British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Ground Source Heat Pumps: Development of GeoReports for potential site characterisation

Carbon Trust Research, Development & Demonstration Project

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Carbon Trust
Research, Development & Demonstration Projects

Progress Report
GSHP site characterisation

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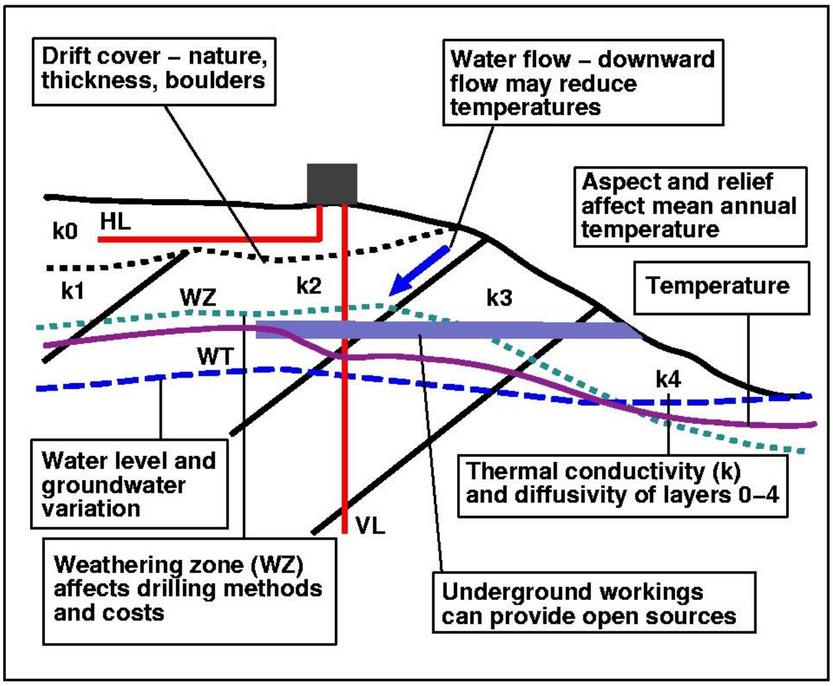
EXECUTIVE SUMMARY

Ground source heat pumps (GSHP) can provide low carbon solutions for space heating and cooling of residential and commercial buildings. GSHP systems have relatively low running costs but relatively high installation costs. Much of the cost is associated with installation of the external loop and is strongly affected by the geological and environmental conditions at the site. The site factors can affect both the heating and cooling performance of the heat pump and the drilling-trenching methods and costs.



Geological factors which can affect GSHP installation

Ground source heat pumps are known to a relatively small proportion of British engineering consultants, architects and heating professionals and even less well known to members of the public.

The aim of the project is to provide more accessible information about GSHP to a wider audience through establishing two new GeoReport products on the BGS web site. These reports present impartial geological, physical property and thermal data to any potential users, installers or designers of GSHP systems in the UK. The GeoReports include *basic* and *detailed* site-specific parameters:

basic GSHP report will 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.

detailed GSHP report will 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 geological prognosis for the top 100 m; an estimate of the degree 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 will be provided.

The project started on 1 June 2003 with a planned duration of 12 months, this was extended due to staff changes and the project concluded on 31st August 2004.

The progress of the project has been reported in bi-monthly reports and Milestone reports, progress being monitored against specific tasks within modules and tabulated below.

The GSHP GeoReports have been integrated into the BGS GeoReports service in such a manner that they can evolve to provide an improving service as more datasets become available. For example, considerable progress has been made on the digitisation of groundwater level maps and the degree of fluctuation. Currently the depth to water is estimated manually from these maps as well as other sources of data. Projects are in progress that are improving coverage using a variety of techniques with the goal of generating predictions of depth to water automatically. This function will then be added to the Basic GSHP GeoReport.

The objectives of the project have been met with the establishment of the GSHP GeoReports service.

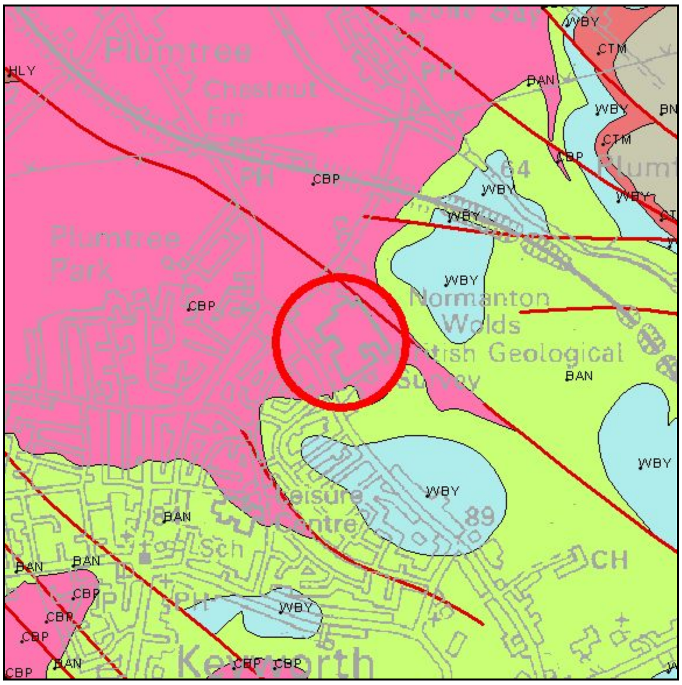
SUMMARY OF WORK CARRIED OUT AND PROGRESS

Introduction

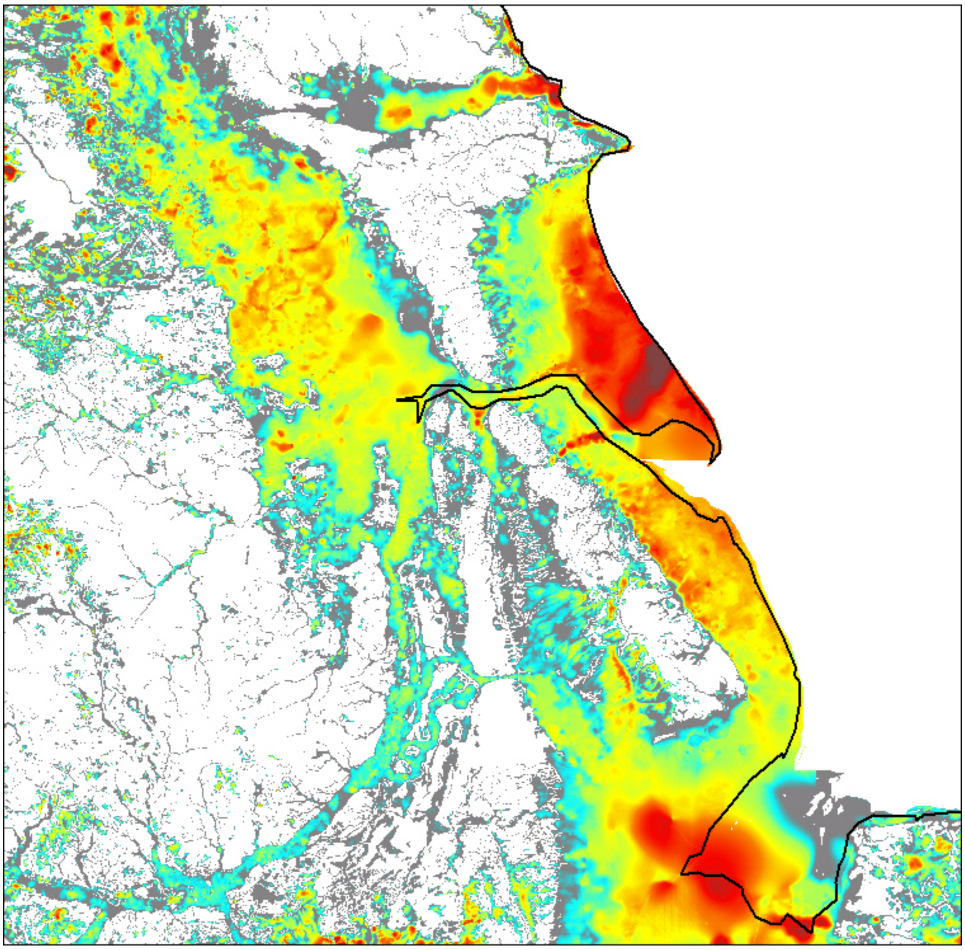
Geological factors have a major impact on the efficiency of a GSHP system. For example a system will work best in areas of silt or clay rather than sand. Additionally the strength of rocks is an important factor if you are considering drilling a vertical loop system. The UK has a wide variety of geology, and therefore the design of the system must take into account the geological characteristics of a site. Other important factors that need to be considered at a site include: subsurface temperature, thermal properties of the rocks, and groundwater flow. As a consequence these geological characteristics and environmental factors were investigated and data collated and generated to input to the GeoReports that detail the suitability of a site for a GSHP, as described below.

Geology

Rock formation (stratigraphy) and rock type (lithology) determine the conductivity, strength and other geological characteristics that indicate the suitability of a site for a ground source heat pump. The characteristics of the bedrock and superficial geological deposits mapped at 1:50,000 scale and depth to rockhead are the data sets provided for the GSHP GeoReports. 1:50,000 scale geology is available in digital form for England, Scotland and Wales as a series of GIS polygon themes for solid; superficial; artificial and mass movement types. The modelled depth to rock-head data for GB provides an estimate of the thickness of the superficial deposits cover.

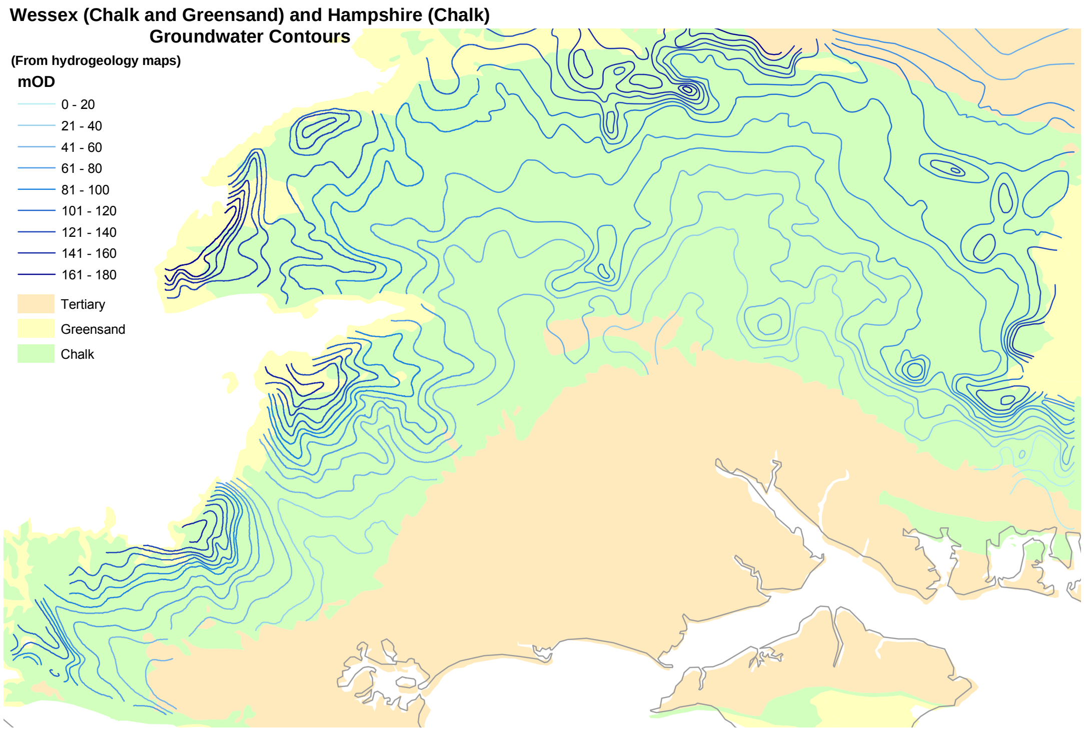


Bedrock Geology around a prospective GSHP site.


Depth to rockhead in the York-Humber region

Hydrogeological data

The key hydrogeological issues related to GSHP are depth to groundwater (and seasonal variations), groundwater flow and artesian risk.
A set of digital vector hydrogeological files of groundwater contours is now available, with metadata related to each file to provide an audit trail. About 70 groundwater level maps have been captured in digital form. The coverage is dependent on having active aquifers and cannot be extrapolated beyond the aquifer boundaries. Typical problems with use of the data are that the seasonal variation in water level may be large, the levels may not refer to the uppermost aquifer, and saturated thickness for confined aquifers is not identified.



Groundwater contours in the Chalk aquifer in the Wessex Basin

Artesian risk is important and zones where artesian wells have been drilled are available. However the risk is associated with the depth of drilling so is less easy to assess for individual sites.
Several models of UK groundwater levels have been generated. A groundwater map of the chalk region was generated from 9 datasets to test a procedure for mapping aquifer groundwater levels for use in GSHP GeoReports. An interpolated groundwater map using the UK river network and a detailed (50m) DTM was used to provide a regional baseline level. In addition wells with rest water level (RWL) in the BGS Wellmaster database were used to generate a map of depth to groundwater.
It is currently not possible to automate the provision of estimates of depth to groundwater and degree of fluctuation. This will continue to require manual expert interpretation by a hydrogeologist. However, the goal in the longer term is to increasingly automate these predictions.

Where groundwater flow is significant, the heat flow in the ground is a coupled mechanism of heat diffusion (conduction) in the aquifer material (including the water it contains) and heat convection (advection) by the groundwater. In general, groundwater flow improves heat exchange as it has a moderating effect on borehole temperatures in both heating and cooling applications.
The key parameters that determine if advective transport of heat is significant are hydraulic gradient, hydraulic conductivity and thermal conductivity. Typical geological scenarios have been modelled using a range of values for the key parameters. It was found that for GSHP systems located in aquifers, advection will impact the heat transport and further investigations may be warranted to assess the significance on the design of the system. Exceptions to this are likely to be where there is little groundwater movement and groundwater gradients are low, for example in coastal locations or in confined aquifers. GSHP sites located in low permeability, non-aquifers, are likely to be unaffected by advective transport of heat.

Geotechnical data

The key geotechnical issues related to GSHP are the nature and strength of the bedrock geology; the thickness and nature of the superficial deposits and the effective depth to hard rock drilling.
A set of strength reference tables for both bedrock and superficial deposits has been created based on geotechnical parameter ranges in accordance with BS5930:1999: *Code of practice for site investigations*. Both bedrock and superficial materials have been considered for applicability to deep bedrock and shallow trench GSHP installations. Typical strength ranges of 'engineering rocks' (bedrock formations) and 'engineering soils' (e.g. dominantly argillaceous bedrock formations and superficial deposits) have been created and linked to BGS's 1:50K Lex_Rock-defined bedrock and superficial deposits for the UK. The strength and density ranges have been codified for ease of linkage to the 1:50K BGS geological mapping units and Lex_Rock codes (See tables below).
Site specific drilling data recording the depth of change from 'soft ground' to 'hard rock' drilling (to obtain approximate depths to engineering rockhead) and depth of casing to ensure borehole stability, have been extracted from site investigation borehole records held in the BGS National Geoscience Data Centre (NGDC). Drill change and casing depths for approximately 2000 boreholes have been incorporated into the existing BGS Corporate Geotechnical Database, with a further 17000 records identified in the BGS Single Onshore Borehole Index (SOBI).

Example of the strength codes generated to aid in the detailed GeoReport assessment.

Artificial ground strength

Rock name	Strength minimum	Strength maximum	Density minimum	Density maximum	Compactness minimum	Compactness maximum
MADE GROUND	VARI	VARI				

Superficial deposits strength

Rock name	Strength minimum	Strength maximum	Density minimum	Density maximum	Compactness minimum	Compactness maximum
ALLUVIUM	VSOF	STIF	LOOS	DENS		
OADBY MEMBER (LIAS-RICH)	FIRM	VSTI				

Bedrock strength

Rock name	Strength minimum	Strength maximum	Density minimum	Density maximum	Compactness minimum	Compactness maximum
BLUE ANCHOR FORMATION	FIRM	WEAK				
CROPWELL BISHOP FORMATION	FIRM	MSTR				
EDWALTON FORMATION	FIRM	MSTR				
GUNTHORPE FORMATION	FIRM	WEAK				
RADCLIFFE FORMATION	FIRM	MSTR				
SNEINTON FORMATION	MWEA	STRO				
NOTTINGHAM CASTLE FORMATION	VWEA	MSTR				

The following two tables explain the strength, density and compactness codes used in the above table:

	Term	Uniaxial Compressive Strength (MPa)	SPT N-values (blows/300mm penetration)	Strength Code
Rocks	Extremely Strong	>200	-	ESTR
	Very Strong	100 - 200	-	VSTR
	Strong	50 - 100	-	STRO
	Moderately Strong	12.5 - 50	-	MSTR
	Moderately Weak	5.0 - 12.5	-	MWEA
	Weak	1.25 - 5.0	-	WEAK
	Very weak rock / hard soil	0.60 - 1.25	-	VWEA
Fine Soils	Very Stiff	0.30 - 0.60	>30	VSTI
	Stiff	0.15 - 0.30	15 to 30	STIF
	Firm	0.08 - 0.15	8 to 15	FIRM
	Soft	0.04 - 0.08	4 to 8	SOFT
	Very soft	<0.04	<4	VSOF

	TERM	SPT N-values (blows/300mm penetration)	Density Code	FIELD ASSESSMENT (very approximate)	Approximate Density Code
Coarse Soils	Very dense	>50	VDEN	Requires pick for excavation. 50 mm wooden peg hard to drive.	DENS
	Dense	30 to 50	DENS		
	Medium dense	10 to 30	MDEN		
	Loose	4 to 10	LOOS	Can be excavated with spade. 50 mm wooden peg easily driven.	LOOS
	Very loose	<4	VLOO		
Fine Soils	Compact	/	COMP	Easily moulded or crushed in fingers	COMP
	Uncompact	/	UNCO	Can be moulded or crushed by strong pressure in the fingers	UNCO

Note: Soil/Rock that does not fit into these tables will be classed as variable (code VARI)

Reference:

British Standards Institution. 1999. *Code of practice for site investigations. BS 5930*. (London: British Standards Institution.)

Thermal data

Temperature difference between the earth and the fluid in the ground heat exchanger drives the transfer of heat. The rate at which heat is transferred to the heat exchanger from the ground, or to the ground, is determined by the thermal properties of the earth. For a vertical loop ground heat exchanger the properties of the bedrock geology of the site will be important. For a horizontal loop system in a shallow (1 – 2 m) trench the properties of the superficial deposits will be important. Thermal conductivity and thermal diffusivity are the two parameters required for estimates of sub-surface temperatures.

Thermal conductivity

The thermal conductivity of a material is the quantity of heat transmitted per unit area, per unit temperature gradient in unit time under steady state conditions. It is the main mechanism for transfer of heat from the interior of the earth to the surface and for transfer of heat from solar warming downwards into the earth.

The composition of the bedrock, the porosity of the rock and the nature of the saturating fluids primarily control the thermal conductivity of the rocks. In general, increasing porosity will decrease the thermal conductivity, but this effect is reduced if the rock is water saturated. Thermal conductivity can vary significantly for many superficial deposits. It is especially affected by water saturation. For sedimentary rocks the primary control on thermal conductivity is porosity, the nature of the sedimentary rock and the extent of saturation. For volcanic rocks porosity is the main influence on thermal conductivity.

For a detailed technical description of thermal conductivity in relation to different geologies and its importance for GSHP please go to Appendix 3.

Thermal diffusivity

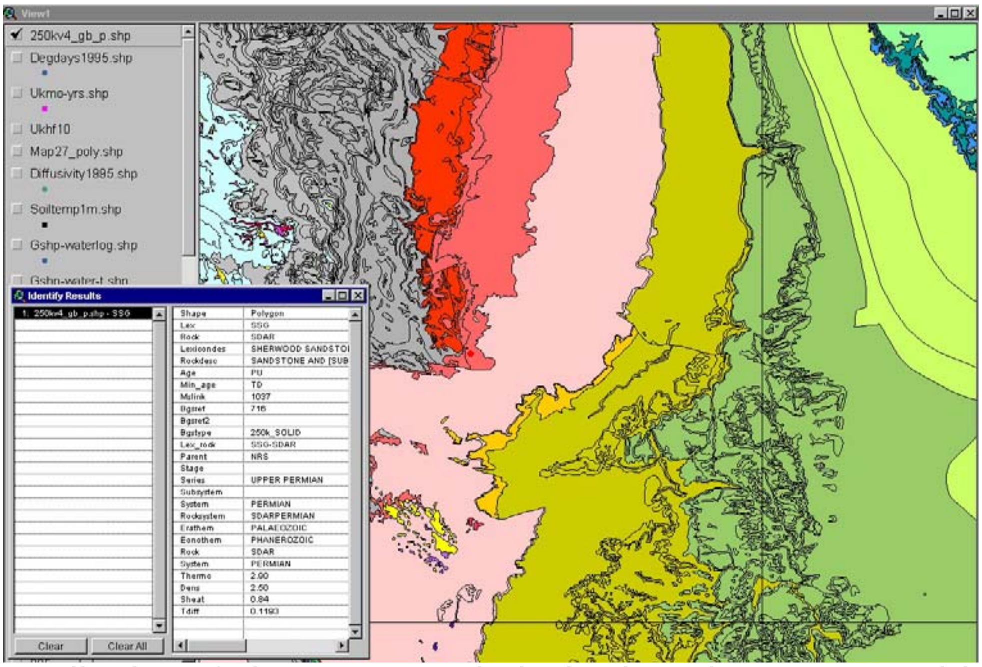
The specific heat capacity c of a material is the amount of heat required to change unit mass of the material by unit temperature. It represents the amount of energy absorbed or dissipated by a material before its temperature will change.

For a detailed technical description of thermal diffusivity in relation to different geologies and its importance for GSHP please go to Appendix 4.

Attribution

The 1:250K bedrock geology has been attributed with basic thermo-physical properties comprising, thermal conductivity, specific heat capacity and density. From these, thermal diffusivity has been attributed.

The 1:250K scale UK bedrock geology map contains 42890 separate vectors. The attribution has been on the basis of the *Lex-Rock* code, which describes the Lexicon name entry for the formation and the rock type lithology. There are 1270 unique *Lex-Rock* combinations in the UK 1:250K scale bedrock geology. However the thermal conductivity data are approximately grouped on lithology type so a classification using *Rock* and *System* was used. There are only 117 unique Rock codes used in the 1:250K scale bedrock geology. The *System* describes the geological age of the *Rock* and can often relate to the level of compaction, density and porosity. There are a total of 277 unique *RockSystem* codes in the 1:250K bedrock geology and these are the items attributed with thermal and physical properties. The attributed table was then linked with the geological vector table.



Attribution of the 1:250K scale bedrock geology vectors with thermal and physical properties.

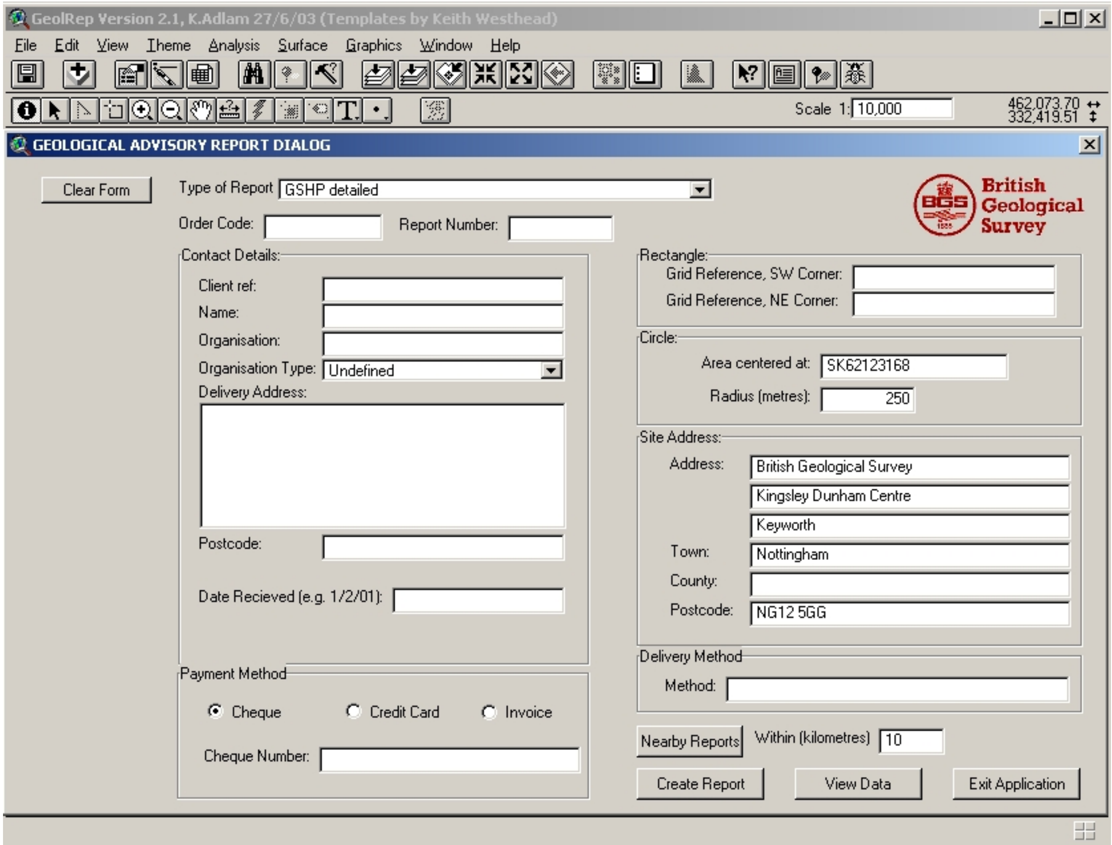
GeoReport writer

The new GSHP GeoReports were developed and web-enabled as part of Task 7. ESRI GIS software has been programmed to link to the various databases and map data to analyse the scientific information for a customer's site. This information is then sent to a word document as text, maps and tables that describe and illustrate the geo-environmental analyses. The system has to be tested to ensure it can be incorporated into the BGS GeoReports web delivery structure.

Initially, a development version of the BGS GeoReport writer was set up to test the generation of the GSHP reports. It was relatively easy to incorporate the geological, hydrogeological and engineering properties information, as these are provided for other BGS GeoReports. Some programming within the reporting system was required to calculate temperature values using modelled and recorded data. The thermal properties of the solid geology have been captured from the attributed 1:250K geology and are linked with the revised heat flux map to provide the geothermal gradient for any site.

Final versions of the two GeoReports were determined, the automated Basic GeoReport process was established and a procedure for the detailed report put in place. The two new GSHP reports created as part of this project (basic and detailed) have been incorporated into the BGS GeoReports system. GeoReports is a service provided by BGS to generate Geoscientific reports via the Internet, some automatically. The GSHP GeoReports have been available since end June 2004 and were be incorporated into the new BGS Web site went it went live in September 2004. A small number of BGS customers, enquiring since June, have been provided with GSHP GeoReports.

The GeoReports web site: www.bgs.ac.uk/georeports contains details of the reports available as well as describing how to request a report.
Requests for reports arrive over the Internet to the Enquiries staff at BGS who then generate the required report using a customised Geographical Information System (GIS):



The Geological Advisory Report Dialog window for preparation of a GeoReport

Some reports are fully automated and require little manual intervention, other than checking, whilst other more detailed reports require additional information provided by BGS geoscientists.
Reports are then despatched according to customer's requirements normally within seven days of the order being placed.

Appendices 1 and 2 present example GeoReports with their current formatting and content; Appendix 1 shows the basic report and Appendix 2 the detailed report.

CO2 Emission Reduction

Ground source heat pumps (GSHP) are the most energy efficient environmentally clean, and cost effective space conditioning systems available. Much primary energy consumption in the UK is for space heating and conditioning. GSHP can deliver energy savings of up to 70% compared to electric resistance heating. Lower energy consumption means associated lower CO_2 emissions.

GSHP are common in Europe and North America but there are only about 300 systems in UK homes. 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 30-50% of the installation cost. Geological parameters impact directly on many aspects of the uncertainty: source 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. Therefore the performance of a GSHP in a 100m borehole is likely to vary significantly with location.

By establishing the GeoReports' site specific functionality potential users, installers or designers of GSHP systems are provided with impartial information that will help to remove uncertainty in the application, develop the industry, ultimately benefit a wide range of manufacturing and service sectors and provide significant carbon emission saving for each installation. The expected carbon emission saving is of the order of 2 tons CO_2 per year for each residential system installed and significantly more (~35 tons) for each commercial installation. The potential market for new and refit GSHP systems in residential properties outside the gas supply region is about 100,000 per year.

CONCLUSIONS

The project has been a success in many ways; firstly by providing the opportunity to carry out interesting and focused scientific analysis, secondly through increasing the knowledge of GSHP within BGS and thirdly for the delivery of a user-oriented digital reporting system, that will enable wider understanding of GSHP throughout the British community. The GSHP GeoReport system pulls-together the scientific data for a specified site, determines the geo-environmental information that is relevant to the site and presents it in a user-friendly format.

Appendix 1: Example of a basic GeoReport: Keyworth, Nottingham

Report prepared for:

Ground Source Heat Pump (Basic)

This report is designed for users investigating sites for the installation of ground source heat pumps (GSHP) at residential sites.

It contains a geological map with descriptions of rock types, estimates of mean annual ground temperatures and thermal conductivities. It is for closed loop systems where yields and water quality, unless corrosive are not relevant.

The report is prepared by BGS geoscientists, based on analysis of records and maps held in the National Geoscience Data Centre. It also contains a listing of the key geoscience data sets held in the NGDC for the area around the site. For some sites, the latest available records are quite old, and while every effort is made to place the analysis in a modern geological context, it is possible in some cases that the geology at a site may differ from that described.

Ground source heat pumps (GSHP) can provide low carbon solutions for space heating and cooling of residential and commercial buildings. GSHP systems have relatively low running costs but relatively high installation costs. Much of the cost is associated with installation of the external loop and is strongly affected by the geological and environmental conditions at the site. The site factors can affect both the heating and cooling performance of the heat pump and the drilling or trenching methods and costs.

Client's Reference:

Section 1: Location details

Area centred at: SK62123168
Radius of site area: 250.0 metres

This report is based on the above location details. However, where the client has submitted a site plan, it is used for the assessment in Section 2.

Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Section 2: Geological map

A geology map around your site is provided in this section, taken from the BGS Digital Geological Map of Great Britain at the 1:50,000 scale (DiGMapGB-50). The map shows the four layers of geology that may be present in an area – **artificial (man-made) deposits**, **landslip deposits, superficial deposits and bedrock**, superimposed on the same map.

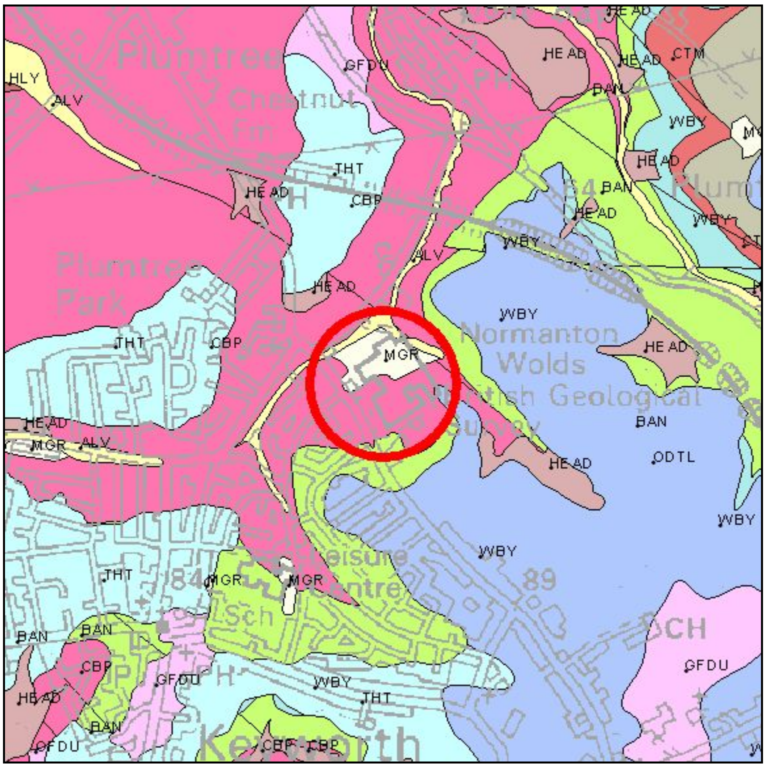
Landslip deposits include natural deposits formed by sliding and mass-movement of soils and rocks on hill slopes (an alternative term for Landslip deposits is 'Mass Movement Deposits').

Artificial deposits include deposits moved and disturbed by man.

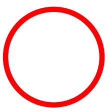
Superficial deposits include fairly recent geological deposits, such as river sands and gravels, or glacial deposits, which lie on the bedrock in many areas (an alternative term for Superficial deposits is 'Drift Deposits').

Bedrock forms the ground underlying the whole of an area, upon which the other geological layers listed above may lie.

Geological formation and rock type affect the cost of installing GSHP and the subsequent performance of the heat pump.



Scale: 1:25000 (1cm = 250m)



SITE LOCATION

Please note that in some areas the Superficial Deposits may completely conceal the Bedrock. In such cases, the concealed Bedrock units will still be listed in the map key.

Key to Landslip deposits:

No deposits are mapped in the search area

Key to Artificial deposits:

Map colour	Computer Code	Rock name	Rock type
	MGR	MADE GROUND	MADE GROUND (ex MGR),FILL,RUBBISH,ASH,SLAG,FORCED GRND,etc.

Key to Superficial deposits:

Map colour	Computer Code	Rock name	Rock type
	ALV	ALLUVIUM	SAND AND SILT
	HEAD	HEAD (UNDIFFERENTIATED)	CLAY AND SILT
	GFDU	GLACIOFLUVIAL DEPOSITS (UNDIFFERENTIATED)	SAND AND GRAVEL
	ODTL	OADBY MEMBER (LIAS-RICH)	DIAMICTON
	THT	THRUSSINGTON TILL	DIAMICTON

Key to Bedrock geology:

Fault

Coal, ironstone or other mineral vein

Note: Faults and Coals, ironstone & mineral veins are shown for illustration and to aid interpretation of the map. Not all such features are shown and their absence on the map face does not necessarily mean that none are present

Map colour	Computer Code	Rock name	Rock type
	BNT	BARNSTONE MEMBER	MUDSTONE AND LIMESTONE, INTERBEDDED
	CTM	COTHAM MEMBER	MUDSTONE
	WBY	WESTBURY FORMATION	MUDSTONE AND SILTSTONE
	BAN	BLUE ANCHOR FORMATION	MUDSTONE
	CBP	CROPWELL BISHOP FORMATION	MUDSTONE AND SILTSTONE
	HLY	HOLLYGATE SANDSTONE MEMBER	SANDSTONE

More information on DiGMapGB-50 and how the various rock layers are classified can be found on the BGS website (www.bgs.ac.uk), under the DiGMap and BGS Rock Classification Scheme areas. Further descriptions of the rocks listed in the map keys can also be obtained by searching against the Computer Code on the *BGS Lexicon of named Rock Units*, which is also on the BGS Website at by following the 'GeoData' link. The computer codes are labelled on the maps to try and help in their interpretation (with a dot at the bottom left hand corner of each label). However, please treat this with caution in areas of complex geology, where some of the labels may overlap several geological formations. If in doubt, please contact BGS enquiries.

The geological formations are listed broadly in order of age in the map keys (youngest first) but only to the formation level (a formation is a package of related rocks). Within formations, please be aware that individual members may not be ordered by age.

Section 3: Temperature

3.1 Surface Temperature

Mean annual air temperature at the site is important because it provides the basis for an estimate of the temperature variation at shallow depth. This will affect the selection of heat pump for a site.

Mean annual air temperature at sea level in mainland UK varies from about 8-12 °C. Highest values are in the south and south-west, with lower values to the north and at sites of greater elevation. Mean site temperature has been estimated using a model based on the 30 year station averages published on the UK Meteorological Office (UKMO) web site www.met-office.gov.uk.

Due to it's temperate climate the January-July mean air temperature swing for much of the UK is less than 15° C, despite occasional short periods of very hot or cold weather. This annual swing in temperatures also occurs in the soil layer, but with an amplitude that reduces with depth. In addition, depending on the thermal diffusivity of the soil, there will also be a time delay between the air temperature and soil temperature at any given depth

3.2 Sub-surface temperatures

The temperature variation at shallow depth in the ground is complicated by the effects of diurnal and seasonal changes in solar radiation. However at depths of about 15m the annual temperature variation is less than ±0.1°C and the temperature is approximately that of the mean ground surface temperature.

Soil temperatures

Transmission of the annual temperature cycle at the surface down into the ground depends on the thermal diffusivity of the soil and the partial amplitude of the ground surface temperature variation. This heat transfer means that in the top 15m of ground the annual temperature cycle is reduced in amplitude and lags that of the surface cycle. For instance at a depth of 3.5 m the minimum soil temperature is likely to be in the first two weeks of April and the maximum temperature about the end of October. The range of temperatures at 3.5m depth is also likely to be about one quarter that at the surface.

Soil temperatures at 2m have been estimated using a soil diffusivity of 0.05 m^2/day. Annual temperature swing is based on a model of the difference in mean January and July air temperatures derived from published UKMO long-term records.

Rock temperatures

At depths below about 15m the temperature profile in the subsurface is affected primarily by thermal conductivity, heat flux and heat transport by moving groundwater.

Regions with known anomalous heat flow and thermal conductivity are especially likely to have an anomalous geothermal gradient. For many regions the effects of most of these factors are considered small so that a geothermal gradient 0.02 °C/m is a general guide.

Observed equilibrium temperature data for the UK indicate that some areas have stable ground temperatures of 15 °C at depths of 100m. Conversely other regions show stable temperatures at 100m depth of only 7 °C. The mean observed equilibrium temperature for the UK at a depth of 100m is close to 12 ±1.6 °C with a range of about 7-15 °C.

An estimate of the local geothermal gradient and the temperature at 100m and 200m depth has been made using the estimated thermal conductivity of the bedrock geology from the 1:250,000 scale geological map and the estimated heat flow at the site.

Estimated Temperature parameters of the site

Mean annual air temperature	9.6 °C
Mean annual temperature swing	8.2 °C
Estimated mean soil temperature	10.6 °C
Minimum annual soil temperature at 2m	7.0 °C
Maximum annual soil temperature at 2m	14.2 °C
Estimated temperature at 100m depth	14.0 °C
Estimated temperature at 200m depth	17.4 °C

Soil temperatures at 2m estimated using a soil diffusivity of 0.05 m^2/day.
Annual temperature swing based on mean January and July air temperatures

Section 4: Thermal conductivity-diffusivity

The temperature difference between the earth and the fluid in the ground heat exchanger drives the transfer of heat. The rate at which heat can be transferred to the heat exchanger from the ground, or to the ground, is determined mainly by the thermal properties of the earth, thermal conductivity and thermal diffusivity.

For a vertical loop ground heat exchanger the properties of the bedrock geology of the site will be important. For a horizontal loop system in a shallow (1-2 m) trench then the properties of the superficial deposits will be important.

Thermal conductivity

Thermal conductivity varies by a factor of more than two (1.5 - 3.5 W/m/K) for the range of common rocks encountered at the surface and can vary significantly for many superficial deposits. It is especially affected by porosity and water saturation.

For superficial deposits and soils the thermal conductivity will depend on the nature of the deposit, the bulk porosity of the soil and the degree of saturation. Superficial deposit and soils are complex aggregates of mineral and organic particles so exhibit a wide range of thermal characteristics.

An approximate guide to the thermal properties of the deposit can be made using a simple classification based on soil particle size and composition. In general relatively higher values of thermal conductivity are associated with granular soils containing silt or clay portions than with clean granular sandy soils. Also clean sands have a low thermal conductivity when dry but a higher value when saturated. There is a very significant difference in the thermal properties of silt and clay so this needs to be identified. The following table gives a good general guide to the expected thermal properties of superficial deposits and soils.

Typical values of thermal conductivity and diffusivity for superficial deposits

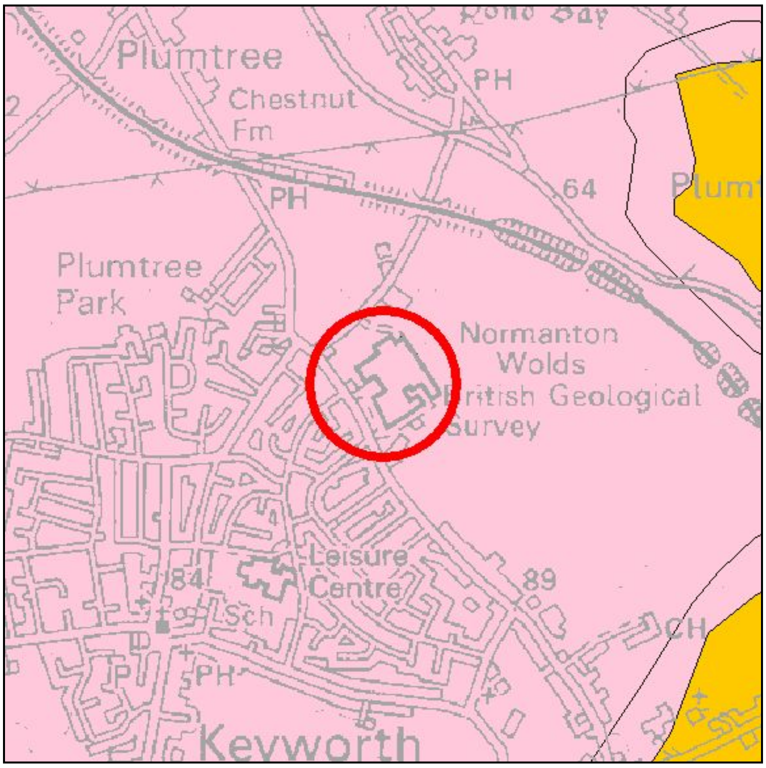
Class	Thermal Conductivity W/m/K	Thermal diffusivity m^2/day
Sand (gravel)	0.77	0.039
Silt	1.67	0.050
Clay	1.11	0.046
Loam	0.91	0.042
Saturated sand	2.50	0.079
Saturated silt or clay	1.67	0.056

Thermal diffusivity

Thermal diffusivity is a measure of ground thermal conduction in relation to thermal capacity and relates the rock thermal conductivity, the specific heat and the density.

Typical rock thermal diffusivities range from about 0.065 m^2 /day for clays to about 0.17 m^2 /day for high conductivity rocks such quartzites. Many rocks have thermal diffusivites in the range 0.077–0.103 m^2 /day

Thermal conductivity-diffusivity (based on 1:250,000 Bedrock Geology)



Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Key to Thermal conductivity-diffusivity:

Map colour	Geology	Thermal conductivity W/m/K	Thermal diffusivity m^2/day
(pink)	PENARTH GROUP	2.20	0.0890
(yellow)	BLUE LIAS FORMATION	2.54	0.1019
(pink)	MERCIA MUDSTONE GROUP	1.87	0.0697

Section 5: Groundwater

The thermal conductivity of rocks is greatly affected by the degree of saturation, which is controlled by the porosity of the rock and the location of the water table and its annual fluctuations.

In lowland areas of the UK with little topographic variation, groundwater is likely to be found at shallow depths of only a few metres. Water table fluctuations will be small as they will be constrained by the ground surface and the base level of the local perennial streams and rivers.

In upland areas underlain by metamorphic and granitic rocks, higher precipitation and water storage in weathered surface layers, soils and bogs will tend to maintain relatively shallow water levels as drainage is poor due to the low fracture porosity of these rocks. Exceptions are found where porous sandstone or limestone, with solution-enlarged fractures, drain rapidly to the adjacent base stream level.

Perched water tables occur where a clay layer in an otherwise permeable sequence, retains a small body of groundwater above the level of the regional water table. These usually occur at shallow depths in alluvial and glacial sediments and are difficult to identify or to assess their extent.

An aquifer is confined when it is overlain by a lower permeability layer that restricts the upward movement of groundwater. When the low permeability layer is penetrated by drilling, the groundwater rises in the borehole to a level controlled by the hydrostatic pressure. This may be above ground level, in which case the borehole flows under artesian pressure. Confined conditions should be anticipated, where possible, in order to plan for the drilling and completion problems that a flowing borehole can generate. However, if a closed-loop system is installed successfully into a confined aquifer then the aquifer will be saturated as will part of the overlying confining layer.

Most GSHP design techniques are based on the assumption that the heat will be dissipated by conduction. If heat advection due to groundwater flow is significant at a site it is likely that this will have a beneficial effect. The significance of advection is controlled by the hydraulic gradient, the hydraulic conductivity and the thermal conductivity of the saturated rock. In most aquifers advection will be significant except where the groundwater gradient is low; e.g. in coastal plains or confined conditions.

The water level at this site cannot currently be predicted automatically but can be estimated in a detailed GSHP GeoReport.

Section 6: Boreholes and water wells located in search area

Borehole location map

Scale: 1:10000 (1cm = 100m)

Borehole records

(A blank Length field indicates the borehole is confidential or no depth has been recorded digitally.)
Total number of records: 16

The 'Office' column shows the office at which the records are held and from where copies can be obtained (see contact details later in the report). KW=Keyworth, MH & MW=Murchison House, WL=Wallingford, EX=Exeter

Regno	Grid_reference	Name	Length	Office	SIR
SK63SW27	SK 62025 31740	BGS KEYWORTH BH1	10.20	KW	
SK63SW28	SK 62125 31795	BGS KEYWORTH BH2	5.00	KW	
SK63SW29	SK 62170 31815	BGS KEYWORTH BH3	5.00	KW	
SK63SW30	SK 62065 31675	BGS KEYWORTH BH4	5.00	KW	
SK63SW31	SK 62135 31710	BGS KEYWORTH BH5	5.00	KW	
SK63SW32	SK 62225 31750	BGS KEYWORTH BH6	5.00	KW	
SK63SW33	SK 62275 31710	BGS KEYWORTH BH7	5.00	KW	
SK63SW34	SK 62145 31560	BGS KEYWORTH BH8	4.50	KW	

Regno	Grid_reference	Name	Length	Office	SIR
SK63SW35	SK 62090 31900	BGS KEYWORTH BH9	5.00	KW	
SK63SW36	SK 62105 31440	BGS KEYWORTH A	50.00	KW	
SK63SW37	SK 62305 31705	BGS KEYWORTH B	63.80	KW	
SK63SW38	SK 61945 31777	BGS KEYWORTH C	62.00	WLKW	
SK63SW39	SK 61980 31770	BGS KEYWORTH		KW	
SK63SW124	SK 62170 31780	KEYWORTH OPEN DAY TEST BORE	50.35	KW	

Water Well location map

Scale: 1:10000 (1cm = 100m)

Water Well Records

Total number of records: 3

All these records are registered in the main Borehole Records collections (see Borehole Records Table and map above), and duplicate, or partial duplicate copies may be held at other sites (at Keyworth KW, Exeter EX or Murchison House MH). These represent records that are held in the National Well Record Archive of water wells and boreholes held at Wallingford (WF) or Murchison House (MW). The Well Registration number is used to index records in the National Well Record Archive please quote this if applying for copies of water wells (see contact details later in the report).

Additional index information may be held for the Water Well Records as indicated below, indicating the information that can be found on the well record itself. If fields are blank, then the well record has not been examined and its contents are unknown. A Yes or a No indicates that the well record has been examined and the information as indicated is, or is not, present. This information should help you when requesting copies of Records.

KEY:
Aquifer = The principal aquifer recorded in the borehole
G = Geological Information present on the log
C = Borehole construction information present on the log
W = Water quality information present on the log
Ch = Water chemistry information present on the log

Well Reg No.	BH Reg No.	Name	Easting	Grid Northing	Depth	Date	Aquifer	G	C	W	Ch
SK63/65A	SK63SW129/BJ	I.G.S. KEYWORTH	462105	331440	50.00	1977	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No
SK63/65B	SK63SW130/BJ	I.G.S. KEYWORTH	462305	331705	63.80	1978	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No
SK63/65C	SK63SW38/BJ	I.G.S. KEYWORTH	461945	331777	61.90	1978	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No

Description of borehole and water well datatsets

Records of boreholes, shafts and wells from all forms of drilling and site investigation work. Some 900,000 records dating back over 200 years and ranging from one to several thousand metres deep. Currently some 50,000 new records are being added to the collection each year.

A small percentage of the borehole records are held commercial-in-confidence for various reasons and cannot be released without the written permission of the originator. If any of the records you need are listed as confidential apply in the normal way. BGS Enquiry Service staff will release the data where this is possible or provide you with the information needed to contact the originator.

Where records are held in more than one office, the contents may differ. Enquiries principally requiring water related information should contact the Wallingford or Edinburgh office.

How to obtain borehole and water well data and how much it will cost?

Borehole Records – *contact BGS Enquiry Service (see end of section)*

Copies of borehole records can be supplied (order form enclosed) at the flat rate of £13 (+VAT) per log with a minimum charge £26 (+VAT). Normal first class postage within the UK is included. Next day recorded delivery or express parcel dispatch is available on request and charged at cost. Copies of documents can be forwarded by facsimile transmission at an additional charge of £0.50 (+VAT) per A4 sheet. Records with additional detailed geological information derived from BGS examination of borehole material may be charged at the current ‘value-added’ rate. If you have a need for data with particular geological characteristics, the please contact the enquiries office to discuss your requirements (additional charges may apply).

Alternatively you can make an appointment to visit the relevant enquiry office and examine the records yourself. The Commercial User Ticket (see below) covers inspection of the borehole logs and includes access to a set of relevant documents for one unit area (typically a 5 km x 5 km area). A further charge of £19 (+ VAT) is due for each additional set examined. Data can be freely extracted from the records but any copies requested will be charged as above.

Water wells – *contact BGS Enquiry Service*

Copies of records can be supplied (order form enclosed) at the flat rate of £13 (+VAT) per log with a minimum charge £26 (+VAT). Normal first class postage within the UK is included. Next day recorded delivery or express parcel dispatch is available on request and charged at cost. Copies of documents can be forwarded by facsimile transmission at an additional charge of £0.50 (+VAT) per A4 sheet. If you have a need for data with particular hydrogeological characteristics, then please contact the relevant enquiries office (England and Wales =Wallingford, Scotland=Edinburgh) to discuss your requirements (additional charges may apply).

Alternatively you can make an appointment to visit the relevant enquiry office and examine the records yourself.

Records for England and Wales are held at Wallingford where the visitor charge is £9.50/hour (+VAT, with a minimum charge of £19 (+VAT).

Records for Scotland are held with the borehole records at our Edinburgh office the above Borehole Record charges cover them and apply.

BGS ENQUIRY SERVICE Contact Details:

Keyworth (KW) Office

For Borehole and other records (excluding water well records & hydrogeological data) in England & Wales (excluding Northern England, and Devon & Cornwall):

Records & Data Enquiries
Kingsley Dunham Centre
Keyworth
Nottingham
NG12 5GG
Tel: 0115 9363109
Fax: 01159 363276

Exeter (EX) Office

For Borehole and other records (excluding water well records & hydrogeological data) in Devon & Cornwall:

Records & Data Enquiries
BGS Exeter Business Centre
Forde House
Park Five Business Centre
Harrier Way
Sowton
Exeter
Devon EX2 7HU
Tel: 01392 445271
Fax: 01392 445371

Wallingford (WL) Office

For water well records and hydrogeological data (water levels, water chemistry and aquifer properties) in England & Wales:

Records & Data Enquiries
British Geological Survey,
Maclean Building,
Wallingford,
Oxford OX10 8BB.
Tel: 01491 838800
Fax: 01491 692345
Email: hydroenq@bgs.ac.uk

Murchison House (MH or MW) Office:

For water well records and hydrogeological data for Scotland, and all other records in Scotland & Northern England:

Records & Data Enquiries
Murchison House
West Mains Road
Edinburgh
EH9 3LA
Tel: 0131 650 0282
Fax: 0131 667 2785
Email: boreholesnorth@bgs.ac.uk

Section 7: More detailed geological reports available from BGS

This report forms part of a range of reports offered by the BGS Enquiry Service, including reports describing site geology, hydrogeology and geological hazards. For details on these please contact:

BGS Central Enquiries Desk
British Geological Survey
Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG
Tel: 0115 936 3143
Fax: 0115 936 3276
Email: enquiries@bgs.ac.uk

Or visit the Enquiry Service pages on the BGS website at www.bgs.ac.uk

Section 8: Terms and Conditions

General Terms & Conditions

This report is supplied in accordance with the GeoReports Terms & Conditions available on the BGS website at www.bgs.ac.uk/georeports and also available from the BGS Central Enquiries Desk at the above address.

Important notes about this report

- The data, information and related records supplied in this report by BGS can only be indicative and should not be taken as a substitute for specialist interpretations, professional advice and/or detailed site investigations. You must seek professional advice before making technical interpretations on the basis of the materials provided.
- Geological observations and interpretations are made according to the prevailing understanding of the subject at the time. The quality of such observations and interpretations may be affected by the availability of new data, by subsequent advances in knowledge, improved methods of interpretation, and better access to sampling locations.
- Raw data may have been transcribed from analogue to digital format, or may have been acquired by means of automated measuring techniques. Although such processes are subjected to quality control to ensure reliability where possible, some raw data may have been processed without human intervention and may in consequence contain undetected errors.
- Detail which is clearly defined and accurately depicted on large-scale maps may be lost when small-scale maps are derived from them.
- Although samples and records are maintained with all reasonable care, there may be some deterioration in the long term.
- The most appropriate techniques for copying original records are used, but there may be some loss of detail and dimensional distortion when such records are copied.
- Data may be compiled from the disparate sources of information at BGS's disposal, including material donated to BGS by third parties, and may not

originally have been subject to any verification or other quality control process.

- Data, information and related records which have been donated to BGS have been produced for a specific purpose, and that may affect the type and completeness of the data recorded and any interpretation. The nature and purpose of data collection, and the age of the resultant material may render it unsuitable for certain applications/uses. You must verify the suitability of the material for your intended usage.
- If a report or other output is produced for you on the basis of data you have provided to BGS, or your own data input into a BGS system, please do not rely on it as a source of information about other areas or geological features, as the report may omit important details.
- The topography shown on any map extracts is based on the latest OS mapping and is not necessarily the same as that used in the original compilation of the BGS geological map, and to which the geological linework available at that time was fitted.
- This report was prepared by the British Geological Survey (NERC) and with support from the Carbon Trust. The publication of this report should not be taken as implying endorsement by the Carbon Trust of any views expressed in the Report or of the services or of the service providers referred to in the report. The Carbon Trust accepts no liability for the accuracy or completeness of, or omissions from, the contents of the Report or for any loss arising from reliance on it.

Report issued by:

BGS Enquiry Service

Appendix 2: Example of a detailed GeoReport: Keyworth, Nottingham

Report prepared for:

Ground Source Heat Pump (Detailed)

This report is designed for users investigating sites for the installation of ground source heat pumps (GSHP).

It contains an evaluation of the expected geological sequence with descriptions of rock types and aquifers beneath the site, potential water levels, temperatures and thermal properties. It is for closed loop systems where water yields and water quality are not relevant. The surface geology is most relevant to a horizontal loop system, and the borehole prognosis, depth to water level and hard rock strength are most relevant to a vertical loop installation.

The report is prepared by BGS geoscientists, based on analysis of records and maps held in the National Geoscience Data Centre. It also contains a listing of the key geoscience data sets held in the NGDC for the area around the site. For some sites, the latest available records are quite old, and while every effort is made to place the analysis in a modern geological context, it is possible in some cases that the geology at a site may differ from that described.

Ground source heat pumps (GSHP) can provide low carbon solutions for space heating and cooling of residential and commercial buildings. GSHP systems have relatively low running costs but relatively high installation costs. Much of the cost is associated with installation of the external loop and is strongly affected by the geological and environmental conditions at the site. The site factors can affect both the heating and cooling performance of the heat pump and the drilling or trenching methods and costs

Client's Reference:

Section 1: Location details

Area centred at: SK62123168
Radius of site area: 250.0 metres

This report is based on the above location details. However, where the client has submitted a site plan, it is used for the assessment in Section 2.

Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Section 2: Geological considerations for the site

The table lists the principal geological considerations that may affect a site, and is based on interpretation of data available to BGS at the time of compilation; additional information may be available in BGS files. The information is designed to act as a checklist and should not be used in place of a detailed site investigation.

Problematic Ground	Should be considered at this site	Comments
Poor Trafficability	✓	Poor trafficability likely to occur when ground saturated by heavy rainfall.
Difficult ground to excavate		
Thickness of Superficial deposits ≥ 5 m		
Running sand	✓	Thin layers and lenses of running sand may be present within the superficial deposits.
≥ 5 m of weathered engineering rock head	✓	Rockhead, variably weathered to clay or clay matrix with harder lithorelicts, likely to be encountered down to c. 10m depth.
Variable rock head		
Bedrock geology likely to be heavily altered		
Variable lithology in bedrock geology	✓	Majority of site underlain by bedrock of mudstone, but thin layers of sandstone are likely to be present at depth.
Presence of highly fractured zones in the rock mass		
Very to extremely strong rock strength		
Aggressive Sulphate conditions	✓	Possibility of high sulphate contents with associated problems for buried concrete.

Section 3: Geological maps

Extracts of geology maps around your site are provided in this section, taken from the BGS Digital Geological Map of Great Britain at the 1:50,000 scale (DiGMapGB-50). The first map shows the three uppermost layers of geology that may be present in an area – **artificial (man-made) deposits**, **landslip deposits and superficial deposits**, superimposed on the same map. On the second map the **bedrock** is shown separately. The third map shows the **total thickness of the superficial deposits** present above the bedrock.

Landslip deposits: These include natural deposits formed by sliding and mass-movement of soils and rocks on hill slopes (an alternative term for Landslip deposits is 'Mass Movement Deposits')

Artificial deposits: These include deposits moved and disturbed by man.

Superficial deposits: These include fairly recent geological deposits, such as river sands and gravels, or glacial deposits, which lie on the bedrock in many areas (an alternative term for Superficial deposits is 'Drift Deposits')

Bedrock forms the ground underlying the whole of an area, upon which the other geological layers listed above may lie.

Geological formation and rock type affect the cost of installing GSHP and the subsequent performance of the pump due to the thermal conductivity of different geology.

More information on DiGMapGB-50 and how the various rock layers are classified can be found on the BGS website (www.bgs.ac.uk), under the DiGMap and BGS Rock Classification Scheme areas. Further descriptions of the rocks listed in the map keys can also be obtained by searching against the Computer Code on the *BGS Lexicon of named Rock Units*, which is also on the BGS Website at by following the 'GeoData' link. The computer codes are labelled on the maps to try and help in their interpretation (with a dot at the bottom left hand corner of each label). However, please treat this with caution in areas of complex geology, where some of the labels may overlap several geological formations. If in doubt, please contact BGS enquiries.

The geological formations are listed broadly in order of age in the map keys (youngest first) but only to the formation level (a formation is a package of related rocks). Within formations, please be aware that individual members may not be ordered by age.

Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Key to Landslip deposits:

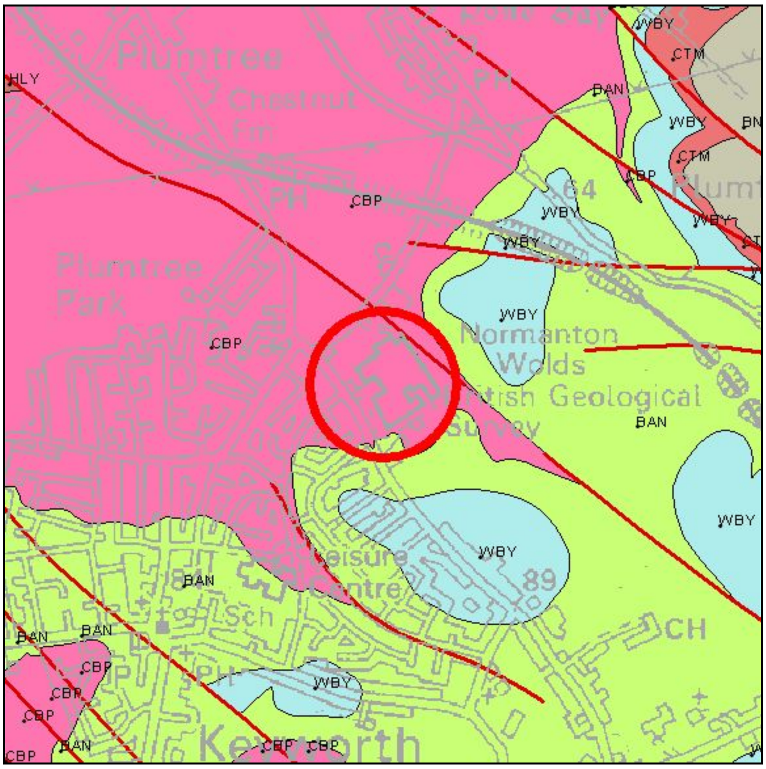
No deposits are mapped in the search area

Key to Artificial deposits:

Map colour	Computer Code	Rock name	Rock type
	MGR	MADE GROUND	MADE GROUND (ex MGR),FILL,RUBBISH,ASH,SLAG,FORCED GRND,etc.

Key to Superficial deposits:

Map colour	Computer Code	Rock name	Rock type
	ALV	ALLUVIUM	SAND AND SILT
	HEAD	HEAD (UNDIFFERENTIATED)	CLAY AND SILT
	GFDU	GLACIOFLUVIAL DEPOSITS (UNDIFFERENTIATED)	SAND AND GRAVEL
	ODTL	OADBY MEMBER (LIAS-RICH)	DIAMICTON
	THT	THRUSSINGTON TILL	DIAMICTON



Scale: 1:25000 (1cm = 250m)

SITE LOCATION

Fault

Coal, ironstone or other mineral vein

Note: Faults and Coals, ironstone & mineral veins are shown for illustration and to aid interpretation of the map. Not all such features are shown and their absence on the map face does not necessarily mean that none are present

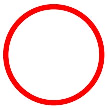
Key to Bedrock geology:

Map colour	Computer Code	Rock name	Rock type
	BNT	BARNSTONE MEMBER	MUDSTONE AND LIMESTONE, INTERBEDDED
	CTM	COTHAM MEMBER	MUDSTONE
	WBY	WESTBURY FORMATION	MUDSTONE AND SILTSTONE
	BAN	BLUE ANCHOR FORMATION	MUDSTONE
	CBP	CROPWELL BISHOP FORMATION	MUDSTONE AND SILTSTONE
	HLY	HOLLYGATE SANDSTONE MEMBER	SANDSTONE

Thickness of Superficial Deposits

The following map is a mathematical model of the thickness of Superficial Deposits produced by analysing information from approximately 600,000 borehole logs held in the BGS archives and also uses the digital data on the extent of Superficial Deposits (shown previously).

Scale: 1:25000 (1cm = 250m)



SITE LOCATION

Key to Superficial thickness

Map colour	Expected Minimum Thickness (m)
	100
	70
	50
	40
	30
	20
	10
	5
	Thickness unknown, but > 1m

Section 4: Borehole prognosis report

Geographical Setting:

The site lies between 60 and 65 m above OD and slopes to the north with a shallow valley on the eastern edge. The slope of the ground has been modified by artificial ground (see below). Small streams bound the northern and eastern edges of the site. These flow to the north-west. The original ground surface may have included enclosed shallow depressions resulting from gypsum dissolution (see **Bedrock Geology**, below).

Geology:

The site has a simple layer-cake geological structure comprising (youngest deposits first) Artificial deposits, Superficial deposits of till and sand, with bedrock deposits of dominantly mudstone. Deeply buried sandstone also underlies the site

Artificial Ground:

Made ground is present across much of the northern part of site and may be up to 3m in thickness. The made ground is likely to comprise mudstone and siltstone excavated from elsewhere on site during its development.

Superficial Deposits:

Alluvium is present as a narrow ribbon along the northern and eastern margins of the site. This comprises of a very soft to stiff grey clay with lenses of fine sand and a thin basal gravel. These deposits are up to 2m thick.
The Oadby Till, Anglian in age, is present in the southeastern corner of the site. It comprises firm to very stiff grey clay (weathering yellow-brown in uppermost 2m), with pebbles and cobbles of flint, limestone and chalk. Boreholes in the area show this till is locally underlain by a thin sand layer, which is water bearing (see hydrogeology section below).

Rockhead Depth:

Over much of the site geological rockhead is at surface, Where buried beneath artificial ground or alluvium it is 2 to 3m below ground level, where buried beneath Oadby Till, rockhead is 1 to 5m below ground level

Bedrock Geology:

The site is underlain by bedrock of the Cropwell Bishop Formation and Blue Anchor Formation. They form part of the Mercia Mudstone Group and are Triassic in age.

The Blue Anchor formation is the youngest bedrock unit present and underlies the southeastern corner of the site. It comprises firm to weak grey-green to yellow-brown, dolomitic siltstone and is approximately 8m thick.

The Cropwell Bishop Formation underlies the remainder of the site and comprises of a firm to medium strong, red-brown mudstone and siltstone (may show sporadic green-grey spots and lenses). The formation contains common, cross-cutting gypsum veins and lenses up to 5cm thick. Elsewhere in this district the formation contains thick beds of workable gypsum, however, nearby borehole data (SK63SW/124) indicates that these beds are absent either as a result of never being deposited in the area, or being dissolved away by circulating groundwater. The mudstones may also contain salt pseudomorphs. The formation is approximately 45m thick in this area.

Beneath the Cropwell Bishop Formation a further c. 130m of Mudstone deposits occur. These are known as the Edwalton, Gunthorpe, Radcliffe and Sneinton Formations and sporadic thin sandstone beds such as the Hollygate Sandstone and Cotgrave Sandstone may also be present at depth.

The Nottingham Castle Sandstone Formation is approximately 40-50m thick in this area and the top of this formation is approximately 180m below ground level.

Additional Geological Considerations:

The area is underlain at depth (approximately 240m below ground level) by the Middle Coal Measures. The coal deposits have not been worked in this area.

The bedrock strata dip to the south-east at between 1 and 2°.

A north-westerly trending fault occurs in the shallow valley along the eastern margin of the site. This has a down-throw of approximately 15m, to the north-east.

It is important to understand the nature of geological faults, and the uncertainties which attend their precise position at the surface. Faults are planes of movement about which adjacent blocks of rock strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation. Geological faults in this area are of ancient origin, are today mainly inactive, and present no threat to property.

Section 5: Geotechnical characteristics

The main geotechnical issues related to GSHP are the nature and strength of the bedrock geology; the thickness and nature of the superficial deposits and the effective depth to hard rock drilling.

An indication of the strength/density/compactness of the bedrock, superficial deposits and artificial deposits anticipated at this site is given in the tables below:

	Strength/Density based on BS 5930	Typical SPT blow N Values	Typical UCS Values (MPa)
Made Ground	Variable	N/A	N/A
Alluvium	Very Soft - Stiff / Loose - Dense	4 to 50	N/A
Oadby Till	Firm - Very Stiff	8 to 30+	0.08 to 0.60
Blue Anchor Formation	Firm - Weak	8 to 30+	0.08 to 5
Cropwell Bishop Formation	Firm - Moderately Strong	8 to 30+	0.08 to 50
Edwalton Formation	Firm - Moderately Strong	8 to 30+	0.08 to 50
Gunthorpe Formation	Firm - Weak	8 to 30+	0.08 to 5
Radcliffe Formation	Firm - Moderately Strong	8 to 30+	0.08 to 50
Sneinton Formation	Moderately Weak - Strong	N/A	5.00 to 100
Nottingham Castle Formation	Very Weak - Moderately Strong	N/A	0.60 to 50

Geotechnical information and datasets

In addition to borehole, shaft and well records held in the BGS National Geoscience Data Centre, some 50,400 Site Investigation reports describing geotechnical data from over 420,000 boreholes provide a geotechnical information source for UK bedrock and superficial deposits. Additional Site Investigation reports (both digital and analogue) are being acquired annually. Drilling information and in situ and laboratory-derived geotechnical parameter data extracted from these reports are held in the Corporate Geotechnical Database. Currently, some 182,400 geotechnical data 'sample suites' from 42,500 boreholes are held in the database, with approximately 25,000 parameter records from 6,000 boreholes being added on average each year.

Where geotechnical information is required for sites not currently entered into the Geotechnical Database, a search of the original site investigation reports and related boreholes can be undertaken. A small percentage of the borehole and site investigation records are held as commercial-in-confidence for various reasons and cannot be released without the written permission of the originator. If any of the records you need are listed as confidential apply in the normal way. BGS Enquiry Service staff will release the data where this is possible or provide you with the information needed to contact the originator.

For enquiries principally requiring geotechnical related information please contact the Keyworth office.

Section 6: Temperature

6.1 Surface Temperature

Mean annual air temperature at the site is important because it provides the basis for an estimate of the temperature variation at shallow depth. This will affect the selection of heat pump for a site.

Mean annual air temperature at sea level in mainland UK varies from about 8-12 °C. Highest values are in the south and south-west, with lower values to the north and at sites of greater elevation. Mean site temperature has been estimated using a model based on the 30 year station averages published on the UK Meteorological Office (UKMO) web site www.met-office.gov.uk.

Due to the temperate climate, the January-July mean air temperature swing for much of the UK is less than 15° C, despite occasional short periods of very hot or cold weather. This annual swing in temperatures also occurs in the soil layer, but with an amplitude that reduces with depth. In addition, depending on the thermal diffusivity of the soil, there will be a time delay between the air temperature and the resultant soil temperature at any given depth.

6.2 Sub-surface temperatures

The temperature variation at shallow depth in the ground is complicated by the effects of diurnal and seasonal changes in solar radiation. However at depths of about 15m the annual temperature variation is less than ±0.1°C and the temperature is approximately that of the mean ground surface temperature.

Soil temperatures

Transmission of the annual temperature cycle at the surface down into the ground depends on the thermal diffusivity of the soil and the partial amplitude of the ground surface temperature variation. This heat transfer means that in the top 15m of ground the annual temperature cycle is reduced in amplitude and lags that of the surface cycle. For instance at a depth of 3.5 m the minimum soil temperature is likely to be in the first two weeks of April and the maximum temperature about the end of October. The range of temperatures at 3.5m depth is also likely to be about one quarter that at the surface.

Soil temperatures at 2m have been estimated using a soil diffusivity of 0.05 m^2/day. Annual temperature swing is based on a model of the difference in mean January and July air temperatures derived from published UKMO long-term records.

Rock temperatures

At depths below about 15m the temperature profile in the subsurface is affected primarily by thermal conductivity, heat flux and heat transport by moving groundwater.

Regions with known anomalous heat flow and thermal conductivity are especially likely to have an anomalous geothermal gradient. For many regions the effects of most of these factors are considered small so that a geothermal gradient 0.02 °C/m is a general guide.

Observed equilibrium temperature data for the UK indicate that some areas have stable ground temperatures of 15 °C at depths of 100m. Conversely other regions show stable temperatures at 100m depth of only 7 °C. The mean observed equilibrium temperature for the UK at a depth of 100m is close to 12 ±1.6 °C with a range of about 7-15 °C.

An estimate of the local geothermal gradient and the temperature at 100m and 200m depth has been made using the estimated thermal conductivity of the bedrock geology from the 1:250,000 scale geological map and the estimated heat flow at the site.

Estimated Temperature parameters of the site

Mean annual air temperature	9.6 °C
Partial amplitude of the annual temperature swing	8.2 °C
Estimated mean soil temperature	10.6 °C
Minimum annual soil temperature at 2m	7.0 °C
Maximum annual soil temperature at 2m	14.2 °C
Estimated temperature at 100m depth	14.0 °C
Estimated temperature at 200m depth	17.4 °C

Soil temperatures at 2m estimated using a soil diffusivity of 0.05 m^2/day.
Annual temperature swing based on mean January and July air temperatures

The actual mean annual air temperature for Keyworth averaged over the last 15 years is 10.2^{o}C. This is taken from a former Meteorological Office recording station. This increase over the UKMO mean could arise from the enclosed nature of the site causing a microclimate effect or as a result of temperature increases over recent years that are not reflected in the 30-year UKMO mean.

Section 7: Thermal conductivity-diffusivity

Temperature difference between the earth and the fluid in the ground heat exchanger drives the transfer of heat. The rate at which heat can be transferred to the heat exchanger from the ground, or to the ground, is determined mainly by the thermal properties of the earth, thermal conductivity and thermal diffusivity.

For a vertical loop ground heat exchanger the properties of the bedrock geology of the site will be important. For a horizontal loop system in a shallow (1-2 m) trench then the properties of the superficial deposits will be important.

Thermal conductivity

Thermal conductivity varies by a factor of more than two (1.5 - 3.5 W/m/K) for the range of common rocks encountered at the surface and can vary significantly for many superficial deposits. It is especially affected by porosity and water saturation.

For superficial deposits and soils the thermal conductivity will depend on the nature of the deposit, the bulk porosity of the soil and the degree of saturation. Superficial deposit and soils are complex aggregates of mineral and organic particles so exhibit a wide range of thermal characteristics.

An approximate guide to the thermal properties of the deposit can be made using a simple classification based on soil particle size and composition. In general relatively higher values of thermal conductivity are associated with granular soils containing silt or clay portions than with clean granular sandy soils. Also clean sands have a low thermal conductivity when dry but a higher value when saturated. There is a very significant difference in the thermal properties of silt and clay so this needs to be identified. The following table gives a good general guide to the expected thermal properties of superficial deposits and soils.

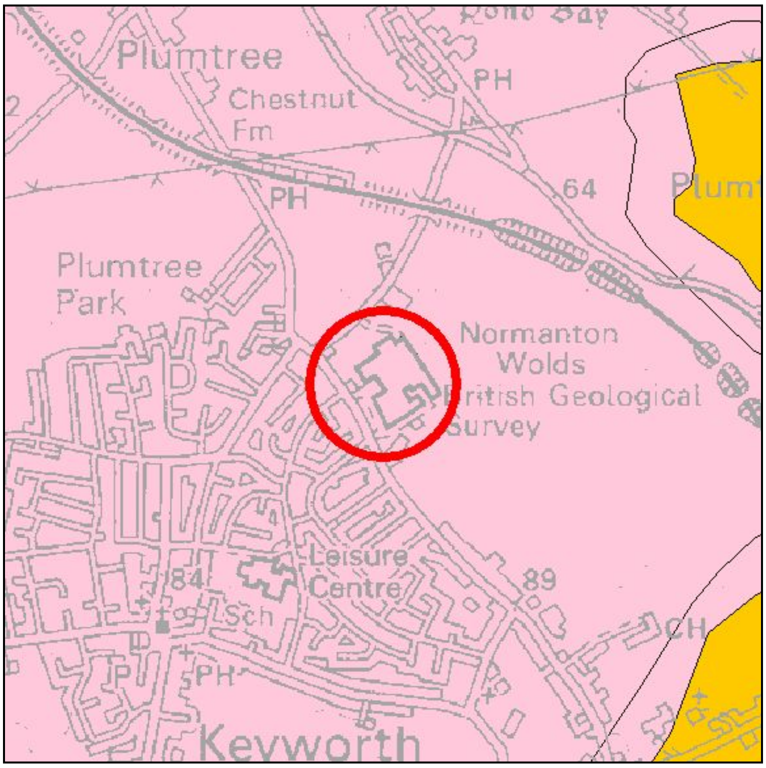
Typical values of thermal conductivity and diffusivity for superficial deposits

Class	Thermal Conductivity W/m/K	Thermal diffusivity m^2/day
Sand (gravel)	0.77	0.039
Silt	1.67	0.050
Clay	1.11	0.046
Loam	0.91	0.042
Saturated sand	2.50	0.079
Saturated silt or clay	1.67	0.056

Thermal diffusivity

Thermal diffusivity is a measure of ground thermal conduction in relation to thermal capacity and relates the rock thermal conductivity, the specific heat and the density.

Typical rock thermal diffusivities range from about 0.065 m^2 /day for clays to about 0.17 m^2 /day for high conductivity rocks such quartzites. Many rocks have thermal diffusivities in the range 0.077–0.103 m^2 /day.



Scale: 1:25000 (1cm = 250m)

Thermal conductivity-diffusivity (based on 1:250,000 Bedrock Geology)

SITE LOCATION

Key to Thermal conductivity-diffusivity:

Map colour	Geology	Thermal conductivity W/m/K	Thermal diffusivity m^2/day
	PENARTH GROUP	2.20	0.0890
	BLUE LIAS FORMATION	2.54	0.1019
	MERCIA MUDSTONE GROUP	1.87	0.0697

Any horizontal ground loop placed within the top 2 – 3 metres will be located in made ground or till. Made ground can be highly variable and may be porous and thus susceptible to drying out during long periods with no rain. This will adversely affect the thermal conductivity. Till (diamicton) is a clay deposited beneath a glacier that contains pebbles and boulders (erratics) of other rock types carried by the glacier. Diamicton is a very hard (over-compacted) clay. Clay has an average thermal conductivity of 1.11 W/m/K. Within the Oadby Till the thermal properties are likely to be reasonably constant within the clay, but will vary in the vicinity of the erratics. The thin sand layer at the base of the till may present a more favourable thermal target since saturated sand has an average thermal conductivity of 2.5 W/m/K.

Any vertical ground loop will be located within the Mercia Mudstone Group. The table below lists average thermal conductivities for the three principle lithologies within the Mercia Mudstone Group for the UK as a whole.

Average thermal conductivities of the Mercia Mudstone Group based on UK boreholes

Number of samples	Mean	Min	Max	Standard dev	Lithology
418	1.82	0.66	4.47	0.51	Mudstone
23	2.03	1.02	3.66	0.49	Siltstone
36	3.35	1.82	5.03	0.87	Sandstone

If the lithologies occur in the ratio of 75% Mudstone, 20% Siltstone and 5% Sandstone, then the bulk average thermal conductivity would be 1.92 W/m/K. This assumes that the bulk conductivity of a rock can be expressed as the geometric mean of the conductivities of its constituents:

$$K_b = K_1^{\phi 1} K_2^{\phi 2} \ldots\ldots.. K_n^{\phi n}$$

Where K_b is the bulk conductivity; K_1……..K_n are the conductivities of the n constituents; and $\phi 1$……..ϕn are the fractions occupied by the n constituents.

Section 8: Groundwater

Background information

The thermal conductivity of rocks is greatly affected by the degree of saturation, which is controlled by the porosity of the rock and the location of the water table and its annual fluctuations.

In lowland areas of the UK with little topographic variation, groundwater is likely to be found at shallow depths of only a few metres. Water table fluctuations will be small as they will be constrained by the ground surface and the base level of the local perennial streams and rivers.

In upland areas underlain by metamorphic and granitic rocks, higher precipitation and water storage in weathered surface layers, soils and bogs will tend to maintain relatively shallow water levels as drainage is poor due to the low fracture porosity of these rocks. Exceptions are found where porous sandstone or limestone, with solution-enlarged fractures, drain rapidly to the adjacent base stream level.

Perched water tables occur where a clay layer in an otherwise permeable sequence, retains a small body of groundwater above the level of the regional water table. These usually occur at shallow depths in alluvial and glacial sediments and are difficult to identify or to assess their extent.

An aquifer is confined when it is overlain by a lower permeability layer that restricts the upward movement of groundwater. When the low permeability layer is penetrated by drilling, the groundwater rises in the borehole to a level controlled by the hydrostatic pressure. This may be above ground level, in which case the borehole flows under artesian pressure. Confined conditions should be anticipated, where possible, in order to plan for the drilling and completion problems that a flowing borehole can generate. However, if a closed-loop system is installed successfully into a confined aquifer then the aquifer will be saturated as will part of the overlying confining layer.

Most GSHP design techniques are based on the assumption that the heat will be dissipated by conduction. If heat advection due to groundwater flow is significant at a site it is likely that this will have a beneficial effect. The significance of advection is controlled by the hydraulic gradient, the hydraulic conductivity and the thermal conductivity of the saturated rock. In most aquifers advection will be significant except where the groundwater gradient is low; e.g. in coastal plains or confined conditions.

Groundwater issues at proposed site

The thin alluvium adjoining the stream could contain some groundwater. The thin sand locally underlying the Oadby Till contains water, this could affect excavations. This water is likely to be of the calcium-bicarbonate type with a total dissolved solids content of less than 500 mg/l.

Both the Blue Anchor and the Cropwell Bishop Formations are generally of low permeability. Small supplies of groundwater may be encountered in the coarser-grained horizons. It is anticipated that the rest water level is likely to be between 5 and 20 m below the ground surface, depending on position within the site. It is anticipated that the rest water level beneath the central grid reference is likely to be about 48 m aOD. However, this could be out by as much as 5 m, as there are significant differences in water levels across the whole BGS site from 57 m aOD in the east to 33 m aOD in the west, which equates to a steep hydraulic gradient of about 1 in 17 westwards. In addition seasonal water level fluctuations may be several metres.

The water quality from the Cropwell Bishop Formation is very hard with a total dissolved solids content often in excess of 1000 mg/l, of which the predominant ions are calcium and sulphate, derived from the gypsum in the rocks. Borehole logging of existing boreholes on the Keyworth site, indicate that the Windmill Skerries within the Cropwell Bishop Formation contained groundwater under pressure with a total dissolved solids content of between 2000 and 2300 mg/l. Beneath this the water becomes more mineralised with water from the Hollygate Sandstone at the top of the Edwalton Formation probably having a total dissolved solids content of around 5000 mg/l. Water with this level of mineralisation can be corrosive.

The Sherwood Sandstone Group occurs at a depth of about 180 m, although it is anticipated that the rest water level will rise to within 30 to 40 m of the ground surface. At this depth, it is likely that the water quality would be poor with high sulphate ion concentrations, possibly in the range 1000 to 2500 mg/l.

This interpretation is based on the information available in the surrounding area. Due to natural geological variation the conditions encountered on drilling may differ and your attention is drawn to the exclusion of warranty, which includes the standard NERC terms of contract. While we may assess the groundwater potential at this site, the prerogative of granting a licence rests with the Environment Agency, Midlands Region. If a borehole is drilled, you should be aware that there is a statutory requirement for the driller (Water Resources Act, 1991/ Geol Survev Act) to supply full information to the BGS for inclusion into the National Well Record Archive/ National Geosciences Data Centre. A form for listing the required information is enclosed.

The thermal and hydraulic properties of the site suggest that heat transport by groundwater movement is unlikely to be significant at this site.

Section 9: Boreholes and water wells located in search area

Borehole location map

Scale: 1:10000 (1cm = 100m)

Borehole records

(A blank Length field indicates the borehole is confidential or no depth has been recorded digitally.)
Total number of records: 16

The 'Office' column shows the office at which the records are held and from where copies can be obtained (see contact details later in the report). KW=Keyworth, MH & MW=Murchison House, WL=Wallingford, EX=Exeter

Regno	Grid_reference	Name	Length	Office	SIR
SK63SW27	SK 62025 31740	BGS KEYWORTH BH1	10.20	KW	
SK63SW28	SK 62125 31795	BGS KEYWORTH BH2	5.00	KW	
SK63SW29	SK 62170 31815	BGS KEYWORTH BH3	5.00	KW	
SK63SW30	SK 62065 31675	BGS KEYWORTH BH4	5.00	KW	
SK63SW31	SK 62135 31710	BGS KEYWORTH BH5	5.00	KW	
SK63SW32	SK 62225 31750	BGS KEYWORTH BH6	5.00	KW	
SK63SW33	SK 62275 31710	BGS KEYWORTH BH7	5.00	KW	
SK63SW34	SK 62145 31560	BGS KEYWORTH BH8	4.50	KW	
SK63SW35	SK 62090 31900	BGS KEYWORTH BH9	5.00	KW	
SK63SW36	SK 62105 31440	BGS KEYWORTH A	50.00	KW	

Regno	Grid_reference	Name	Length	Office	SIR
SK63SW37	SK 62305 31705	BGS KEYWORTH B	63.80	KW	
SK63SW38	SK 61945 31777	BGS KEYWORTH C	62.00	WLKW	
SK63SW39	SK 61980 31770	BGS KEYWORTH		KW	
SK63SW124	SK 62170 31780	KEYWORTH OPEN DAY TEST BORE	50.35	KW	

Water Well location map

Scale: 1:10000 (1cm = 100m)

Water Well Records

Total number of records: 3

All these records are registered in the main Borehole Records collections (see Borehole Records Table and map above), and duplicate, or partial duplicate copies may be held at other sites (at Keyworth KW, Exeter EX or Murchison House MH). These represent records that are held in the National Well Record Archive of water wells and boreholes held at Wallingford (WF) or Murchison House (MW). The Well Registration number is used to index records in the National Well Record Archive please quote this if applying for copies of water wells (see contact details later in the report).

Additional index information may be held for the Water Well Records as indicated below, indicating the information that can be found on the well record itself. If fields are blank, then the well record has not been examined and its contents are unknown. A Yes or a No indicates that the well record has been examined and the information as indicated is, or is not, present. This information should help you when requesting copies of Records.

KEY:
Aquifer = The principal aquifer recorded in the borehole
G = Geological Information present on the log
C = Borehole construction information present on the log
W = Water quality information present on the log
Ch = Water chemistry information present on the log

Well Reg No.	BH Reg No.	Name	Easting	Grid Northing	Depth	Date	Aquifer	G	C	W	Ch
SK63/65A	SK63SW129/BJ	I.G.S. KEYWORTH	462105	331440	50.00	1977	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No
SK63/65B	SK63SW130/BJ	I.G.S. KEYWORTH	462305	331705	63.80	1978	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No
SK63/65C	SK63SW38/BJ	I.G.S. KEYWORTH	461945	331777	61.90	1978	MERCIA MUDSTONE GROUP	Yes	Yes	Yes	No

Description of borehole and water well datatsets

Records of boreholes, shafts and wells from all forms of drilling and site investigation work. Some 900,000 records dating back over 200 years and ranging from one to several thousand metres deep. Currently some 50,000 new records are being added to the collection each year.

A small percentage of the borehole records are held commercial-in-confidence for various reasons and cannot be released without the written permission of the originator. If any of the records you need are listed as confidential apply in the normal way. BGS Enquiry Service staff will release the data where this is possible or provide you with the information needed to contact the originator.

Where records are held in more than one office, the contents may differ. Enquiries principally requiring water related information should contact the Wallingford or Edinburgh office.

How to obtain borehole and water well data and how much it will cost?

Borehole Records – *contact BGS Enquiry Service (see end of section)*

Copies of borehole records can be supplied (order form enclosed) at the flat rate of £13 (+VAT) per log with a minimum charge £26 (+VAT). Normal first class postage within the UK is included. Next day recorded delivery or express parcel dispatch is available on request and charged at cost. Copies of documents can be forwarded by facsimile transmission at an additional charge of £0.50 (+VAT) per A4 sheet. Records with additional detailed geological information derived from BGS examination of borehole material may be charged at the current ‘value-added’ rate. If you have a need for data with particular geological characteristics, the please contact the enquiries office to discuss your requirements (additional charges may apply).

Alternatively you can make an appointment to visit the relevant enquiry office and examine the records yourself. The Commercial User Ticket (see below) covers inspection of the borehole logs and includes access to a set of relevant documents for one unit area (typically a 5 km x 5 km area). A further charge of £19 (+ VAT) is due for each additional set examined. Data can be freely extracted from the records but any copies requested will be charged as above.

Water wells – *contact BGS Enquiry Service*

Copies of records can be supplied (order form enclosed) at the flat rate of £13 (+VAT) per log with a minimum charge £26 (+VAT). Normal first class postage within the UK is included. Next day recorded delivery or express parcel dispatch is available on request and charged at cost. Copies of documents can be forwarded by facsimile transmission at an additional charge of £0.50 (+VAT) per A4 sheet. If you have a need for data with particular hydrogeological characteristics, then please contact the relevant enquiries office (England and Wales =Wallingford, Scotland=Edinburgh) to discuss your requirements (additional charges may apply).

Alternatively you can make an appointment to visit the relevant enquiry office and examine the records yourself.

Records for England and Wales are held at Wallingford where the visitor charge is £9.50/hour (+VAT, with a minimum charge of £19 (+VAT).

Records for Scotland are held with the borehole records at our Edinburgh office the above Borehole Record charges cover them and apply.

BGS ENQUIRY SERVICE Contact Details:

Keyworth (KW) Office

For Borehole and other records (excluding water well records & hydrogeological data) in England & Wales (excluding Northern England, and Devon & Cornwall):

Records & Data Enquiries
Kingsley Dunham Centre
Keyworth
Nottingham
NG12 5GG
Tel: 0115 9363109
Fax: 01159 363276

Exeter (EX) Office

For Borehole and other records (excluding water well records & hydrogeological data) in Devon & Cornwall:

Records & Data Enquiries
BGS Exeter Business Centre
Forde House
Park Five Business Centre
Harrier Way
Sowton
Exeter
Devon EX2 7HU
Tel: 01392 445271
Fax: 01392 445371

Wallingford (WL) Office

For water well records and hydrogeological data (water levels, water chemistry and aquifer properties) in England & Wales:

Records & Data Enquiries
British Geological Survey,
Maclean Building,
Wallingford,
Oxford OX10 8BB.
Tel: 01491 838800
Fax: 01491 692345
Email: hydroenq@bgs.ac.uk

Murchison House (MH or MW) Office:

For water well records and hydrogeological data for Scotland, and all other records in Scotland & Northern England:

Records & Data Enquiries
Murchison House
West Mains Road
Edinburgh
EH9 3LA
Tel: 0131 650 0282
Fax: 0131 667 2785
Email: boreholesnorth@bgs.ac.uk

Section 10: More detailed geological reports available from BGS

This report forms part of a range of reports offered by the BGS Enquiry Service, including reports describing site geology, hydrogeology and geological hazards. For details on these please contact:

BGS Central Enquiries Desk
British Geological Survey
Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG
Tel: 0115 936 3143
Fax: 0115 936 3276
Email: enquiries@bgs.ac.uk

Or visit the Enquiry Service pages on the BGS website at www.bgs.ac.uk

Section 11: Terms and Conditions

General Terms & Conditions

This report is supplied in accordance with the GeoReports Terms & Conditions available on the BGS website at www.bgs.ac.uk/georeports and also available from the BGS Central Enquiries Desk at the above address.

Important notes about this report

- The data, information and related records supplied in this report by BGS can only be indicative and should not be taken as a substitute for specialist interpretations, professional advice and/or detailed site investigations. You must seek professional advice before making technical interpretations on the basis of the materials provided.
- Geological observations and interpretations are made according to the prevailing understanding of the subject at the time. The quality of such observations and interpretations may be affected by the availability of new data, by subsequent advances in knowledge, improved methods of interpretation, and better access to sampling locations.
- Raw data may have been transcribed from analogue to digital format, or may have been acquired by means of automated measuring techniques. Although such processes are subjected to quality control to ensure reliability where possible, some raw data may have been processed without human intervention and may in consequence contain undetected errors.
- Detail which is clearly defined and accurately depicted on large-scale maps may be lost when small-scale maps are derived from them.
- Although samples and records are maintained with all reasonable care, there may be some deterioration in the long term.
- The most appropriate techniques for copying original records are used, but there may be some loss of detail and dimensional distortion when such records are copied.
- Data may be compiled from the disparate sources of information at BGS's disposal, including material donated to BGS by third parties, and may not originally have been subject to any verification or other quality control process.

- Data, information and related records which have been donated to BGS have been produced for a specific purpose, and that may affect the type and completeness of the data recorded and any interpretation. The nature and purpose of data collection, and the age of the resultant material may render it unsuitable for certain applications/uses. You must verify the suitability of the material for your intended usage.
- If a report or other output is produced for you on the basis of data you have provided to BGS, or your own data input into a BGS system, please do not rely on it as a source of information about other areas or geological features, as the report may omit important details.
- The topography shown on any map extracts is based on the latest OS mapping and is not necessarily the same as that used in the original compilation of the BGS geological map, and to which the geological linework available at that time was fitted.
- This report was prepared by the British Geological Survey (NERC) and with support from the Carbon Trust. The publication of this report should not be taken as implying endorsement by the Carbon Trust of any views expressed in the Report or of the services or of the service providers referred to in the report. The Carbon Trust accepts no liability for the accuracy or completeness of, or omissions from, the contents of the Report or for any loss arising from reliance on it.

Report issued by:

BGS Enquiry Service

Appendix 3: Thermal conductivity - Technical Description

The thermal conductivity of a material is the quantity of heat transmitted per unit area, per unit temperature gradient in unit time under steady state conditions. It is the main mechanism for transfer of heat from the interior of the earth to the surface and for transfer of heat from solar warming downwards into the earth. Under steady state conduction the heat flow density (q) is defined by the product of the thermal conductivity (λ) and the temperature gradient $\delta T/\delta z$. In general thermal conductivity varies inversely with temperature but for applications involving GSHP this variation is not significant.

The composition of the bedrock, the porosity of the rock and the nature of the saturating fluids primarily control the thermal conductivity of the rocks. In general, increasing porosity will decrease the thermal conductivity, but this effect is reduced if the rock is water saturated. Various mixing models have been used in estimating the thermal conductivity of the bedrock

fraction, including the arithmetic and the harmonic means, which respectively define the upper and lower limits of the thermal conductivity. The geometric mean has been demonstrated to provide good estimates for the thermal conductivity of the bedrock fraction i.e..

$$\lambda_b = \lambda_1^{\phi 1}\lambda_2^{\phi 2}\ldots\ldots..\lambda_n^{\phi n}$$

Where λ_b is the bulk conductivity; $\lambda_1\ldots\ldots..\lambda_n$ are the conductivities of the n constituents; and $\phi 1\ldots\ldots..\phi n$ are the fractions occupied by the n constituents.

Thermal conductivity varies by a factor of more than two for the range of common rocks encountered at the surface and can vary significantly for many superficial deposits. It is especially affected by water saturation. For many rocks thermal conductivity is isotropic whereas for some foliated rocks the property shows a significant anisotropy (variation in direction of measurement).

Thermal conductivity can be measured on samples in the borehole or in the field using a variety of steady state and transient methods. The British Geological Survey has a database of thermal conductivity measurements made on borehole and rock samples using the divide-bar and the needle probe methods. However in-situ thermal conductivity may differ significantly from laboratory values even after the likely effects of saturation, temperature or pressure have been considered.

For sedimentary rocks the primary control on thermal conductivity is porosity, the nature of the sedimentary rock and the extent of saturation. For chemical sediments and low porosity (<30%) shale, sandstone and siltstone the mean thermal conductivity is in the range 2.2 - 2.6 W m^{-1} K^{-1}. Water has a thermal conductivity of 0.6 W m^{-1} K^{-1} and air a thermal conductivity of 0.0252 W m^{-1} K^{-1}. Ice at 0 °C has a much higher thermal conductivity (2.2 W m^{-1} K^{-1}) than water at the same temperature, so that in some situations frozen ground can deliver a better performance to the heat exchanger than unfrozen ground. A quartz sandstone with 5% porosity might

have a thermal conductivity of about 6.5 W m^{-1} K^{-1}, but this would decrease to about 2.5 W m^{-1} K^{-1} if the rock had a porosity of 30% and was completely saturated with water. For sedimentary rocks that exhibit intergranular porosity, the thermal conductivity will increase significantly with just 10 - 20% saturation to over 90% of the expected value for saturated rock.
For volcanic rocks porosity is also the main influence on thermal conductivity. Low porosity tuffs, lavas and basalts may have values above 2 W m^{-1} K^{-1}, but at 10% porosity with water saturation this might reduce to about 1.5 W m^{-1} K^{-1}.
For igneous plutonic rocks that generally have a much lower porosity, the thermal conductivity variation is less. Plutonic rocks with low feldspar content (<60%), including granite, granodiorite, diorite, gabbro and many dykes have a mean thermal conductivity of about 3.0 W m^{-1} K^{-1}.
For metamorphic rocks, porosity is often very low and thermal conductivity can be related to quartz content. The thermal conductivity of quartzite is high, typically above 5.5 W m^{-1} K^{-1}. For schist, hornfels, quartz mica schist, serpentinite and marble the mean thermal conductivity is about 2.9 W m^{-1} K^{-1}.

For superficial deposits and soils the thermal conductivity will depend on the nature of the deposit, the bulk porosity of the soil and the degree of saturation. Superficial deposit and soils are complex aggregates of mineral and organic particles so exhibit a wide range of thermal characteristics. An approximate guide to the thermal properties of the deposit can be made using a simple classification based on soil particle size and composition. In general relatively higher values of thermal conductivity are associated with granular soils containing silt or clay portions than with clean granular sandy soils. Also clean sands have a low thermal conductivity when dry but a higher value when saturated. There is a very significant difference in the thermal properties of silt and clay. Table 1 gives a good general guide to the expected thermal properties of superficial deposits and soils.

Typical values for superficial thermal conductivity and diffusivity

Class	Thermal Conductivity W m^{-1} K^{-1}	Thermal diffusivity m^2 day^{-1}
Sand (gravel)	0.77	0.039
Silt	1.67	0.050
Clay	1.11	0.046
Loam	0.91	0.042
Saturated sand	2.50	0.079
Saturated silt or clay	1.67	0.056

Appendix 4: Thermal diffusivity - Technical Description

The specific heat capacity c of a material is the amount of heat required to change unit mass of the material by unit temperature. It represents the amount of energy absorbed or dissipated by a material before its temperature will change. The specific heat of most common minerals increases with temperature but at ambient temperatures a mean value of specific heat capacity for siltstone sandstone and shale is about 800 J kg^{-1} K^{-1}. Water has a high specific heat capacity (4187 J kg^{-1} K^{-1}) in relation to common minerals so that the contribution of water to the overall specific heat capacity of a rock or soil is considerable.

Heat transfer to a ground collector is affected primarily by surface area, the thermal conductivity and the 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).

$$\chi = \lambda \ / \ c \ \rho$$

Rock density varies by a factor of about 2 across a range 1.50 – 3.10 Mg m^{-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}.

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 heat capacity, in the range 0.87 - 0.93 J g^{-1} K^{-1}. Porous rocks and soils have significantly higher specific heat capacity 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}.

Typical rock thermal diffusivities range from about 0.065 m^2 day^{-1} for clays to about 0.17 m^2 day^{-1} for high conductivity rocks such as anhydrite and pure quartzite. Many rocks have thermal diffusivities in the range 0.077 – 0.103 m^2/day. Generally thermal conductivity and specific heat are increased for saturated rocks and diffusivity is also enhanced. Table 2 gives representative values for a few rock types.

Typical values for rock thermal diffusivity

Rock	Thermal diffusivity m^2 day^{-1}
Basalt	0.059
Dunite	0.082
Granite	0.086
Granodiorite	0.062
Gneiss	0.106
Quartzite	0.255
Salt	0.264
Anhydrite	0.194
Clay	0.082
Clay marl	0.081
Limestone	0.091
Marl	0.097
Marly clay	0.077
Sandstone	0.143

Thermal diffusivity is also the parameter that controls the propagation of the annual temperature profile at the surface of the earth downwards through the soil and rock so that knowledge of the sub-surface temperature profile over time can deliver an estimate of the thermal diffusivity of the ground. Similarly, the phase shift of the minimum and maximum sub-surface temperatures can be used to estimate diffusivity.