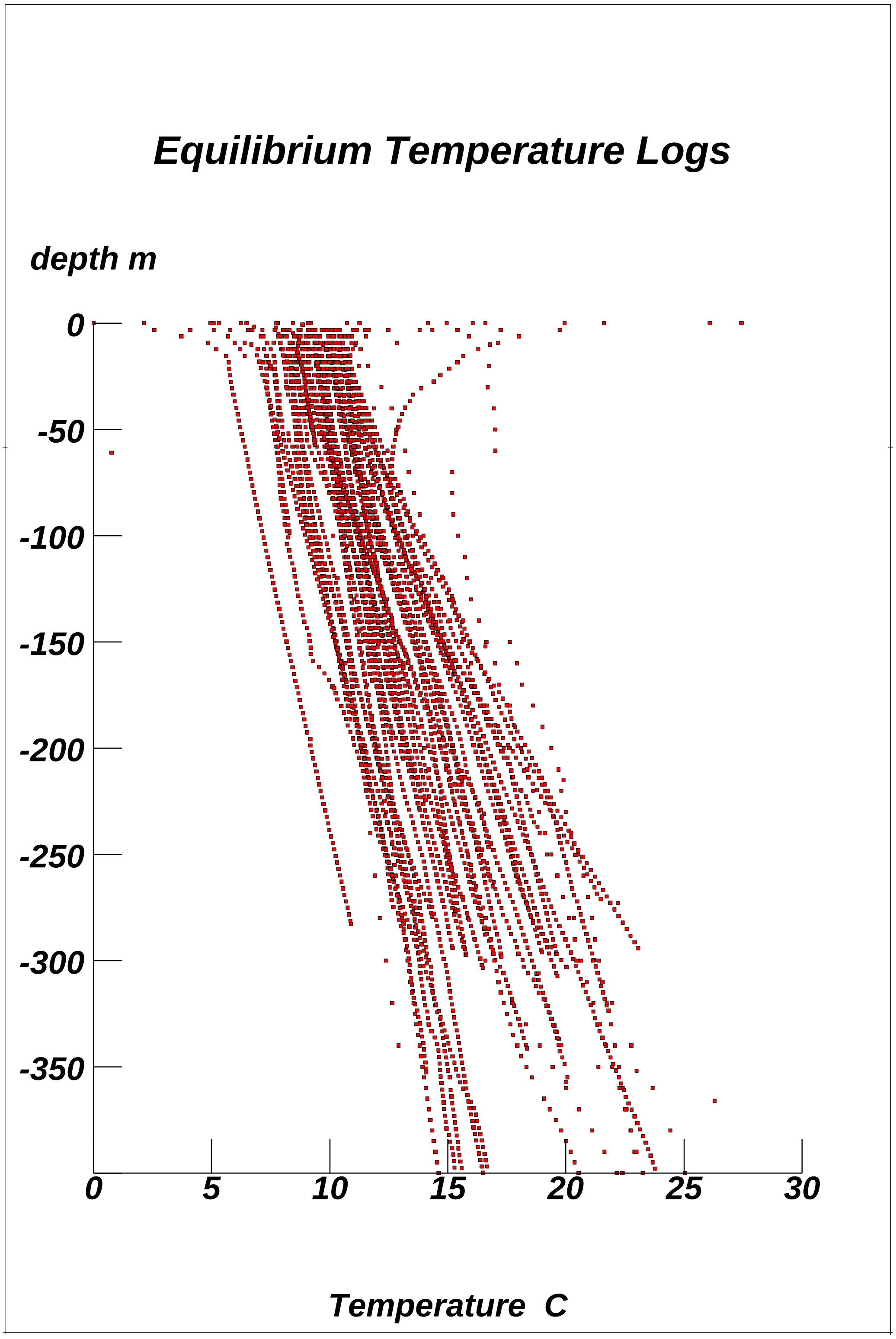

Figure 8 UK equilibrium temperature logs

The mean temperature for the UK at a depth of 100m is close to 12 ±1.6 °C with a range of about 7-15 °C (Figure 9).

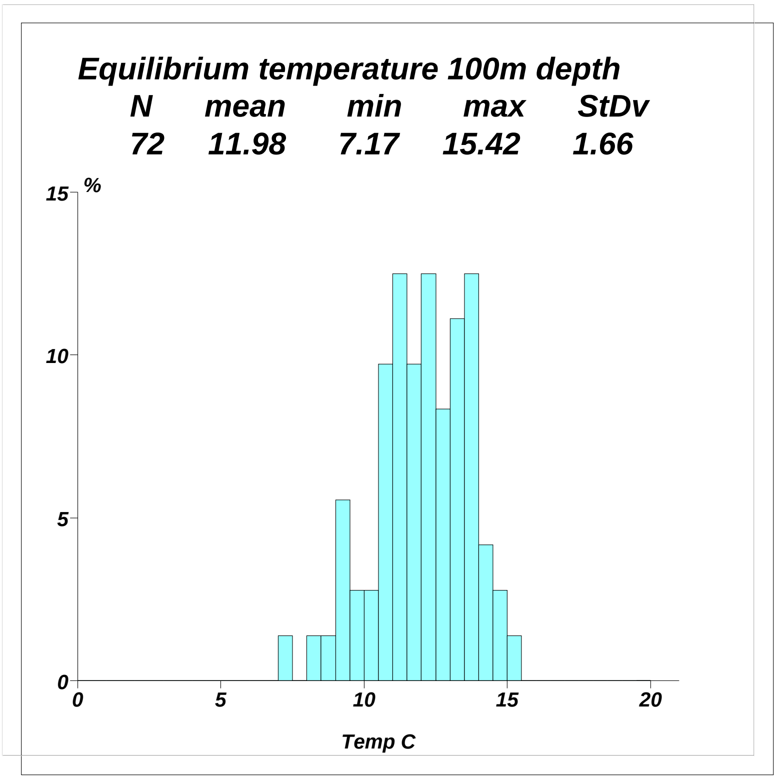

Figure 9 Histogram of UK equilibrium temperatures at 100m depth

The equilibrium data show interesting regional variations in general accord with UK climate. Data for SW England (Figure 10) also have a strong geological component as the highest temperatures are associated with the high heat production, high heat flow granites.

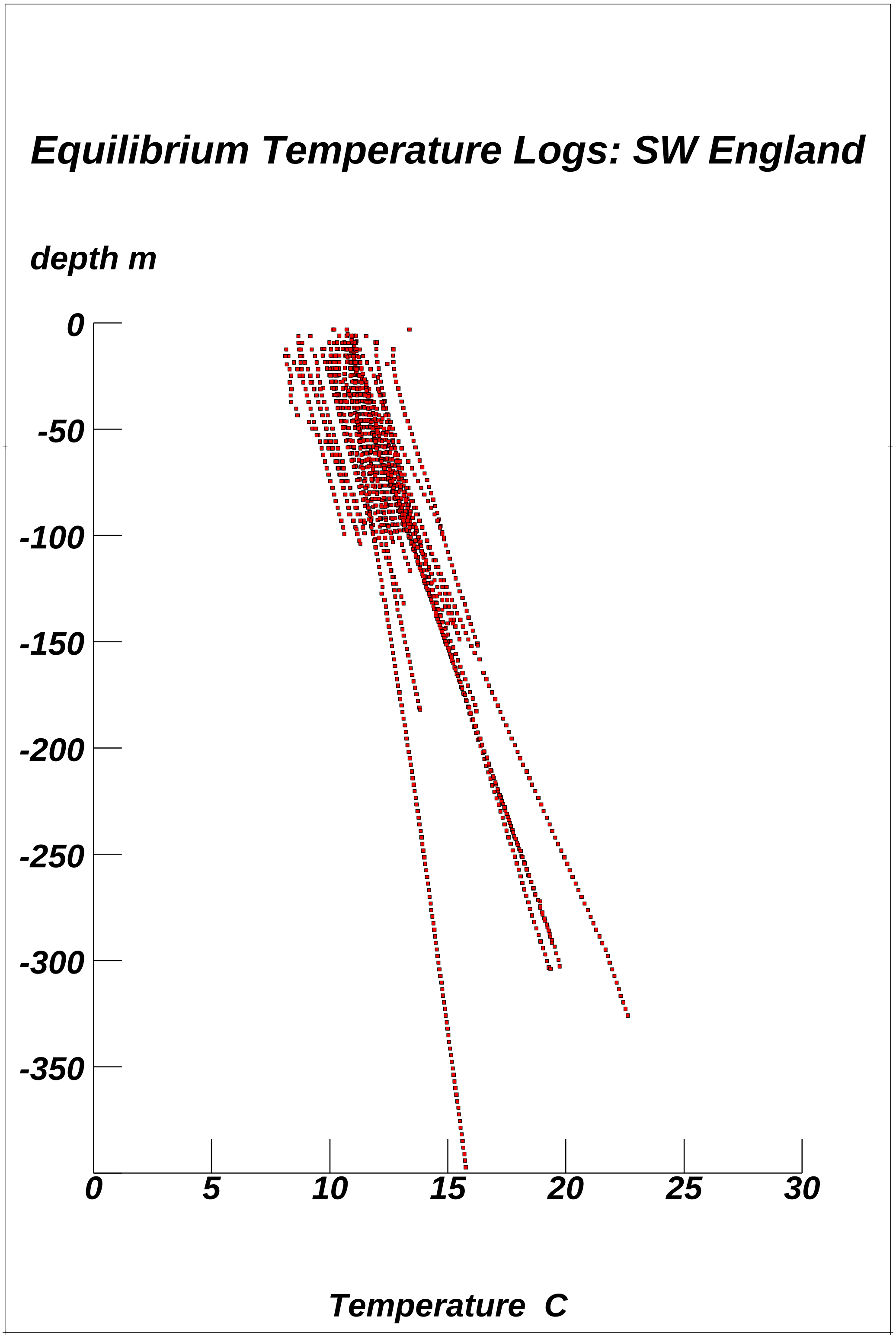

Figure 10 Equilibrium temperature logs for boreholes in SW England

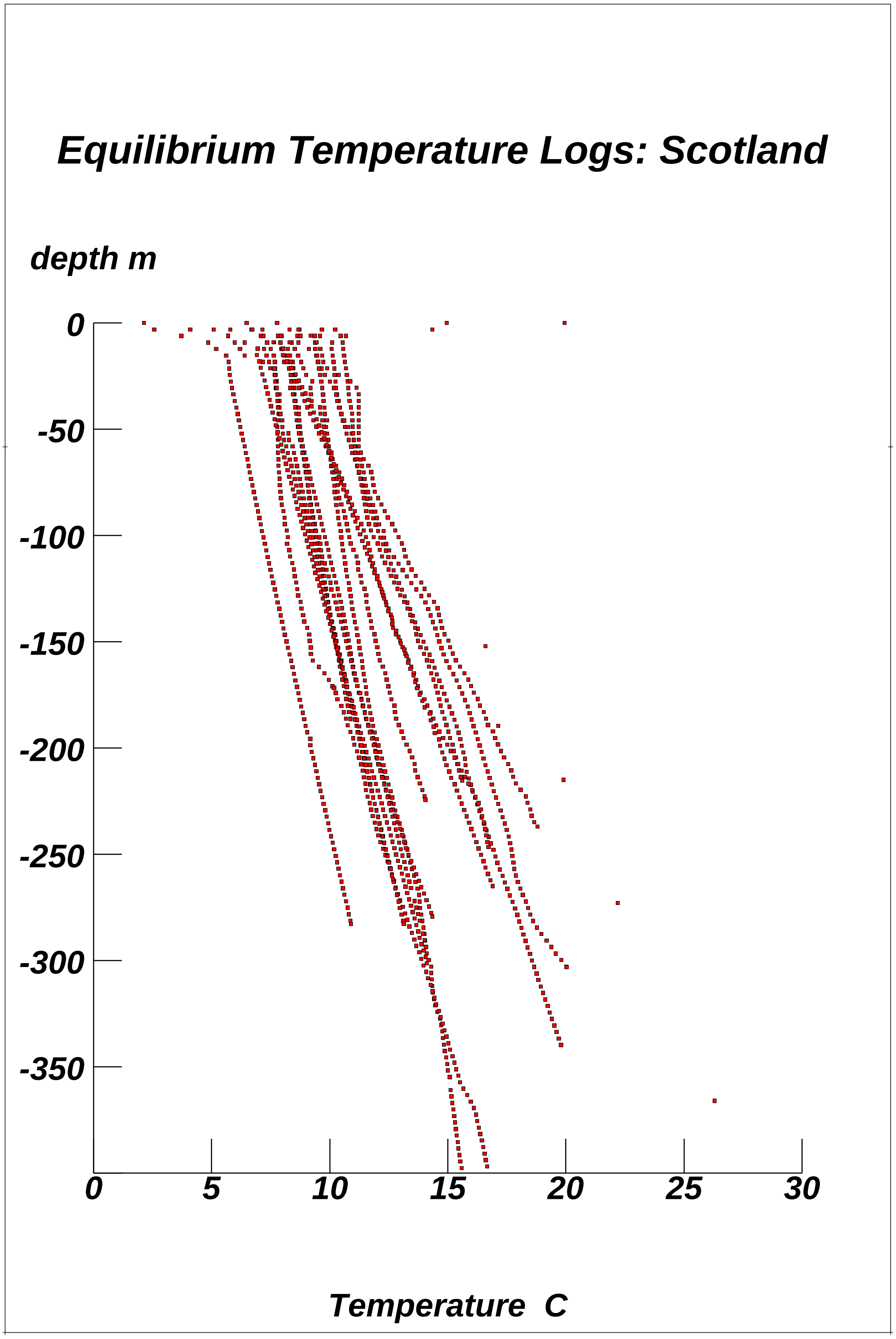

Figure 11 Equilibrium temperature logs for boreholes in Scotland

Equilibrium temperature logs for Scotland (Figure 11) show the effects of cooler mean annual air temperature (MAAT) but also show a significant spread at depths of 100m. This reflects the variation in MAAT primarily with elevation.

3.3.2.3 WATER QUALITY SAMPLE DATA

BGS has about 4000 observations of groundwater temperature from water quality samples taken from rivers, wells and boreholes. Many of these data are poorly referenced for position and many are from surface water samples. However there are about 350 samples from depths of greater than 2m and these may be useful to help define the UK sub-surface temperature field and help indicate zones of groundwater flow.

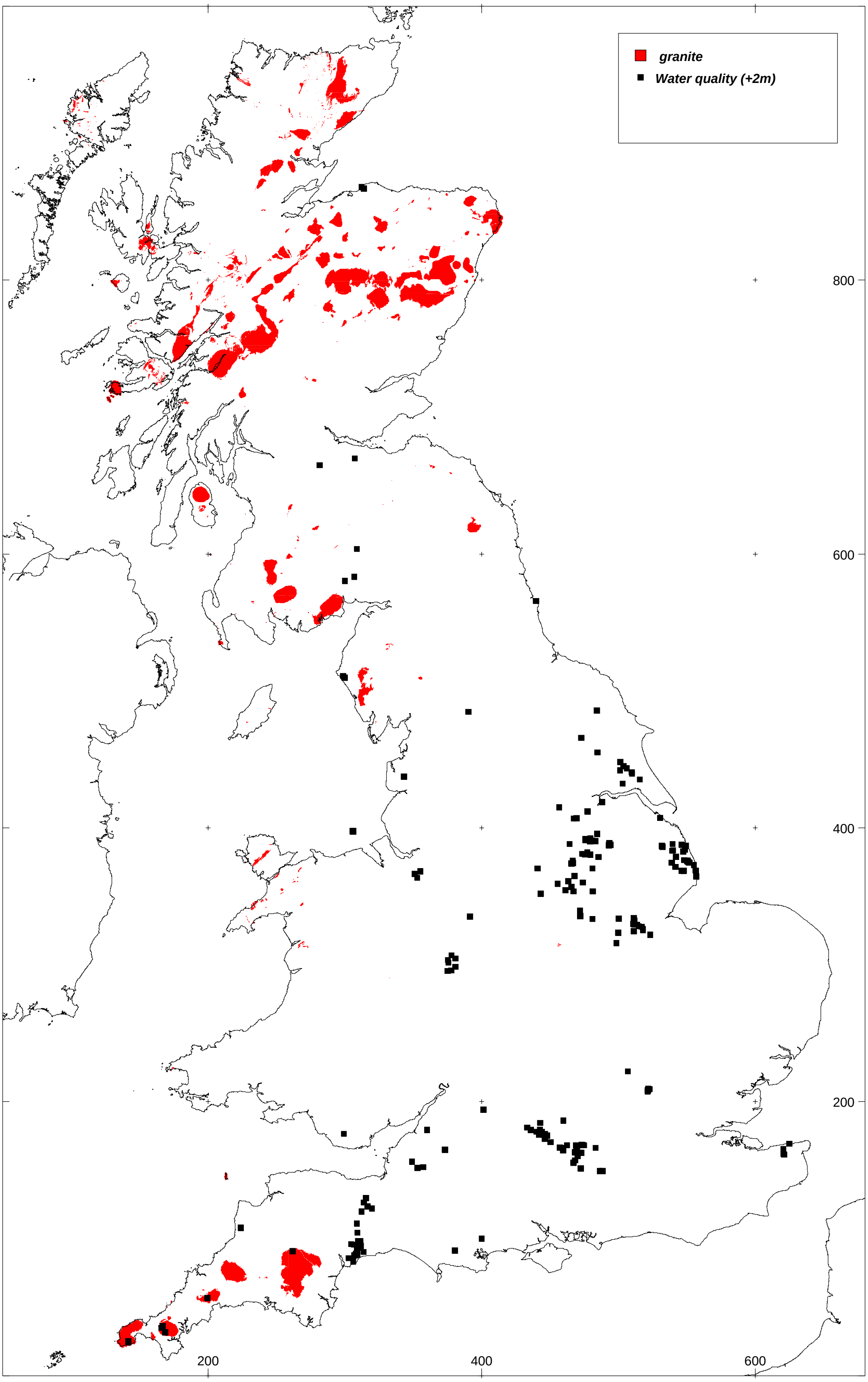

Figure 12 Location of water quality samples at depths greater than 2m

3.3.2.4 WATER WELL TEMPERATURE LOGS

BGS Hydrogeology has collected log data from water wells for many years and holds an archive of over 100,000 paper records of water wells and boreholes, supported by the WELLMASTER digital database (Figure 13). This data is currently being verified and transferred to the Single Onshore Borehole Index (SOBI).

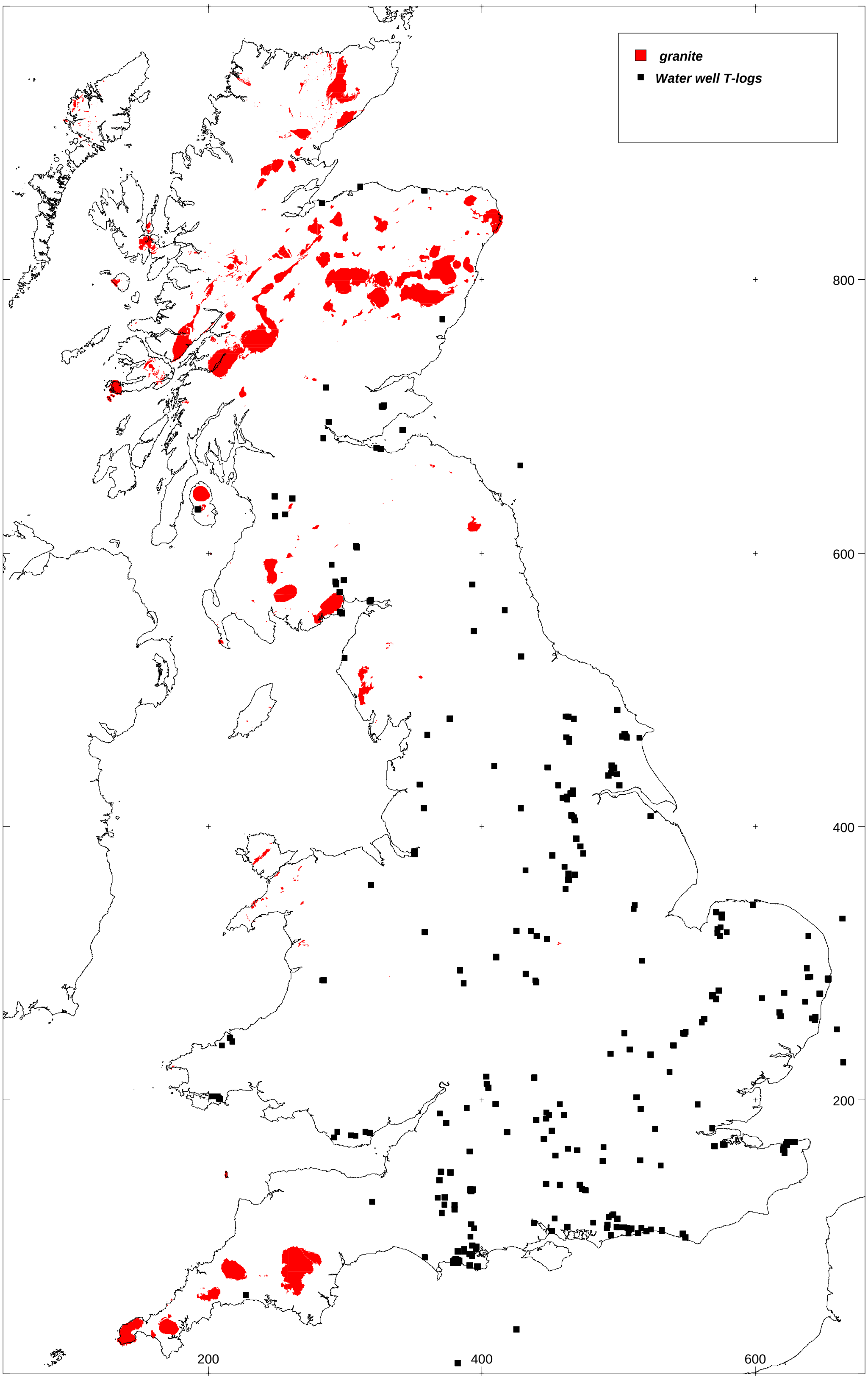

Figure 13 Location of wells with a temperature log in the WELLMASTER database.

Many water wells have been logged during a pumping test. Many of these logs include a temperature log either in steady state or while the well was being tested. These data can be used to help define the UK sub-surface temperature field and help indicate zones of groundwater flow. These data are currently being integrated into the SOBI (Single Onshore Borehole Index) database and many of the log records will be incorporated into the WELLOG database of digital borehole logs. Figure 13 shows the distribution of WELLMASTER wells with some form of temperature log although many of these wells will now be transferred to the WELLOG database.

3.3.2.5 Borehole wireline logs

Deep commercial boreholes are generally logged at several stages during drilling and each borehole may have several logging trips for various tools at each run. Many trips measure temperature at the bottom of the run and these observations recorded on the log header records are the source of most BHT data in the UK Geothermal Catalogue. However many wells will also have a temperature log providing a record of the transient temperature down the hole during breaks in drilling. The borehole records at BGS indicate about 1830 temperature logs distributed at about 1200 sites. Many of these are deep temperature logs with the top log interval well below 100m depth. Many logs are also recorded in the same well. However there are temperature logs with a top interval above 100m and a bottom log interval below 100m depth for 460 sites (Figure 5). These can be used to help verify the UK shallow sub-surface temperature field.

3.4 THERMAL PROPERTIES

3.4.1 Thermal conductivity

Rock thermal conductivity is largely determined by composition and porosity. In sedimentary rocks it ranges from about 1.5 W m^{-1} K^{-1} for clays to about 3.5 W m^{-1} K^{-1} for sandstones. Increasing porosity generally decreases thermal conductivity although water saturation will tend to reverse this trend. Routine sampling at intervals of between 3 and 10m within heat flow boreholes provides the main source of thermal conductivity data. Prior to 1984, most heat flow boreholes outside southwest England were situated on the Upper Palaeozoic or Mesozoic sedimentary crust. Conductivity data from these boreholes allowed a general summary of the thermal conductivity of these formations to be made (Table 2.2 in Downing and Gray 1986). The mean thermal conductivity of over 1100 samples of Mesozoic strata for instance was 1.97 W m^{-1} K^{-1}. Sampling of Lower Palaeozoic and older strata has been more restricted, although about one third of later heat flow boreholes drilled (1984-87) were on basement lithologies.

Although thermal conductivity shows some dependence on temperature, resulting in a general increase in geothermal gradient with depth, this effect is usually overshadowed in the shallow sedimentary crust, by the general increase of thermal conductivity with depth and age. Overall the data suggest that the higher mean thermal conductivities for basement lithologies results in a lowering of predicted temperatures at depth.

Downing and Gray (1986) quoted a mean thermal conductivity of 2.87 W m^{-1} K^{-1} for Lower Palaeozoic strata, whereas new data for selected sites on such formations give generally higher values. For example, the mean thermal conductivity of samples from the Selkirk heat flow borehole in low porosity slates, is 3.33 W m^{-1} K^{-1}, while data from the Morley Quarry borehole in Precambrian basement give a mean thermal conductivity over 4.1 W m^{-1} K^{-1}.

In contrast, data from the heat flow boreholes have confirmed the low thermal conductivity of Carboniferous strata. The mean of observations in the Maryhill borehole in Glasgow is 2.40 W m^{-1} K^{-1} while for the Glenrothes borehole in Fife, the mean Carboniferous thermal conductivity is 2.34 W m^{-1} K^{-1}. At the Harewood borehole near Leeds, the lower section of Carboniferous mudstone, from depths of 100 to 270m, has a mean thermal conductivity of only 1.20 ±0.15 W m^{-1} K^{-1}, producing a local geothermal gradient of 56 °C km^{-1}.

Where available, the arithmetic mean thermal conductivity for samples from each of the heat flow boreholes was included in the summary of heat flow data in the UKGC (Rollin 1987). This data should be read in conjunction with the geological range of the sampled data. The numerical geology codes indicate the stratigraphic range of the borehole in terms of the map codes used on the published 1:625,000 geological maps of Great Britain. For boreholes, which sample a restricted geological sequence, this can give a reasonable guide to thermal conductivity; in other cases this is not so.

The mean basement conductivity for the later heat flow boreholes on pre-Carboniferous rocks is 3.33 W m^{-1} K^{-1}, while the mean of all the 1984-87 data (1199 measurements) is 2.79 ±1.0 W m^{-1} K^{-1}. This is significantly different from the mean conductivity of 2.18 ±0.92 W m^{-1} K^{-1} for all the thermal conductivity data (1863 samples) for the 29 heat flow measurements made as part of the 1981-84 geothermal programme (Wheildon, Gebski and Thomas-Betts, 1985). The data histogram (Figure 14) indicates a slightly skewed distribution with local concentrations of conductivity occur around 1.90 and 3.30 W m^{-1} K^{-1}. This partly reflects the location of the sample sites in relation to basement or sedimentary cover, but also the natural conductivity contrast between the two common lithologies sandstone and shale. The frequency distribution of conductivity data population also shows this variation.

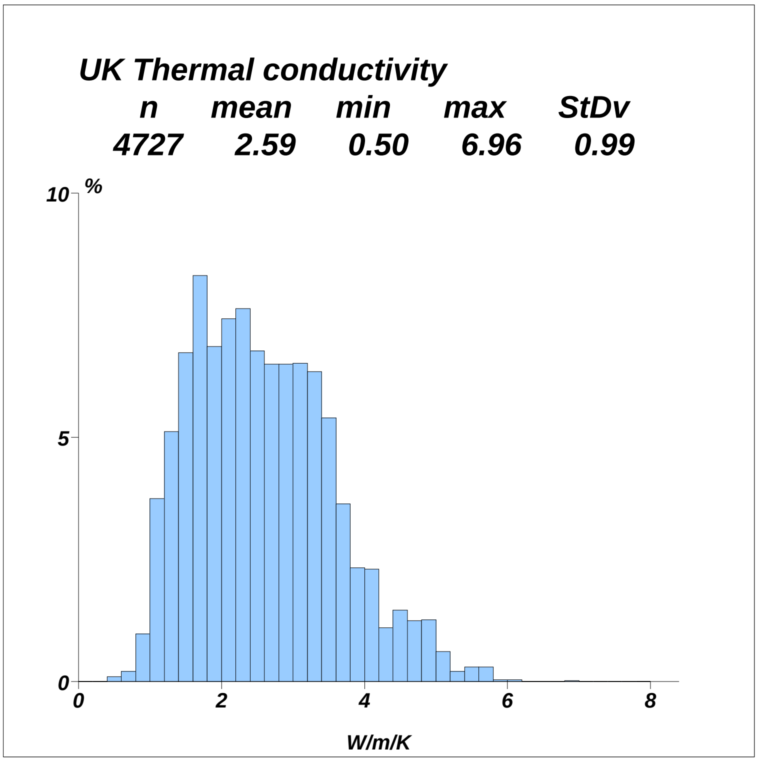

Figure 14 Histogram of UK thermal conductivity measurements

Incidentally, if the mean UK geothermal gradient in the top few kilometres of the sedimentary crust (26 °C km^{-1}) is combined with the mean UK heat flow (58 mWm^{-2}), the expected mean thermal conductivity is 2.23 W m^{-1} K^{-1}, similar to the mean of the earlier conductivity sample population. The higher mean conductivity for the later heat flow boreholes indicates the sampling bias towards the basement lithologies. Conversely, since the temperature data are biased towards the cover sequences, a more realistic geothermal gradient for most of the exposed basement areas and the deep crust might be about 17 °C km^{-1}, based on a heat flow of 58 mWm^{-2} and a thermal conductivity of 3.33 W m^{-1} K^{-1}.

Table 3 is based on the summary given in Downing and Gray (1986), extended to include the Palaeozoic rocks where sampled. Because of the dependence of conductivity on porosity and lithology, mean values are difficult to assign for some of the stratigraphic units. Reliability should be gauged by the frequency of sampling and the likely lithological variation of the unit concerned.

Table 3 Thermal conductivity from measured samples for selected formations in the UK (after Rollin 1987)

System	Formation	Lithology	Code	nk	cond	se
Palaeogene						
	Barton Beds	SMST	109	10	2.12	0.06
		MDST	109	2	1.46	0.05
	Bracklesham Beds	SMST	109	14	2.20	0.16
		MDST	109	4	1.58	0.01
	London Clay	SMST	108	5	2.45	0.07
	Reading Beds	SMST	107	4	2.33	0.04
		MDST	107	10	1.63	0.11
Cretaceous						
	Chalk	CHLK	106	41	1.79	0.54
	Upper Greensand	SDST	105	18	2.66	0.19
	Gault	SMST	105	32	2.32	0.04
		MDST	105	4	1.67	0.11
	Hastings Beds	SLST.	102	2	2.01	
		SLCL	102	3	1.26	
Jurassic						
	Kimmeridge Clay	MDST	99	58	1.51	0.09
	Ampthill Clay	MDST	98	60	1.29	0.03
	Oxford Clay	MDST	97	27	1.56	0.09
	Kellaways	MDST	97	21	1.52	0.03
	Cornbrash	LMST	96	5	2.29	0.17
	Forest Marble	MDST	95	37	1.80	0.07
	Frome Clay	MDST	95	15	1.72	1.10
	Fullers Earth	MDST	95	47	1.95	0.05
	Upper Lias	SDST	93	13	2.87	0.12
		MDST	93	11	1.27	0.03
		SLMD	93	11	2.22	1.10
	Middle Lias	MDST	92	3	1.66	0.15
	Lower Lias	MDST	91	37	1.80	1.10
Rhaetic						
	Penarth Group	SLMD	90	19	2.53	0.11
Triassic						
	Mercia Mudstone	MDST	90	225	1.88	0.03
	Keuper Marl	MDST	90	41	2.28	0.33
	Sherwood Sandstone	SDST	89	64	3.41	0.09
		MDST	89	6	2.37	0.23
	Bunter Sandstone	SDST	89	8	2.54	0.07
Permian						
	Permian Marls	MARL	87	6	2.12	0.28
		ANHY	87	8	5.40	0.13
		HALI	87	14	4.87	0.22
	Magnesian Limestone	LMST	86	12	3.32	0.17
Carboniferous						
	Westphalian	SDST	82	37	3.31	0.62
		SLST	82	12	2.22	0.29
		MDST	82	25	1.49	0.41
		COAL	82	8	0.31	0.08
	Namurian	SDST	81	7	3.75	0.16
	Tournasian	LMST	80	14	3.14	0.13
		SDST	80	76	4.19	0.08
Devonian						
	Upper ORS	SDST	78	27	3.26	0.11
	Middle	SLST	77	129	2.49	0.08
	Old Red Sandstone	SDST	75-76	76	3.51	0.41
	SW England	SLAT	75-78	206	2.69	
Silurian						
	Selkirk	SLAT	72	67	3.33	0.05

	Ordovician					
	Central Wales	MDST	69	62	2.83	0.06
Precambrian						
	Charnian		60	116	3.93	0.06
	Longmyndian		60	96	3.01	0.05
	Dalradian Supergroup	PSAM	13-25	42	3.29	0.13
	Moine Supergroup	PSAM	8-12	41	3.47	0.10
Intrusive						
	Hercynian granite	GRAN	34	895	3.30	0.18
	Caledonian granite	GRAN	34	270	3.29	0.23
	Dolerite	DOLR	36	12	1.75	0.05
Extrusive						
	Basalt	BASA	53	17	1.80	0.11

Notes: nk number of samples; cond thermal conductivity W/m/K; se standard error; Code, geological code 001-115

Lithology codes: SMST, sandy mudstone, MDST, mudstone, LMST, limestone, PSAM, psammite, SDST, sandstone, SLST, siltstone, SLCL, silty clay, SLMD, silty mudstone, HALI, halite, ANHY, anhydrite, SLAT, slate,

Appendix 4 provides a summary of thermo-physical properties for the UK geological units based on the classification used on the 1:625,000 Geological Map.

Despite the recent new data from basement sites, the distribution of thermal conductivity with depth in the sedimentary crust, is one of the major uncertainties in temperature predictions to depths greater than about 2 km. In this respect deep temperature predictions are inherently more reliable in granites which have been shown, by geophysical interpretation, to extend to mid-crustal depths and are likely to be relatively homogeneous in terms of density and thermal conductivity.

BGS has an extensive database of thermal conductivity of UK rock formations. However, many of the +9900 LEXRock codes in DiGMapBG-50 will not have been directly sampled and some form of attribution of thermal properties to codes is required. A possible solution to this would be to use the BGS WELLOG analysis software to estimate formation thermal conductivities from digital wireline well logs. BGS has a large database of digital well logs which can be used to compute various petrophysical properties. Many publications describe methods for using wireline log data to derive rock thermal conductivity (Vacquier et al 1988, Demongodin et al 1991, Vasseur et al 1995).

3.4.2 Thermal diffusivity

Thermal conductivity and heat flux define the geothermal gradient in the subsurface but for shallow boreholes the temperature gradient is probably less important than the effects of thermal conductivity and thermal diffusivity on heat exchange and GSHP system performance. Heat transfer to a ground collector is affected primarily by the surface area and the thermal conductivity and thermal diffusivity. Thermal diffusivity χ is a measure of ground thermal conduction in relation to thermal capacity and relates the rock thermal conductivity (λ), the specific heat c and the density ρ.

$$\chi = \lambda / c \rho \quad [6]$$

Rock density varies by a factor of about 2 across a range 1.50 –3.10 Mgm^{-3} with unconsolidated sands and soil having low densities and mafic igneous rocks such as gabbros and peridotite with densities above 3.0 Mgm^{-3}.

Thermal conductivity varies by a factor of about 4 and varies considerably with rock type and porosity. The common range of values for sedimentary rocks is from about 1.5 – 3.5 W m^{-1} K^{-1} for Kimmeridge Clay to Devonian sandstone. UK granites typically have thermal conductivities in the range 3.0 - 3.5 W m^{-1} K^{-1}.

The specific heat of hard sedimentary and igneous rocks is reasonably constant and close to 0.85 J g^{-1} K^{-1}. Clay and marl rocks have higher specific heats, in the range 0.87-0.93 J g^{-1} K^{-1}. Porous rocks and soils have significantly higher specific heats if saturated with water. Clays and soils with high saturation levels can have specific heat values up to about 2.0 J g^{-1} K^{-1}.

Table 4 shows the approximate effect on performance of a vertical-loop GSHP system for different rock thermal conductivities.

Table 4 Approximate energy yield in relation to thermal properties for vertical-loop GSHP

Rock	**conductivity Wm^{-1}K^{-1}**	**extraction rate W/m**	**energy yield kWh/yr/m**
Hard rock	3.0	<80	135
Saturated unconsolidated	2.0	45-50	100
Dry unconsolidated	1.0	<30	65

Typical rock thermal diffusivities range from about 0.75 10^{-6} m^2 s^{-1} for clays to about 2.0 10^{-6} m^2 s^{-1} for high conductivity rocks such as anhydrite and pure quartzites. Many rocks have thermal diffusivites in the range 0.9-1.2 10^{-6} m^2 s^{-1} (0.077 –

0.103 m^2/day). Generally thermal conductivity and specific heat are increased for saturated rocks and diffusivity is also enhanced. Table 5 gives representative values for a few rock types.

Table 5 Typical values for rock diffusivity

Rock	**Thermal diffusivity 10^{-6} m^2 s^{-1}**
Basalt	0.685
Dunite	0.947
Granite	1.000
Granodiorite	0.719
Gneiss	1.224
Quartzite	2.952
Salt	3.060
Anhydrite	2.242
Clay	0.950
Clay marl	0.934
Limestone	1.054
Marl	1.118
Marly clay	0.894
Sandstone	1.645

For deep temperature models of the UK, BGS has compiled thermal conductivity, rock density and heat production for the main chronostratigraphic classes (001-115) shown on the published 1:6350000 geological map. This provides a set of baseline properties to calculate thermal diffusivity although this parameter will vary substantially with the porosity of the rock and the extent of saturation. These data are reproduced in Appendix 4 with a calculated thermal diffusivity.

3.5 GEOTECHNICAL PROPERTIES

Rock and cover sequence type will affect the method and cost of drilling. This might relate to the basic rock strength of the drilled section, the nature and depth of the cover sequence, the need to case or line sections of hole and the depth of weathered rock.

BGS has about 1250 records of Unconfined Compressive Strength (UCS) in our geotechnical database abstracted from c. 603 borehole locations. BGS also have a huge number of 'soil' strength parameters for clay and many mudrock formations which can be bored by soft ground boring techniques, but the UCS values are the important ones for indicating the presence of stronger rocks requiring rock drilling techniques.

There are currently no weathering layer maps available or produced by BGS. In the geotechnical database BGS does have weathering data descriptions as recorded on site investigation logs. We have data from about 21000 boreholes in the geotechnical database, but it is uncertain how many of these record good weathering descriptions. However, BGS does have records for c. 1600 boreholes that indicate depths at which drilling changed from soft ground to rock drilling techniques. This drilling change depth is a good indicator of the borehole hitting fairly strong 'competent' rock and is virtually equivalent to 'engineering rockhead'. This might be a useful parameter to record in terms of drilling for the GSHP industry.

Summary rock strength reference tables can be derived from data currently held in the BGS geotechnical database, but geographical cover is limited. Summary tables (often not in digital form) of rock strength (and other properties) were also prepared for many of the applied geological mapping projects carried out by BGS for DOE and DEFRA. Some of these projects had no geotechnical databasing input but often had the summary properties of the rocks briefly assessed from published data or from assessment of a limited number of site investigation logs. Such summary assessment usually provided a classification of the rocks in the area under study as weak/strong/moderately strong. In addition, in some cases, a separate engineering geological report on the rock properties was prepared. However, the rock strength classifications for these areas were not nearly as comprehensive as that done for those projects which also included a component to database the geotcechnical properties. A list of the areas for which applied geological mapping projects were carried out by BGS is given in Table 6. Many of these studies are urban regions with a potential market for GSHP installations.

Table 6 Areas with applied geological mapping projects

Deeside		*
Wrexham		*
Morpeth-Bedlington	#	
Bradford		*
Leeds		*
Garforth-Castleford-Pontefract		*
Wigan	#	
Stoke	#	
Birmingham	#	
Nottingham		*
Coventry		*
SE Essex		*
SW Essex		*
Southampton	#	
Exeter	#	
Manchester		*
Firth of Forth	#	
Cromarty	#	

- * Geotechnical data incorporated into BGS database
- # summary geotechnical properties

3.6 HYDROGEOLOGY

Most major aquifers in the UK are covered by hydrogeological maps. Data on the physical properties of major aquifers in England and Wales are also available on CD-ROM. The wells are digitally indexed for location, borehole name, depth and date of drilling, borehole construction, the geological log, and details of water strike, levels and yield and summaries of water quality.

Groundwater levels are monitored at approximately 5000 sites mostly in England and Wales. An important part of the National Groundwater Archive is a database of water levels measured by the Environment Agency, Scottish Environment Protection Agency and the Depratment of the Environment in selected observation boreholes in the UK. Approximately 170 boreholes are used, chosen generally to be representative of natural groundwater conditions across major UK aquifers. This database can be used to retrieve datasets of considerable historical value for modelling of water resources and climate change, as well as providing an overview of the impact of climate on water resources. The basic data have been used to examine a number of important hydrogeological fields: especially aquifer properties and hydro-geochemistry. There are reasonable time series data for about 1500 boreholes. Long series data can be used to study climate change, assess water resources status and prediction of flood and drought conditions. Most observations show important seasonal variations with correlated with antecedent winter rainfall. Some records show the effects of abstractions. In many urban areas such as London, substantial abstraction from about 1850 has lowered groundwater levels. However, reduction in water abstraction, associated with a decline in manufacturing, has resulted in a recent rise in groundwater levels to the extent that this affects subsurface infrastructure.

Water saturation significantly increases the thermal conductivity of porous rocks such that thermal conductivity can be increased by a factor of 100%. Saturation is important for both consolidated strata and unconsolidated sediments since sandstones in many part of the UK can have porosity values up to 20%. The depth of saturation levels in these strata might also be crucial to the design of GSHP systems, especially on local topographic highs.

Fluid flow and the associated heat transport effects can be very considerable but are often difficult to predict. Fluid flow is an extremely effective means of heat transfer and very small flow vectors can produce very large variations in the predicted subsurface temperature profile. These flows can have a positive or negative effect depending on the nature of the flows. Generally flow vectors with an upward component will provide a positive contribution to the subsurface temperature. These effects are seen in several of the equilibrium temperature logs for the UK heat flow boreholes, in many shallow water well temperature logs and also in many deeper wells with BHT data. To a certain extent some heat transport effect must be considered possible in all boreholes, and the nature of this effect will affect the deviation of the temperature profile from the one-dimensional conductive model. The likelihood of fluid flow and heat transport can be assessed in relation to several parameters derived from BGS data. These will include the structural components of the site, the presence of faulting, the nature of porosity and permeability and the anticipated hydraulic head.

4 Use of data for GSHP

A critical need in the design of a closed loop GSHP is a reasonable knowledge of the thermal conditions and properties of the host soil and rock formations. The main requirements are source temperature, thermal conductivity and thermal diffusivity. If site thermal conductivity and diffusivity are incorrect then performance of the exchange loop is poorly predicted. A 10% error in thermal conductivity and diffusivity typically produces an error in design length of about 5% and can significantly affect cost of drilling.

Source temperature is important although in many cases the GSHP installation will work regardless of the source temperature. However for commercial designs, if site temperatures are overestimated, continuous heating loads may result in ground freezing and reduced system performance. Conversely if ground temperature is high the potential for passive cooling may be limited.

A geological prognosis for drilling is also essential to help remove uncertainty regarding the host formation for the external loop. The depth, nature and thickness of the superficial deposits will be important to estimate drilling and casing requirements. Good borehole prognosis might also help to identify potentially favourable or unfavourable host formation within target depths. Drilling costs are relatively high in the UK. Any improvement in drilling prognosis and practise might help to reduce drilling costs. For commercial installations a better prognosis of temperature might save significantly on drilling costs.

4.1 EXISTING FACILITIES

BGS has some existing functions which are of direct application to the GSHP industry. These are the specific enquiry service and the GeoReports service.

4.1.1 GeoReports service

BGS has launched an on-line enquiry service to provide users with impartial information and interpretations of corporate data within defined schema. The main schema currently available are focused towards geoscience data listing; geological assessment; radon protection and water borehole prognosis. The GeoReport facility is at www.bgs.ac.uk/georeport. The Figure 15 summarises the main options in the current reports:

The main reports which are considered to be of immediate use to the GSHP industry are the Water Borehole Report and the Geological Reports.

Water borehole prognosis
This report is aimed at users investigating sites for the abstraction of smaller groundwater supplies (less than 5 l/s). Note that reports are also available for larger water supplies – but please contact BGS Enquires separately to order.

The Water borehole prognosis report contains an evaluation of the potential geological sequence beneath the site, and its aquifer properties, groundwater yields, rest levels and water quality. The report is based on analysis by BGS Hydrogeology of records and maps held in the National Well Records Archive (part of the National Geoscience Data Centre).

This report will be carried out for a specific grid reference only (search radius does not apply)

Report comparison

Modules (Click the table headings for further details)

Reports (Click on the report name for further details)

Reports	Price	OS 1:50000 map extract	Geological map extracts	Geoscience data listing	Radon Protection Measures	Radon Protection Measures +	Geology Description	Geohazards Description	Hydrogeology Description	Hydrogeology Description +	Sketch cross section	Well prognosis
Geoscience data list	£11.75	✕	✕	●	✕	✕	✕	✕	✕	✕	✕	✕
Geology map extracts	£11.75	✕	(1)	✕	✕	✕	✕	✕	✕	✕	✕	✕
Radon protective measures standard	£35.25	●	✕	✕	(2)	✕	✕	✕	✕	✕	✕	✕
Radon protective measures detailed	£140.00	●	✕	✕	✕	(2)	✕	✕	✕	✕	✕	✕
Water borehole prognosis	£175.00	●	(1)	✕	✕	✕	✕	✕	✕	✕	✕	●
Geological assessment basic	£140.00	●	✕	●	✕	✕	●	✕	✕	✕	✕	✕
Geological assessment standard	£195.00	●	✕	●	✕	✕	●	●	●	✕	●	✕
Geological assessment detailed	£275.00	●	(1)	●	(2)	✕	●	●	✕	●	●	✕

Notes :
1. Geology map extracts are not available for certain areas. View availability map
2. Radon protection measures reports are not yet available for Scotland. View availability map

Figure 15 Summary of the GeoReports functions currently (01/03/03) available

Geological Assessment Reports
Geological assessment — basic

This report is aimed at users carrying out preliminary site assessments or at people who have a general interest in the rocks around their property.

The report describes the rock types that might be encountered at the surface or at 'rockhead' beneath a site (meaning the rocks lying directly beneath the soil layer). It also briefly considers mining and quarrying hazard, and contains a listing of the key geoscience data sets held in the National Geoscience Data Centre for the area around the site (same as included in the separate Geoscience data list report). The report **does not**, however, consider natural geological hazards (in particular natural subsidence and radon), the concealed (buried) geology, or hydrogeology at the site (these are described in the standard or detailed geological assessment reports, available separately).

Geological assessment — standard

This report is aimed at users carrying out preliminary site assessments, who require a brief indication of the geology and any related geological hazards around the site.

In addition to the features included in the basic geological assessment, the standard report also considers natural ground subsidence and aquifer vulnerability, as well as concealed (buried) geology if relevant to the stability of the surface. The report **does not**, however, consider radon hazard or hydrogeology at the site (these are described in the detailed geological assessment report, available separately).

Geological assessment — detailed

This report is aimed at users carrying out preliminary site assessments, who require a comprehensive assessment of the geology, hydrogeology and any geological hazards around the site.

In addition to the features included in the basic and standard geological assessments, the detailed report also considers radon hazard (in terms of the level of radon protection required in new dwellings) and the detailed hydrogeology of the site. Other features include a sketch cross-section of the site (showing how the various rock layers relate to each other) and colour geological maps extracts taken from the BGS 1:50 000 scale digital geological map of Great Britain (as included in the separate geology map extracts report).

4.1.2 Specific enquiries

BGS operates a number of established enquiry services based on key BGS data sets that provide advice of particular concern to **site assessments**. The main areas of site specific enquiry are:

- Radon Protective Measures (RPM)
- Advice on Site and Area Geology
- BGS borehole and well record archives
- Advice on Site and Well Hydrogeology
- Geological hazards advice (pollution, mining, subsidence, earthquakes, landslides, flooding)

Some of these functions have already been transferred to the GeoReports enquiry system, although BGS will still respond to site-specific enquires of a specialist nature.

4.2 DEVELOPMENT POTENTIAL

4.2.1 Models of shallow temperature

Models of shallow subsurface temperature for the UK are currently inadequate. Part of this is because models are difficult to verify without access to the BGS geothermal database. Improved models of temperature at depths of 50m 100m and 200m would be a useful guide for GSHP installers, designers and users. A design plan to develop inproved drilling progosis, physical property data and subsurface temperature is shown in Figure 16. A new subsurface temperature map (Tz) would be verified with temperature observations and thermal and geotechnical properties would de accessed from BGS data tables.

A prerequisite for a subsurface temperature model is an improved ground surface temperature model based on mean annual air temperatures (MAAT). These data are available from the Meteorological Office (METO). Aspect, topography and elevation should be incorporated into the ground temperature model to provide a site-specific estimate of mean annual temperature. Important geothermal parameters which affect subsurface temperature should be incorporated into the shallow temperature model. Primarily these will be thermal conductivity and heat flow.

4.2.2 Attribution of properties to LEXRock

Functions already exist to provide a solid and drift geology from address location by grid reference or postcode. This will return a LEXRock code which can be linked to descriptions in the BGS Lexicon. However there is considerable work involved in linking the thermophysical properties to the Lexicon. This needs to be done to provide formation specific properties at any site.Primarily thermal conductivity and diffusivity need to be linked to the Lexicon either by attribution of each measurement or by summary tables of properties which can be linked to LEXRock codes.

4.2.3 Soft rock/weathering maps

The term ‘rockhead’ has been used to describe various geological surfaces. Most commonly it refers to the interface between drift and solid geology. In engineering terms it usually relates to the interface of hard competent rock and might be at the solid-drift boundary, or a weathering layer. In terms of drilling costs engineering rock head or the depth to competent rock might be the most important. BGS should aim to access borehole records with good weathering and drilling reports to establish maps of engineering rockhead. This may be restricted to urban regions where density of bores is greatest, but these are also anticipated to be the regions of greatest demand for commercial GSHP installations.

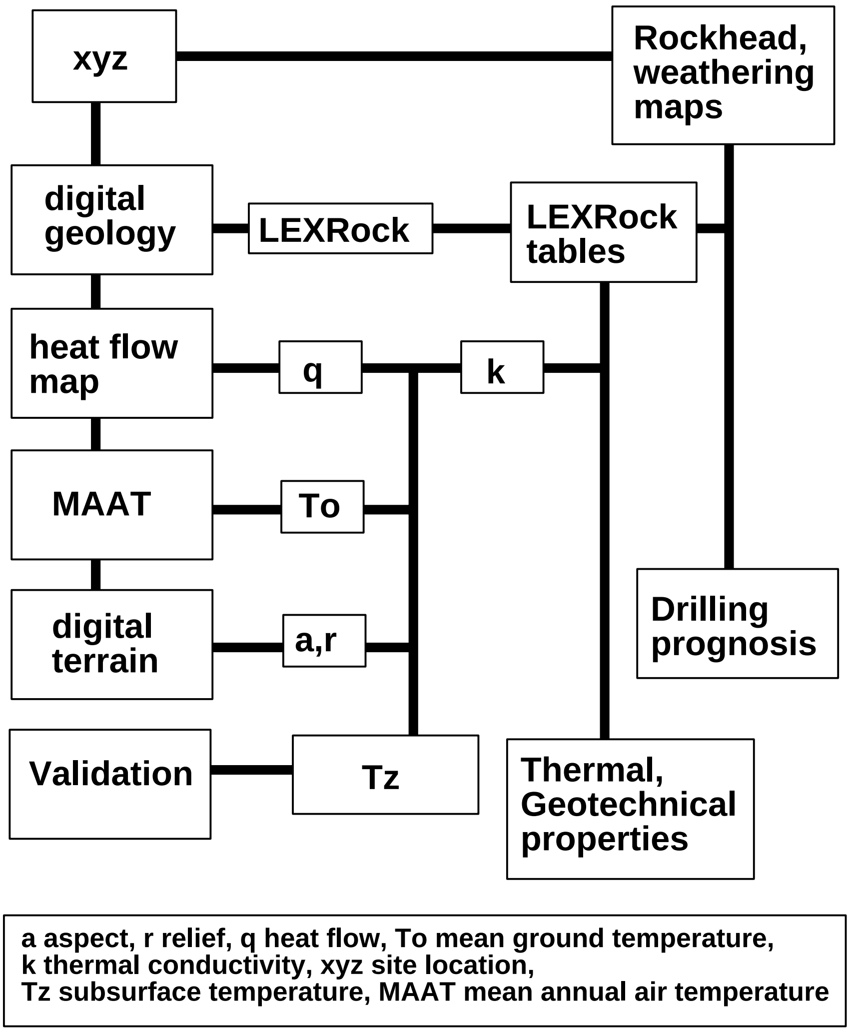

Figure 16 Design plan to produce GHSP characterisation from BGS data.

4.2.4 Improved GeoReports

There would seem to be a need for one or two GeoReports to provide the GSHP industry with basic parameters for system design and specification:

- A level 1 report should aim to provide a basic geological description of the surface geology; an estimate of the mean annual ground temperature and the temperature at 100m depth; an estimate of the likely rock thermal conductivity and diffusivity.
- A level 2 report would develop modules within the detailed geological report and the hydrogeological report to provide a geological prognosis for the top 100m; an estimate of the likely level of water saturation; an estimate of the depth to water level and of the seasonal changes in water level. In addition an estimate of likely depth to hard rock drilling and some estimate of hard rock strength would be provided. All the components of level 1 would also be included

Current prices for natural gas mean that there is an additional cost barrier to installation of GSHP in those parts of the UK served by mains natural gas. This suggests that there may be a relative advantage for GSHP in those regions of the UK not served by mains natural gas and that these areas should be key targets for any new GeoReports service. However, these areas are likely to be those with less primary relevant data. Furthermore, commercial installations are likely to have a more widespread distribution so that the Level 2 and Level 1 GeoReports should aim for national coverage.

5 Conclusions

1. BGS has a vast amount of geoscience data for the UK, much related to surface mapping and shallow drilling. All of the UK now has digital geological vectors at a scale of 1:50000 attributed for rock formation (Lexicon) and rock lithology (Rock).

2. BGS has a unique set of observations on the subsurface temperature field of the UK derived from wireline log header records (BHT), equilibrium temperature logs, water and commercial well temperature logs, water quality and chemistry sampling. Many of these data are not yet in a digital form. Effort should be directed at making these data available in digital form and using the data to verify a new shallow (200m) subsurface temperature model for the UK, designed for the GSHP industry.

3. BGS has probably the most complete database of UK rock geophysical properties including rock thermal conductivity and density. These data can be used to provide baseline thermal properties for the UK solid geology. BGS also has many drilling and site investigation records which provide details of ground conditions during drilling. These can be used to provide estimates of rock strength for UK formations and provide estimates of soft ground depths (depths to hard rock drilling).

4. The GeoReports facility established on the BGS web site has features which are of use to commercial GSHP installers, especially the detailed geological report and the hydrogeological report. There are currently no on-line facilities for the GSHP industry to assess site temperature and thermophysical properties. The BGS data could provide a set of specific enquiry functions to help the UK GSHP industry especially in relation to site temperature and rock properties.

6 Recommendations

1. Seek to establish an impartial on-line GeoReports service to provide temperature prediction and site characterisation for the GSHP community. This will involve a project containing components to:

- Link the attributed (LEXRock) geological vectors to a database of engineering and geotechnical properties to provide a guide to drilling conditions at the site.
- Link the attributed (LEXRock) geological vectors to an improved database of thermal properties to provide a guide to source heat exchange parameters.
- Develop a new shallow temperature prediction model for the UK which will include spatial variation, thermal conductivity, heat flow, site aspect and relief. Verify this temperature model using existing measured subsurface temperature data.
- Develop new depth to water table maps and digitise existing maps for the main aquifers of the UK. Develop new hydrogeological models of groundwater fluctuations and flow, which might provide improved assessment of heat transfer by fluid flow at any site.

2. Use existing functions in the BGS GeoReports system to provide basic background characterisation to new commercial GSHP projects as part of the Market Barriers project. This will provide assessment of the existing functions, highlight inadequacies and help focus the development of item 1.

Appendix 1 Notes on DiGMapGB-50 vector attributes

BACKGROUND

The DiGMapGB (Digital Geological Map of Great Britain) project started in 1998 and the first edition of the 1:50 000 scale dataset has been completed and released as DiGMapGB-50 Version 1. Each available geological map in England & Wales and Scotland is now obtainable as a digital file of polygon data. Line data such as faults and coal seams are also available if required. These digital maps or tiles are prepared with the geological data arranged in up to four separate geological themes: solid (or bedrock geology), drift (or superficial geology), mass movement deposits (such as landslips), and artificial ground (such as man made ground), in so far as this information is available.

Maps which were only available as paper copies have been digitised for DiGMapGB, and recently published maps, compiled digitally, have been reprocessed as appropriate to the same standard. The data are routinely released in ArcView ®, MapInfo ® and Geographics ® formats, and other formats may be available on request.

The digital tiles are geologically attributed to the latest version of the BGS Digital Map Production System (DMPS97). The different types of geological linework are identifiable, for example as: artificial, mass movement, drift or solid boundaries, faults, coal seams, marine bands etc. Where required, additional 'hidden' lines have been added to close polygons that do not appear on the printed map, and do not represent real geological lines; rather they show the minimum extent of polygons and allow them to be infilled with colour.

A two-part label, called a 'LEXRock' seed, such as 'MMG-MDST', identifies every polygon on each theme. The first part is the Lex code, an abbreviation of the name of the unit as defined in the BGS Stratigraphic Lexicon. In stratified units this is a name in a lithostratigraphic hierarchy; in intrusive units it is a name in a lithodemic heirarchy. Here MMG is the code for 'Mercia Mudstone Group'. The second part, is the rock code an abbreviation of the lithology as defined in the BGS database or dictionary Dic_Rock_Type. Here MDST is the code for 'mudstone'. The lithology represented by this coding is usually the single predominant lithology present, or the two or three main lithologies. Other minor or trace lithologies, not referred to may also be present.

Having completed the available individual map tiles as DiGMapGB-50 Version 1 it is planned to upgrade them to Version 2. For this the geology shown on the individual tiles will be reviewed over large regions by re-examining all the tiles in each 100 x 100km Ordnance Survey square. Each tile, in for example square TQ, will be refitted with its neighbours as appropriate. This may require further minor revisions to the geological lines and to the Lex-Rock classifications. Customers holding a current licence will be entitled to these upgrades, once available.

SOURCES OF INFORMATION

Each tile is typically based on the latest 1: 50 000 or 1:63 360 (one inch to one mile) scale geological map, and shows the geological lines essentially as published. Major revisions to the linework have generally been avoided, although in a few cases, where the published 1:50 000 / one-inch maps are seriously deficient, new lines have been imported from recent 1:10 000 or 1:25 000 scale detailed maps.

In some areas where there are no suitable geological maps published, new geological lines have been compiled for DiGMapGB-50 by fitting the best available old linework to the modern topographic base. Where this was not possible, 1:250 000 scale digital data for the solid from the DiGMapGB-250 dataset are available.

The DiGMapGB-50 digital tiles are not simply copies of the printed maps, some required significant additional geological interpretation. Lines have been added where needed to close polygons, for example to complete the solid geology where it was previously unmapped beneath superficial deposits. Many of the tiles in DiGMapGB-50 Version 1 have misfits with their neighbours. Some of these misfits are cartographic errors that have arisen due to the varying techniques used in the compilation of the original published maps. These will be rectified in Version 2. Other misfits, commonly occurring between maps of different ages, will be considered by geologists and re-fitted, where practicable. This refitting will not be possible with older maps and such misfits will not be resolved until those maps are resurveyed. Most geological data relating to specific points, such as fossil localities, boreholes or dip arrows, have been omitted from DiGMapGB-50 Version 1.

GEOLOGICAL NOMENCLATURE

Regardless of the source or vintage of each map, the geology has been reviewed and the nomenclature revised as far as reasonably possible to conform to the most up-to-date accepted usage. For a recent map, these changes, if any, will be minimal. In contrast on an old map some, and possibly many, of the deposits or rock units may have been renamed for DiGMapGB-50. Such changes will be reflected in future editions of the printed maps when they are republished. A Lex-Rock form is available which shows how the revised terminology used for DiGMapGB-50 relates to that on the existing published map.

Additional Lexicon information may be available in the Geodata area on the BGS Internet site. The sources of information specific to each digital tile are available.

Appendix 2 Explanation of DiGMapGB-50 attributes

The fields of information, shown emboldened below, as supplied with DiGMapGB-50 Version 1_05 data are explained briefly. Some of these fields are recent additions to meet customer demand and are not included in earlier datasets. The information included is subject to ongoing changes.

SHAPE: The shape files of data are polygons.

LEX_ROCK: A two-part code, LEX & ROCK, used to label each polygon of DiGMapGB data and for creating legends.

LEX: Lexicon Code. First part of the LEX_ROCK label. Up to 5 characters (mostly letters). An abbreviation of the named rock unit as listed in the BGS Lexicon: e.g. 'GOG'. Note 1

LEX_D: Description of the Lexicon code above giving the name of the unit: e.g. GREAT OOLITE GROUP is the name of the unit coded as GOG. Note 2.

ROCK: A code, up to 5 letters, for the type of rock, and forming the second part of the Lex_Rock label. It is an abbreviation of the lithology as listed in a BGS database or dictionary called Dic_Rock_Type: e.g. 'LMST'.

ROCK_D: Description of the Dic_Rock_Type code above giving the lithology of the unit: e.g. the lithological description of the rock coded as LMST is LIMESTONE.

RANK: Rank of the unit in the lithostratigraphic or lithodemic hierarchy: e.g. GROUP or SUITE. Note 3

BED_EQ: Lexicon Code for the unit at bed or equivalent level where applicable.

BED_EQ_D: Description of BED_EQ.

MB_EQ: Lexicon Code for the unit at member or equivalent level where applicable.

MB_EQ_D: Description of MB_EQ.

FM_EQ: Lexicon Code for the unit at formation or equivalent level where applicable.

FM_EQ_D: Description of FM_EQ.

SUBGP_EQ: Lexicon Code for the unit at subgroup or equivalent level where applicable.

SUBGP_EQ_D: Description of SUBGP_EQ.

GP_EQ: Lexicon Code for the unit at group or equivalent level where applicable.

GP_EQ_D: Description of GP_EQ.

SUPGP_EQ: Lexicon Code for the unit at supergroup or equivalent level where applicable.

SUPGP_EQ_D: Description of SUPGP_EQ.

AGE_NO: A number, representing the AGE field; or the maximum age code where the unit spans more than one division; used for GIS querying, e.g. 1322120.Note 4.

MIN_AGE_NO:: Minimum age number, representing the MIN_AGE field, where the unit spans more than one division; used for GIS querying. Note 4

AGE: Age code of the unit, to the most accurate chronostratigraphical division possible; or the maximum age code where the unit spans more than one division: e.g. CR. Note 5

MIN_AGE: Minimum age code of the unit, to the highest chronostratigraphical division, where the unit spans more than one division: e.g. CO. Note 5

STAGE: Name of the chronostratigraphical Stage applicable; or that of maximum age where the rock unit spans more than one Stage: e.g. ASBIAN.

MIN_STAGE: Name of the Stage with the minimum age applicable, where the rock unit spans more than one Stage: e.g. ALPORTIAN.

SERIES: Name of the chronostratigraphical Series applicable; or that of maximum age where the rock unit spans more than one Series: e.g. VISEAN.

MIN_SERIES: Name of the Series with the minimum age applicable, where the rock unit spans more than one Series: e.g. NAMURIAN.

SUBSYS: Name of the chronostratigraphical Sub-System applicable; or that of maximum age where the rock unit spans more than one Sub-System: e.g. DINANTIAN.

MIN_SUBSYS: Name of the Sub-System with the minimum age applicable, where the rock unit spans more than one Sub-System: e.g. SILESIAN.

SYSTEM: Name of the chronostratigraphical System applicable; or that of maximum age where the rock unit spans more than one System: e.g. CARBONIFEROUS.

MIN_SYSTEM: Name of the System with the minimum age applicable, where the rock unit spans more than one System.

ERATH: Name of the chronostratigraphical Erathem applicable; or that of maximum age where the rock unit spans more than one Erathem: e.g. PALAEOZOIC.

MIN_ERATH: Name of the Erathem with the minimum age applicable, where the rock unit spans more than one Erathem.

EONATH: Name of the chronostratigraphical Eonathem applicable; or that of maximum age where the rock unit spans more than one Eonathem: e.g. PHANEROZOIC.

MIN_EONATH: Name of the Eonathem with the minimum age applicable, where the rock unit spans more than one Eonathem.

BGSREF: The default printing colour for the LEX_ROCK code; defined as a 3 digit number. Further details are available if required.

BGSREF_LEX: Alternative colour at the LEX code level, as defined above.

BGSREF_FM: Alternative colour at Formation level, FM_EQ, as defined above.

BGSREF_GP: Alternative colour at Group level, GP_EQ, as defined above.

BGSREF_ROCK: Alternative colour for the lithology ROCK code, as defined above.

BGSTYPE: Type of geology. The theme such as Artificial, Mass Movement, Drift or Solid; or it may refer to particular usage such as 1:250 000 scale; or Offshore only. Note 6

SHEET: Geological map sheet (number and name) that the polygon appears on: e.g. EW069_BRADFORD; SC032E_EDINBURGH.

VERSION: Version number of the digital data: e.g. 1_05. Data with the same number have the same structure; as new fields are added or other major changes made so the version number is changed.

RELEASED: Date DiGMapGB-50 data converted into final format for release.

NOM_SCALE: Nominal scale of the source of information used to prepare the digital data, e.g. 1: 50 000. Note 7

NOM_OS_YR: The latest year date of Ordnance Survey information contained in the topographic base used for the original printed geological map (or the base used for DiGMapGB compilations). Fuller details are available if required.

NOM_BGS_YR: The latest year date of the principal BGS geological information contained in the 1:50 000 digital tile. This is usually the year of publication of the most up-to-date map sheet. Where no published map was available it is the year of compilation for DiGMapGB-50. Fuller details are available if required.

MSLINK: Used for BGS QA purposes.

Additional notes

note 1: The Lexicon is a database of named rock units and definitions which can be viewed on the BGS Internet site. The majority of stratified rock units are given a lithostratigraphical name, whilst none stratified units such as igneous intrusions and some metamorphic bodies have a lithodemic name.

note 2: Direct access to the Lexicon can be obtained via the BGS web site by prefixing the LEX code with the BGS web address: www.bgs.ac.uk/scripts/lexicon/lexicon.idc?pub=. This can be built into scripts, extensions or macros within a GIS. Script available for ArcView3.2

note 3: See other explanatory notes on the BGS web site.

note 4: A 7-digit number that allows rock units to be ordered, selected or queried by their age.

note 5: The age of the rock is given by a one- or two-letter code which indicates the chronostratigraphical division from Stage (the most detailed) through Series, Sub-System, System and Erathem to Eonothem (the least detailed):

note 6: Source map scale or offshore data.

note 7: Digital data are normally only used at scales similar to the source data; for example 1:50 000 data are not suitable for use at 1:10 000 scale without great caution.

Appendix 3 Stratigraphic Classifications

LITHOSTRATIGRAPHIC

Rocks are often deposited in layers or strata, and the sequence of these strata can be correlated from place to place. These sequences of different rocks are used to establish the changing geological conditions or geological history of the area through time. The description, definition and naming of the rock units is termed lithostratigraphy (rock stratigraphy). The strata can also be described in other ways depending on the types of information available; for example in biostratigraphy (life stratigraphy) fossils are used and in chronostratigraphy (time stratigraphy) the age is used.

Lithostratigraphy is fundamental to most geological studies. Rock units are described using their gross lithological characteristics and named according to their perceived rank in a formal hierarchy. The main lithostratigraphic ranks in this hierarchy are: Supergroup, Group, Formation, Member and Bed. The units are usually named after a geographical locality, typically the place where exposures were first described.

These formal ranks are often appended to names in the Lexicon. The formation is the fundamental rock unit for mapping purposes. A group is an assemblage of related and adjacent formations and a supergroup an assemblage of groups. A member is a sub-division of a formation and a bed is the smallest formal unit. Some possible lithostratigraphic relationships are shown schematically below.

Supergroup D	Group G	Formation V	Member X	
				Bed Z
			Member W	
		Formation U		
		Formation T		
	Group F	Formation S		
		Formation R		
		Formation Q		
		Formation P		
		Formation O		
				Bed Y

Table of lithostratigraphical hierarchical terminology

Formations need not be subdivided nor grouped together. In this hierarchical scheme each unit may have parent and child relationships with other units of greater and lesser rank respectively. Thus Formation V has Group G as its parent and is itself the parent of Members X and W.

LITHODEMIC

Lithodemic terms are necessary for rocks that cannot be successfully accommodated in the lithostratigraphic scheme. They generally apply to intrusive, highly deformed and/or highly metamorphosed and genetically mixed assemblages of rocks. Only three ranks are formally defined -- supersuite, suite and lithodeme; other ranks are used informally. Terms used for igneous lithodemes include central complex, pluton, dyke-swarm, sill-complex.

Some possible lithodemic relationships are shown schematically below, with informal terms italicised.

<table>
<tr><td rowspan="8">Supersuite A</td><td rowspan="5">Suite D</td><td rowspan="3">Subsuite F</td><td rowspan="3">Pluton H</td><td rowspan="2">Intrusion X</td><td>Zone1</td></tr>
<tr><td>Zone 2</td></tr>
<tr><td>Intrusion Z</td><td></td></tr>
<tr><td rowspan="2">Subsuite G</td><td>Dyke-swarm J</td><td>Subswarm P</td><td>Dyke O</td></tr>
<tr><td>Sill-complex K</td><td></td><td>Sill R</td></tr>
<tr><td rowspan="3">Suite E</td><td rowspan="3"></td><td rowspan="2">Central complex L</td><td></td><td>Plug W</td></tr>
<tr><td></td><td>Vent M</td></tr>
<tr><td>Pluton N</td><td></td><td></td></tr>
</table>

Table of lithodemic hierarchical terminology

Lithodemes need not be subdivided nor grouped together. In this hierarchical scheme each unit may have parent and child relationships with other units of greater and lesser rank respectively. Thus Pluton H has Subsuite F as its parent and is itself the parent of Intrusions X and Z.

CHRONOSTRATIGRAPHIC

In chronostratigraphy a formal hierarchy of principal terms has also been established as shown in the table below. The terms for the corresponding divisions of geological time (geochronological divisions) are placed beneath the chronstratigraphical terms; for example rocks of the Carboniferous System were deposited during the Carboniferous Period. A system may be subdivided into subsystems; for example the Carboniferous has two, Silesian and Dinantian.

Chronostratigraphical Divisions	Eonothem	Erathem	System	Series	Stage
Geochronological Divisions	Eon	Era	Period	Epoch	Age
Example	*Phanerozoic*	*Palaeozoic*	*Carboniferous*	*Westphalian*	*Bolsovian*

Table of chronostratigraphical and geochronological terminology

Appendix 4 Baseline thermophysical properties for UK 1:625000 chronostratigraphic codes

Conductivity	Density	Heat prodn.	Thermal diffusivity	Code	Lithostratigraphic description	System/Supergroup
$Wm^{-1}K^{-1}$	Mgm^{-3}	μWm^{-3}	$10^{-6}\ m^2s^{-1}$	0-115		
3.01	2.80	1.80	1.26	1	Gneiss	Lewisian
3.01	2.80	1.80	1.26	2	Metasedimentary rocks	Lewisian
3.01	2.80	1.80	1.26	3	Marble	Lewisian
3.01	2.80	1.80	1.26	4	Anorthosite	Lewisian
3.01	2.80	1.80	1.26	5	Ultrabasic	Lewisian
3.01	2.80	1.80	1.26	6	Basic rock	Lewisian
3.01	2.80	1.80	1.26	7	Granite	Lewisian
3.43	2.74	1.72	1.47	8	Migmatitic gneiss	Moine
3.43	2.74	1.72	1.47	9	Psammite	Moine
4.27	2.74	1.72	1.83	10	Grampian Group	Dalradian
3.43	2.74	1.72	1.47	11	Pelitic schists	Moine
3.43	2.74	1.72	1.47	12	Granite-gneiss	Moine
3.26	2.74	1.67	1.40	13	Schists Shetland-Tyrone	Dalradian
3.26	2.74	1.67	1.40	14	Hornblende-epidote schist	Dalradian
3.26	2.74	1.67	1.40	15	Chlorite schist	Dalradian
3.26	2.74	1.67	1.40	16	Boulder Bed-conglomerate	Dalradian
4.43	2.80	1.67	1.86	17	Quartzite-psammite-schist	Dalradian
3.86	2.80	1.67	1.62	18	Quartz mica schist	Dalradian
3.26	2.80	1.67	1.37	19	Grits-quartz-mica schists	Dalradian
3.26	2.80	1.67	1.37	20	Mica schist - phyllites	Dalradian
3.26	2.80	1.67	1.37	21	Mica schists	Dalradian
3.26	2.80	1.67	1.37	22	Black schist and chert	Dalradian
3.26	2.80	1.67	1.37	23	Graphitic schist	Dalradian
3.26	2.80	1.67	1.37	24	Limestone	Dalradian
3.26	2.80	1.67	1.37	25	Limestone	Dalradian
2.88	2.80	1.70	1.21	26	Serpentinite	Precambrian
2.88	2.80	1.70	1.21	27	Amphibolite	Precambrian
2.88	2.80	1.70	1.21	28	Foliated granite	Precambrian
2.96	2.75	1.72	1.27	29	Hornblende schist	Precambrian
2.82	2.75	1.72	1.21	30	Mica schist and gneiss	Precambrian
2.36	2.83	0.30	0.98	31	Ultrabasic	Intrusive
2.10	2.83	0.30	0.87	32	Gabbro	Intrusive
2.35	2.83	0.30	0.98	33	Diorite	Intrusive
3.27	2.63	3.00	1.46	34	Granite	Intrusive
2.03	2.63	3.00	0.91	35	Dolerite	Intrusive
3.20	2.63	3.00	1.43	36	Porphyrite lamprophyre	Intrusive
2.79	2.63	3.00	1.25	37	Felsite trachyte	Intrusive
3.20	2.63	3.00	1.43	38	Agglomerate in vent	Intrusive
2.90	2.75	1.00	1.24	39	Andesitic lava and tuff	Precambrian
2.10	2.80	0.50	0.88	40	Basalt spilite and tuff	Precambrian
3.29	2.75	1.00	1.41	41	Rhyolite trachyte and tuff	Precambrian
2.85	2.80	0.50	1.20	42	Basalts spilite and tuff	Silurian-Ordovician
2.10	2.80	0.50	0.88	43	Basaltic tuff	Silurian-Ordovician
2.35	2.75	1.00	1.01	44	Andesitic lava tuff	Silurian-Ordovician
2.35	2.75	1.00	1.01	45	Andesitic tuff	Silurian-Ordovician
3.95	2.75	1.00	1.69	46	Rhyolitic tuff	Silurian-Ordovician
2.35	2.75	1.00	1.01	47	Ignimbrite	Silurian-Ordovician
2.35	2.75	1.00	1.01	48	Undifferntiated tuff	Silurian-Ordovician
2.10	2.75	0.50	0.90	49	Basalt and spilite	Devonian
2.00	2.75	1.00	0.86	50	Andesitic lavas and tuff	Devonian

2.90	2.75	1.00	1.24	51	Rhyolite trachyte	Devonian
2.90	2.75	1.00	1.24	52	Tuff and ignimbrite	Devonian
2.08	2.75	0.50	0.89	53	Basalt and spilite	Carboniferous
2.40	2.75	0.50	1.03	54	Rhyolite trachyte	Carboniferous
2.52	2.75	0.50	1.08	55	Undifferentiated tuff	Carboniferous
2.40	2.75	0.50	1.03	56	Basalt	Permian
1.67	2.75	0.50	0.71	57	Basalt and spilite	Tertiary
1.62	2.75	1.00	0.69	58	Rhyolite trachyte	Tertiary
2.90	2.75	1.00	1.24	59	Undifferentiated tuff	Tertiary
3.41	2.75	0.85	1.46	60	Mona-Lleyn-Charnwood-Longmynd	Precambrian
3.36	2.75	0.85	1.44	61	Stoer Sleat Torridon	Torridonian
3.36	2.75	0.85	1.44	62	Quartzite	Cambrian
3.36	2.75	0.85	1.44	63	Serpulite grit fucoid beds	Cambrian
3.93	2.75	0.85	1.68	64	Lower	Cambrian
3.36	2.75	0.85	1.44	65	Middle	Cambrian
2.20	2.75	0.85	0.94	66	Upper	Cambrian
2.87	2.72	1.29	1.24	67	Durness limestone	Cambrian
3.14	2.72	1.29	1.36	68	Llanvirn Arenig	Ordovician
2.87	2.72	1.29	1.24	69	Llandeilo	Ordovician
2.94	2.72	1.29	1.27	70	Caradoc	Ordovician
2.87	2.72	1.29	1.24	71	Ashgill	Ordovician
3.01	2.72	1.95	1.30	72	Llandovery	Silurian
3.08	2.72	1.95	1.33	73	Wenlock	Silurian
3.33	2.72	1.95	1.44	74	Ludlow	Silurian
2.70	2.60	1.53	1.22	75	Lower Old Red sandstone	Devonian
2.70	2.60	1.53	1.22	76	Lower	Devonian
2.61	2.50	1.53	1.23	77	Middle Old Red Sandstone	Devonian
3.35	2.50	1.53	1.58	78	Upper Old Red Sandstone	Devonian
2.66	2.55	0.82	1.23	79	Courceyan	Carboniferous Dinantian
2.73	2.66	0.67	1.21	80	Tournasian Visean	Carboniferous Dinantian
2.40	2.53	0.45	1.12	81	Namurian	Carboniferous Silesian
2.49	2.50	1.40	1.17	82	Westphalian A-B	Carboniferous Silesian
2.57	2.52	1.20	1.20	83	Westphalian C-D	Carboniferous Silesian
3.15	2.51	0.75	1.48	84	Stephanian	Carboniferous Silesian
3.20	2.70	0.80	1.39	85	Basal breccias sandstones	Permian
3.59	2.70	0.80	1.56	86	Magnesian Limestone	Permian
2.38	2.50	1.85	1.12	87	Middle Upper marls mudstone	Permian
2.75	2.42	1.48	1.34	88	Pebble Beds	Permian
2.75	2.49	1.10	1.30	89	Sandstone Beds	Permian-Triassic
2.07	2.43	1.86	0.95	90	Mudstones Marls	Triassic
1.55	2.34	1.69	0.74	91	Lower Lias	Jurassic
1.99	2.50	1.25	0.88	92	Middle Lias	Jurassic
1.97	2.50	1.69	0.88	93	Upper Lias	Jurassic
2.18	2.50	0.66	0.97	94	Inferior Oolite	Jurassic
1.88	2.50	0.66	0.84	95	Great Oolite	Jurassic
2.01	2.50	0.66	0.89	96	Cornbrash	Jurassic
1.40	2.30	1.45	0.68	97	Oxford Clay Kellaways Beds	Jurassic
1.62	2.30	1.45	0.78	98	Corallian Ampthill CLay	Jurassic
1.45	2.30	1.45	0.70	99	Kimmeridge Clay	Jurassic
2.51	2.35	1.00	1.19	100	Portland	Jurassic
2.03	2.35	1.00	0.96	101	Purbeck	Jurassic
1.75	2.10	0.92	0.93	102	Hastings	Cretaceous Lower
2.00	2.10	1.35	1.06	103	Weald	Cretaceous Lower
1.67	2.20	1.35	0.84	104	Lower Greensand	Cretaceous
1.81	2.20	1.35	0.91	105	Upper Greensand Gault	Cretaceous
1.88	2.00	0.48	1.04	106	Chalk	Cretaceous
1.51	1.80	1.14	0.93	107	Woolwich Thanet Beds	Paleocene Palaeogene
1.89	1.80	1.14	1.17	108	London Clay	Eocene Palaeogene
2.22	1.80	1.14	1.37	109	Barton Bracklesham Bagshot	Eocene Palaeogene
1.38	1.80	1.14	0.85	110	Bovey St Agnes sands	Oligocene Palaeogene

1.70	1.80	1.14	1.05	111	Hampstead Bembridge Beds	Oligocene Palaeogene
1.78	1.80	1.14	1.10	112	Lenham Beds	Pliocene Neogene
1.70	1.80	1.14	1.05	113	Coralline Crag	Pliocene Neogene
1.70	1.80	1.14	1.05	114	St Erth Beds	Pliocene Neogene
1.91	1.80	1.14	1.18	115	Norwich Crag Red Crag	Recent Pleistocene

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