British Geological Survey
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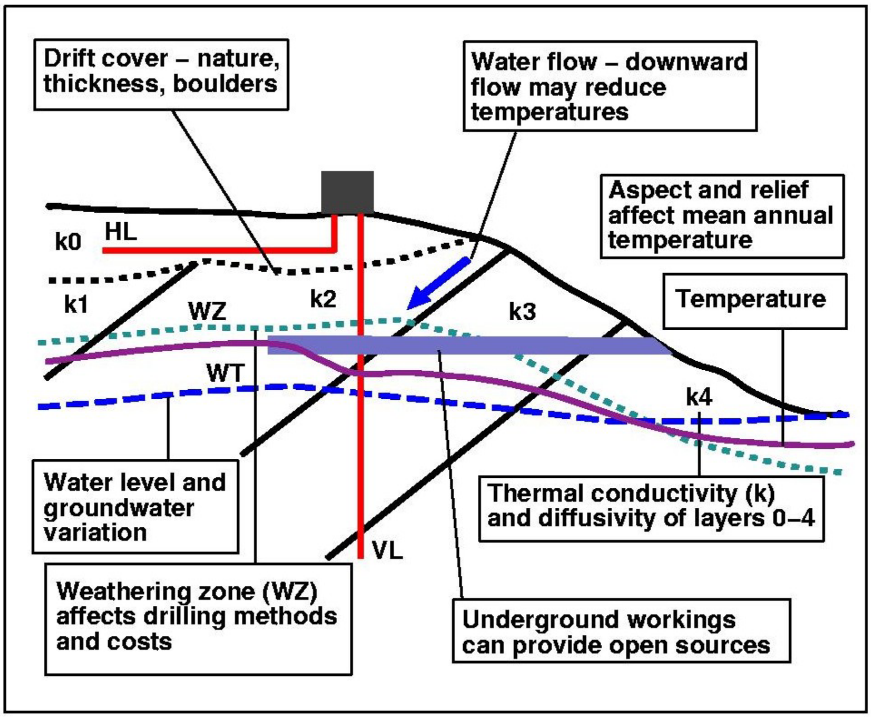
Ground source heat pumps: development of GeoReports for potential site characterisation, issue 1.2

Carbon Trust R&D projects

Commissioned Report CR/05/217N



BRITISH GEOLOGICAL SURVEY

CARBON TRUST R&D PROJECTS PROGRAMME

COMMISSIONED REPORT CR/05/217N

Ground source heat pumps: development of GeoReports for potential site characterisation, issue 1.2

I N Gale

Front cover

Geological factors which can affect GSHP installation

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Carbon Trust
Research, Development & Demonstration Projects

Final Report
GSHP site characterisation

Author:	Ian Gale
Organisation:	British Geological Survey
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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.

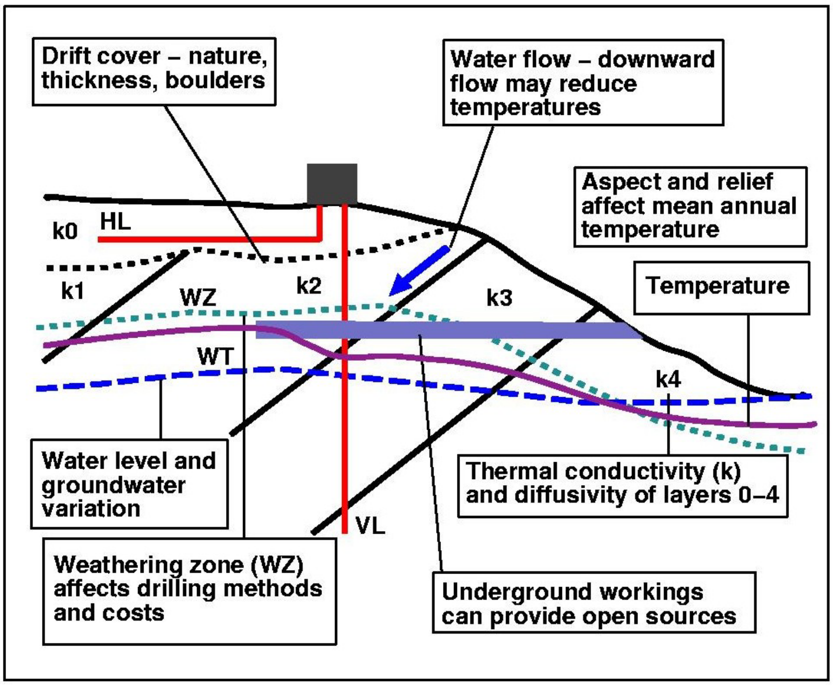

Figure 1 Geological factors which can affect GSHP installation.

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 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.

1 Summary of work carried out and progress

1.1 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.

1.2 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.

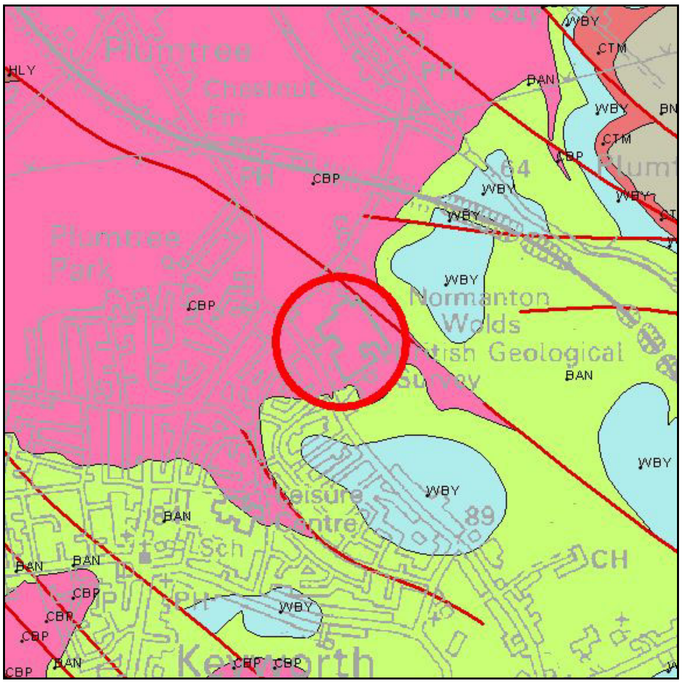

Figure 2 Bedrock Geology around a prospective GSHP site.

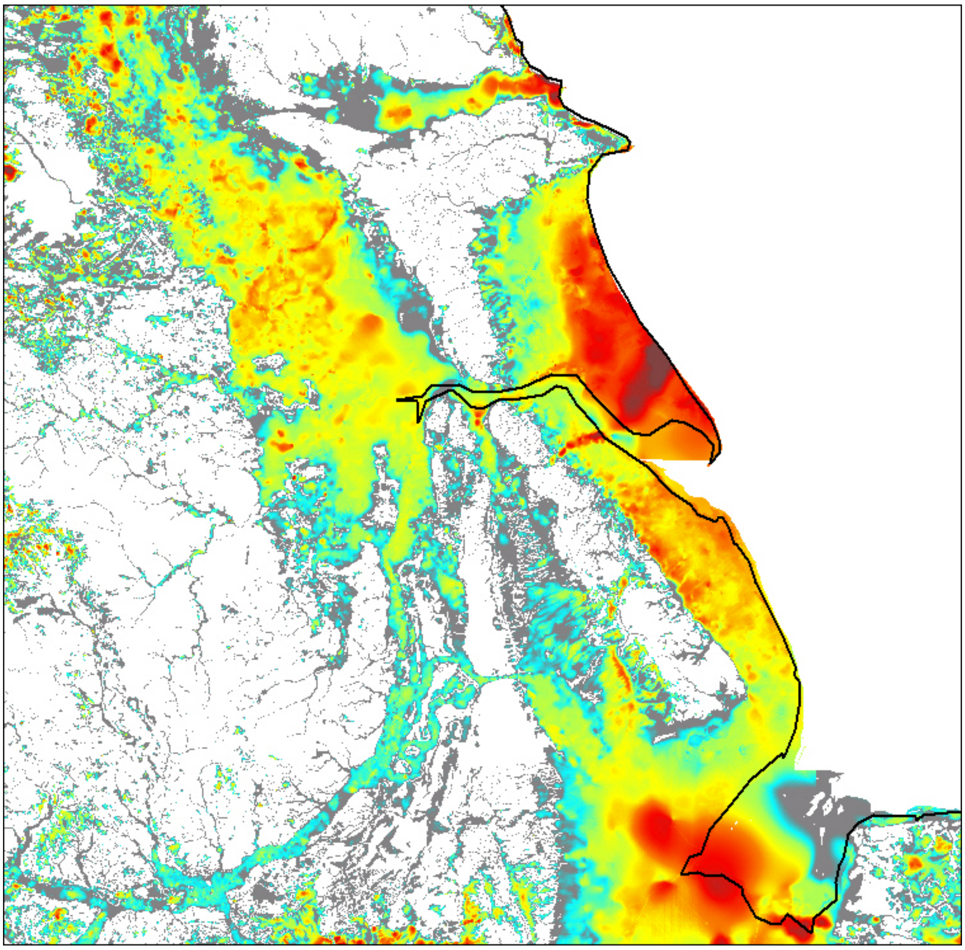

Figure 3 Depth to rockhead in the York-Humber region.

1.3 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.

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.

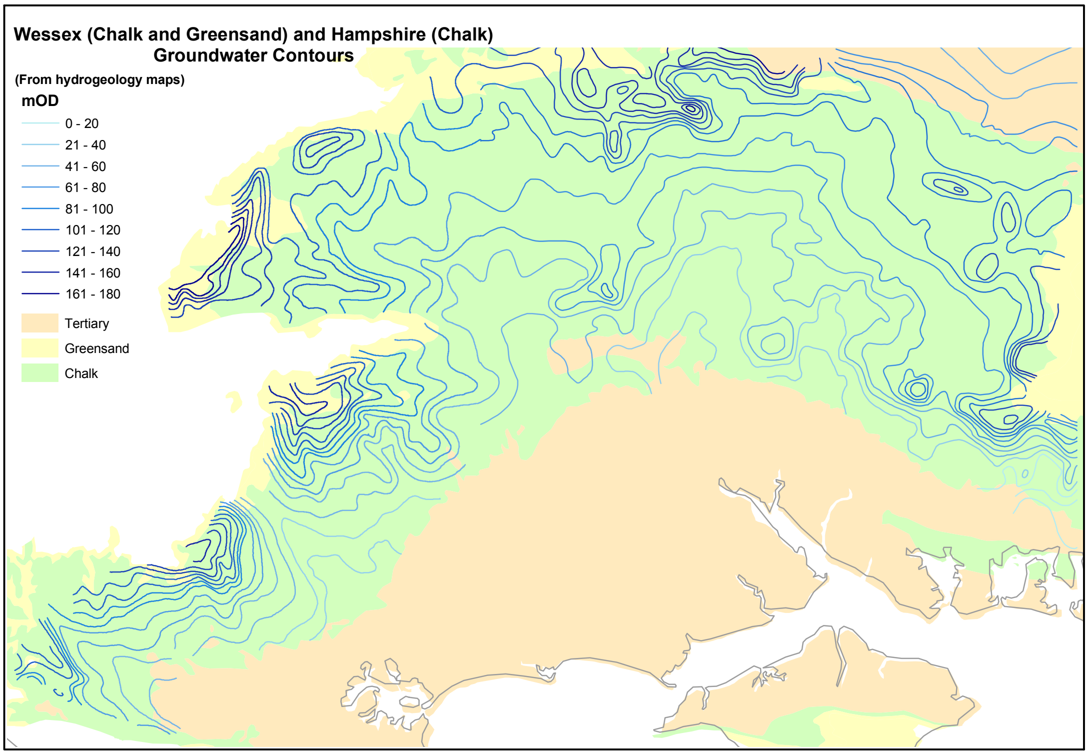

Figure 4 Groundwater contours in the Chalk aquifer in the Wessex Basin.

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.

1.4 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).

1.4.1 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				

Tables explaining the strength, density and compactness codes used in on p.4.

	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.)

1.5 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.

1.5.1 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.

1.5.2 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.

1.5.3 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.

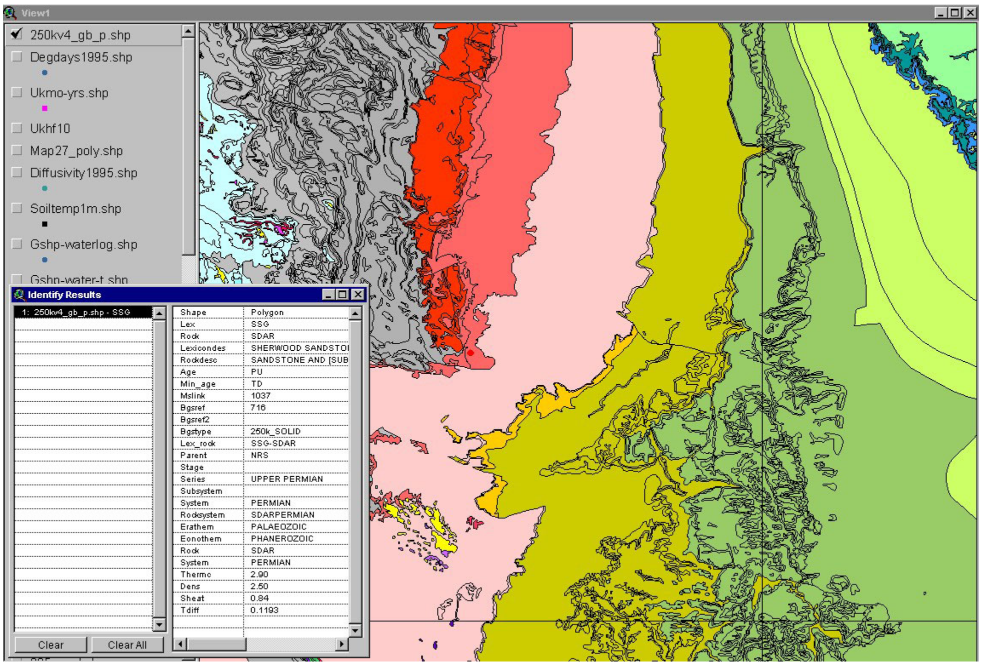

Figure 5 Attribution of the 1:250K scale bedrock geology vectors with thermal and physical properties.

1.6 GEOREPORT WRITER

The new GSHP GeoReports were developed and web-enabled. 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.

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):

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. sAppendices 1 and 2 present example GeoReports via a link to the GeoReports web page.

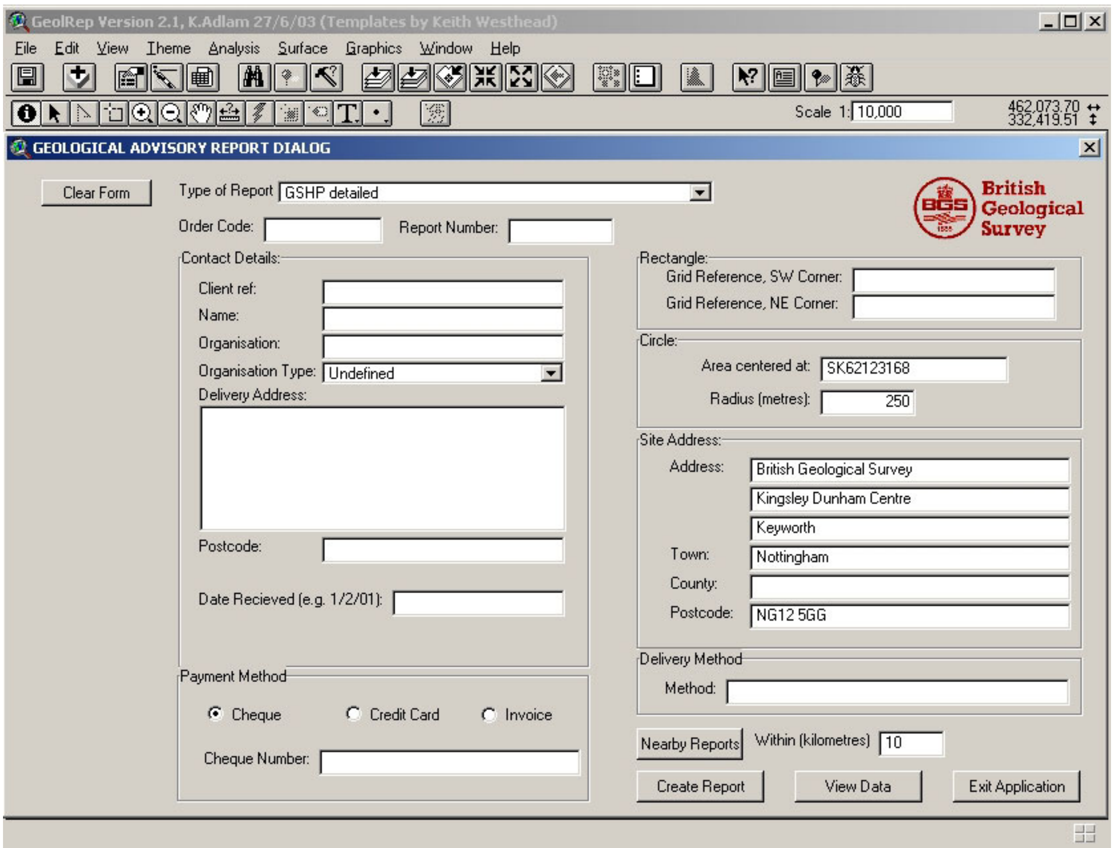

Figure 6 The Geological Advisory Report Dialog window for preparation of a GeoReport.

1.7 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.

2 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

http://www.bgs.ac.uk/sgs/samples/GSHPB.pdf

Appendix 2 Example of a detailed GeoReport: Keyworth, Nottingham

http://www.bgs.ac.uk/sgs/samples/GSHPD.pdf

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 (8) and the temperature gradient ∗T/∗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..

$$8_b = 8_1^{N1} 8_2^{N2} \dots\dots 8_n^{Nn}$$

Where 8_b is the bulk conductivity; $8_1 \dots\dots 8_n$ are the conductivities of the n constituents; and N1……..Nn 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).

$$\chi = 8 / c \rho$$

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.