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An Introduction

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> Nature has given us illimitable sources of prepared low-grade heat. Will human organisations cooperate to provide the machine to use nature's gift?
>
> John A. Sumner (1976)

Many of you will be familiar with the term *geothermal energy*. It probably conjures mental images of volcanoes or of power stations replete with clouds of steam, deep boreholes, whistling turbines and hot saline water. This book is *not* primarily about such geothermal energy, which is typically high temperature (or high enthalpy, in technospeak) energy and is accessible only at either specific geological locations or at very great depths. This book concerns the relatively new science of *thermogeology*. Thermogeology involves the study of so-called *ground source heat*: the mundane form of heat that is stored in the ground at normal temperatures. Ground source heat is much less glamorous than high-temperature geothermal energy, and its use in space heating is often invisible to those who are not 'in the know'. It is hugely important, however, as it exists and is accessible everywhere. It genuinely offers an attractive and powerful means of delivering CO_2-efficient space heating and cooling.

Let me offer the following definition of *thermogeology*:

> Thermogeology is the study of the occurrence, movement and exploitation of low enthalpy heat in the relatively shallow geosphere.

An Introduction to Thermogeology: Ground Source Heating and Cooling, Second Edition. David Banks.
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By 'relatively shallow', we are typically talking of depths of down to 300 m or so. By 'low enthalpy', we are usually considering temperatures of less than 40°C.[1]

1.1 Who should read this book?

This book is designed as an introductory text for the following audience:

- graduate and postgraduate level students;
- civil and geotechnical engineers;
- buildings services and heating, ventilation and air conditioning (HVAC) engineers who are new to ground source heat;
- applied geologists, especially hydrogeologists;
- architects;
- planners and regulators;
- energy consultants.

1.2 What will this book do and not do?

This book is not a comprehensive manual for designing ground source heating and cooling systems for buildings: it is rather intended to introduce the reader to the concept of thermogeology. It is also meant to ensure that architects and engineers are aware that there is an important geological dimension to ground heat exchange schemes. The book aims to cultivate awareness of the possibilities that the geosphere offers for space heating and cooling and also of the limitations that constrain the applications of ground heat exchange. It aims to equip the reader with a *conceptual model* of how the ground functions as a heat reservoir and to make him or her aware of the important parameters that will influence the design of systems utilising this reservoir.

While this book will introduce you to design of ground source heat systems and even enable you to contribute to the design process, it is important to realise that a sustainable and successful design needs the integrated skills of a number of sectors:

- The thermogeologist
- The architect, who must ensure that the building is designed to be heated using the relatively low-temperature heating fluids (and cooled by relatively high-temperature chilled media) that are produced efficiently by most ground source heat pump/heat exchange schemes.

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[1] Although in conventional geothermal science, anything up to around 90°C is still considered 'low enthalpy'!

- The buildings services/HVAC engineer, who must implement the design and must design hydraulically efficient collector and distribution networks, thus ensuring that the potential energetic benefits of ground heat exchange systems are not frittered away in pumping costs.
- The electromechanical and electronic engineer, who will be needed to install the heat pump and associated control systems
- The pipe welder and the driller, who will be responsible for installing thermally efficient, environmentally sound and non-leaky ground heat exchangers.
- The owner, who needs to appreciate that an efficient ground heat exchange system must be operated in a wholly different way to a conventional gas boiler (e.g. ground source heat pumps often run at much lower output temperatures than a gas boiler and will therefore be less thermally responsive).

If you are a geologist, you must realise that you are not equipped to design the infrastructure that delivers heat or cooling to a building. If you are an HVAC engineer, you should acknowledge that a geologist can shed light on the 'black hole' that is your ground source heat borehole or trench. In other words, you need to talk to each other and work together! For those who wish to delve into the hugely important 'grey area' where geology interfaces in detail with buildings engineering, to the extent of consideration of pipe materials and diameters, manifolds and heat exchangers, I recommend that you consult one of several excellent manuals or software packages available. In particular, I would name the following:

- the manual of Kavanaugh and Rafferty (1997) – despite its insistence on using such unfamiliar units as $\mathrm{Btu\,ft^{-1}\,{}^{\circ}F^{-1}}$, so beloved of our American cousins;
- the set of manuals issued by the International Ground Source Heating Association (IGSHPA) – IGSHPA (1988), Bose (1989), Eckhart (1991), Jones (1995), Hiller (2000), and IGSHPA (2007);
- the recent book by Ochsner (2008a);
- the newly developed Geotrainet (2011) manual, which has a specifically European perspective and has been written by some of the continent's foremost thermophysicists, thermogeologists and HVAC engineers;
- the German Engineers' Association standards (VDI, 2000, 2001a,b, 2004, 2008);
- numerous excellent booklets aimed at different national user communities, such as that of the Energy Saving Trust (2007).

1.3 Why should you read this book?

You should read this book because *thermogeology is important for the survival of planet Earth!* Although specialists may argue about the magnitude of climate change ascribable to greenhouse gases, there is a broad consensus (IPCC, 2007) that the continued emission of fossil carbon (in the form of CO_2) to our atmosphere has the potential to detrimentally alter our planet's climate and ecology. Protocols negotiated via international conferences, such as those at Rio de Janeiro (the so-called Earth Summit) in 1992 and at Kyoto in 1997, have attempted to commit nations to dramatically reducing their emissions of greenhouse gases [carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)] during the next decades.

Even if you do not believe in the concept of anthropogenic climate change, recent geopolitical events should have convinced us that it is unwise to be wholly dependent on fossil fuel resources located in unstable parts of the world or within nations whose interests may not coincide with ours. Demand for fossil fuels is increasingly outstripping supply: the result of this is the rise in oil prices over the last decade. This price hike is truly shocking, not least because most people seem so unconcerned by it. A mere 10 years ago, in 1999, developers of a new international oil pipeline were worrying that the investment would become uneconomic if the crude oil price fell below $15 USD per barrel. At the time of writing, Brent crude is some $105 per barrel, and peaked in 2008 at over $140 (Figure 1.1). The increasingly efficient use of the fuel resources we do have access to, and the promotion of local energy sources, must be to our long-term benefit.

I would not dare to argue that the usage of ground source heat alone will allow us to meet all these objectives. Indeed, many doubt that we will be able to adequately reduce fossil carbon emissions soon enough to significantly brake the effects of global warming. If we are to make an appreciable impact on net fossil carbon emissions, however, we will undoubtedly need to consider a wide variety of strategies, including the following:

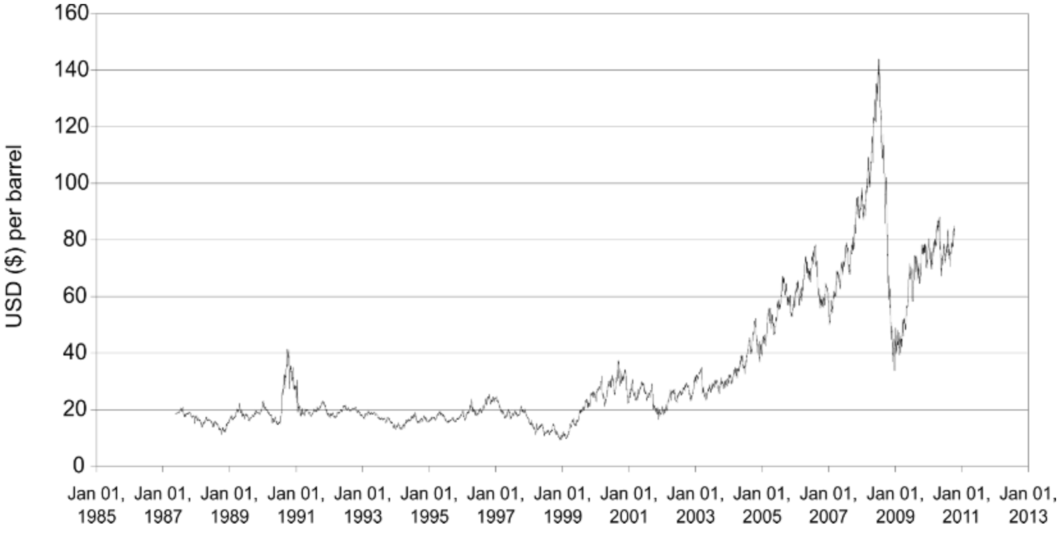

Figure 1.1 Spot prices for Brent Crude Oil in the period 1987–2010 (USD per barrel). Based on the data from the US Energy Information Administration (EIA).

1. A reduction in energy consumption, for example, by more efficient usage of our energy reserves.
2. Utilisation of energy sources not dependent on fossil carbon. The most strategically important of these non-fossil-carbon sources is probably nuclear power (although uranium resources are finite), followed by hydroelectric power. Wind, wave, biomass, geothermal and solar powers also fall in this category.
3. Alternative disposal routes for fossil carbon dioxide, other than atmospheric emission: for example, underground sequestration by injection using deep boreholes.

I will argue, however, that utilisation of *ground source heat* allows us to significantly address issues (1) and (2). Application of *ground source heat pumps* (see Chapter 4) allows us to use electrical energy highly efficiently to transport renewable environmental energy into our homes (Box 1.1).

If the environmental or macroeconomic arguments don't sway you, try this one for size: *Because the regulatory framework in my country is forcing me to install energy-efficient technologies!* The Kyoto Protocol is gradually being translated into European and national legislation, such as the British Buildings Regulations, which not only require highly thermally efficient buildings, but also low-carbon space heating and cooling technologies. Local planning authorities may demand a certain percentage of 'renewable energy' before a new development can be permitted. Ground source heating or cooling may offer an architect a means of satisfying ever more stringent building regulations. It may assist a developer in getting into the good books of the local planning committee.

BOX 1.1 Energy, Work and Power

Energy is an elusive concept. In its broadest sense, energy can be related to the ability to do *work*. Light energy can be converted, via a photovoltaic cell, to electrical energy that can be used to power an electrical motor, which can do *work*. The chemical energy locked up in coal can be converted to heat energy by combustion and thence to mechanical energy in a steam engine, allowing *work* to be done. In fact, William Thomson (Lord Kelvin) demonstrated an equivalence between energy and work. Both are measured in *joules* (J).

Work (W) can defined as the product of the *force* (F) required to move an object and the *distance* (L) it is moved. In other words,

$$W = FL$$

Force is measured in *newtons* and has a dimensionality $[\mathrm{M}][\mathrm{L}][\mathrm{T}]^{-2}$. Thus, work and energy have the same dimensionality $[\mathrm{M}][\mathrm{L}]^2[\mathrm{T}]^{-2}$ and $1\,\mathrm{J} = 1\,\mathrm{kg\,m^2\,s^{-2}}$.

Power is defined as the *rate* of doing work or of transferring energy. The unit of power is the *watt* (W), with dimensionality $[\mathrm{M}][\mathrm{L}]^2[\mathrm{T}]^{-3}$.

1 watt = 1 joule per second = $1\,\mathrm{J\,s^{-1}} = 1\,\mathrm{kg\,m^2\,s^{-3}}$.

Finally, the most powerful argument of all: *Because you can make money from ground source heat.* You may be an entrepreneur who has spotted the subsidies, grants and tax breaks that are available to those who install ground source heating schemes. You may be a consultant wanting to offer a new service to a client. You may be a drilling contractor – it is worth mentioning that, in Norway and the United Kingdom, drillers are reporting that they are now earning more from drilling ground source heat boreholes than from their traditional business of drilling water wells. You may be a property developer who has sat down and looked cool and hard at the economics of ground source heat, compared it with conventional systems and concluded that the former makes not only environmental sense, but also economic sense.

1.4 Thermogeology and hydrogeology

You don't have to be a hydrogeologist to study thermogeology, but it certainly helps. A practical hydrogeologist often tries to exploit the earth's store of groundwater by drilling wells and using some kind of pump to raise the water to the surface where it can be used. A thermogeologist exploits the earth's heat reservoir by drilling boreholes and using a ground source heat pump to raise the temperature of the heat to a useful level. The analogy does not stop here, however. There is a direct mathematical analogy between groundwater flow and subsurface heat flow.

We all know that water, left to its own devices, flows downhill or from areas of high pressure to low pressure. Strictly speaking, we say that water flows from locations of high *head* to areas of low head (Box 1.2). Head is a mathematical concept which combines both pressure and elevation into a single value. Similarly, we all know that heat tends to flow from hot objects to cold objects. In fact, a formula, known as Fourier's law, was named after the French physicist Joseph Fourier. It permits us to quantify the heat flow conducted through a block of a given material (Figure 1.2):

$$Q = -\lambda A \frac{d\theta}{dx} \tag{1.1}$$

where

Q = flow of heat in joules per second, which equals watts ($\mathrm{J\,s^{-1} = W}$),

λ = thermal conductivity of the material ($\mathrm{W\,m^{-1}\,K^{-1}}$),

A = cross-sectional area of the block of material under consideration ($\mathrm{m^2}$),

θ = temperature (°C or K),

x = distance coordinate in the direction of decreasing temperature (note that heat flows in the direction of decreasing temperature: hence the negative sign in the equation),

$\frac{d\theta}{dx}$ = temperature gradient ($\mathrm{K\,m^{-1}}$).

The hydrogeologists have a similar law, Darcy's law, which describes the flow of water through a block of porous material, such as sand:

BOX 1.2 Head

We know intuitively that water tends to flow downhill (from higher to lower elevation). We also know that it tends to flow from high to low pressure. We can also intuitively feel that water elevation and pressure are somehow equivalent. In a swimming pool, water is static: it does not flow from the water surface to the base of the pool. The higher elevation of the water surface is somehow compensated by the greater pressure at the bottom of the pool.

The concept of *head* (h) combines elevation (z) and pressure (P). Pressure (with dimension [M][L]$^{-1}$[T]$^{-2}$) is converted to an equivalent elevation by dividing it by the water's density (ρ_w: dimension [M][L]$^{-3}$) and the acceleration due to gravity (g: dimension [L][T]$^{-2}$), giving the formula

$$h = z + \frac{P}{\rho_w g}$$

Groundwater always flows from regions of high head to regions of low head. Head is thus a measure of groundwater's potential energy: it provides the potential energy gradient along which groundwater flows according to Darcy's law.

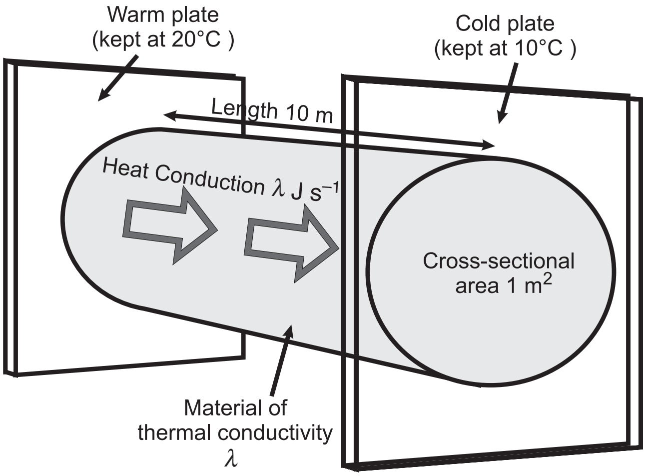

Figure 1.2 The principle of Fourier's law. Consider an insulated bar of material of cross-sectional area 1 m^2 and length 10 m. If one end is kept at 20°C and the other end at 10°C, the temperature gradient is 10 K per 10 m, or 1 K m^{-1}. Fourier's law predicts that heat will be conducted from the warm end to the cool end at a rate of λ J s^{-1}, where λ is the thermal conductivity of the material (in W m^{-1} K^{-1}). We assume that no heat is lost by convection or radiation.

$$Z = -KA\frac{dh}{dx} \tag{1.2}$$

where

Z = flow of water ($m^3 s^{-1}$),

K = hydraulic conductivity of the material ($m\,s^{-1}$), often referred to as the permeability of the material,

A = cross-sectional area of the block of material under consideration (m^2),

h = head (m),

x = distance coordinate in the direction of decreasing head (m),

$\frac{dh}{dx}$ = head gradient (dimensionless).

A hydrogeologist is interested in quantifying the properties of the ground to ascertain whether it is a favourable target for drilling a water well (Misstear *et al.*, 2006). Two properties are of relevance. Firstly, the permeability (or *hydraulic conductivity*)

BOX 1.3 Maslow, Geology and Human Needs

> Food is the first thing – morals follow on.
>
> Bertolt Brecht, A Threepenny Opera

Abraham Maslow (1908–1970) was an American humanist and psychologist, who studied and categorised fundamental human needs. His ideas are often summarised in some form of tiered structure – a hierarchy of needs – where the lowest levels of need must be fulfilled before a human can pursue happiness and aspire to satisfy his or her higher-level needs. The most familiar conceptualisation involves the following:

Tier 5 – Self-actualisation: includes art, morality
Tier 4 – Esteem: self-respect, respect of others, sense of achievement
Tier 3 – Belonging: friendship, family
Tier 2 – Safety: employment, resources, health, property
Tier 1 – The fundamentals: sex, respiration, food, water, homeostasis, excretion, sleep

Humble hydrogeologists, environmental geochemists and thermogeologists may not be glamorous, but they can comfort themselves with the fact that they are satisfying basic human needs in Tier 1. Hydrogeologists provide potable water and secure disposal of wastes via pit latrines and landfills; environmental geochemists ensure that our soils are fit for cultivation. Thermogeologists contribute to ensuring homeostasis – a flashy word that basically means a controlled environment (shelter), of which space heating and cooling are fundamental aspects.

For sex and sleep, the Geologist's Directory may not be able to assist you.

is an intrinsic property of the rock or sediment that describes how good that material is at allowing groundwater to flow through it. Secondly, the *storage coefficient* describes how much groundwater is released from pore spaces or fractures in a unit volume of rock, for a 1 m decline in groundwater head. A body of rock that has sufficient groundwater storage and sufficient permeability to permit economic abstraction of groundwater is called an *aquifer* (from the Latin 'water' + 'bearing').

In thermogeology, we again deal with two parameters describing how good a body of rock is at *storing* and *conducting* heat. These are the *volumetric heat capacity* (S_{VC}) and the *thermal conductivity* (λ). The former describes how much heat is released from a unit volume of rock as a result of a 1 K decline in temperature, while the latter is defined by Fourier's law (Equation 1.1). We could define an *aestifer* as a body of rock with adequate thermal conductivity and volumetric heat capacity to permit the economic extraction of heat (from the Latin *aestus*, meaning 'heat' or 'summer').[2] In reality, however, all rocks can be economically exploited (depending on the scale of the system required – see Chapter 4; Box 1.3) for their heat content, rendering the definition rather superfluous.

Table 1.1 summarises the key analogies between thermogeology and hydrogeology, to which we will return later in the book.

Table 1.1 The key analogies between the sciences of hydrogeology and thermogeology (see Banks, 2009a). Note that θ_o = average natural undisturbed temperature of an aestifer, T = transmissivity, t = time, s = drawdown and $W()$ is the well function (see Theis, 1935).

	Hydrogeology	**Thermogeology**
What are we studying?	Groundwater flow	Subsurface heat flow
Key physical law	Darcy's law $Z = -KA\dfrac{dh}{dx}$	Fourier's law (conduction only) $Q = -\lambda A\dfrac{d\theta}{dx}$
Flow	Z = groundwater flow ($m^3 s^{-1}$)	Q = conductive heat flow = ($J s^{-1}$ or W) q = heat flow per metre of borehole ($W m^{-1}$)
Property of conduction	K = hydraulic conductivity ($m s^{-1}$)	λ = thermal conductivity ($W m^{-1} K^{-1}$)
Measure of potential energy	h = groundwater head (m)	θ = temperature (°C or K)
Measure of storage	S = groundwater storage (related to porosity)	S_{VC} or S_C = specific heat capacity ($J m^{-3} K^{-1}$ or $J kg^{-1} K^{-1}$)
Exploitable unit of rock	Aquifer (Lat. *aqua*: water)	Aestifer (Lat. *aestus*: heat)
Transient radial flow	Theis equation $s = \dfrac{Z}{4\pi T} W\left(\dfrac{r^2 S}{4Tt}\right)$	Carslaw's equation $\theta_o - \theta = \dfrac{q}{4\pi\lambda} W\left(\dfrac{r^2 S_{VC}}{4\lambda t}\right)$
Tool of exploitation	Well and pump	Borehole or trench and heat pump
Measure of well/borehole efficiency	Well loss = CZ^2 where C is a constant	Borehole thermal loss = $R_b q$ where R_b = borehole thermal resistance

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[2] The word *aestifer* may sound like a very artificial concoction – but it has an ancient pedigree (Banks, 2009a). Virgil (in the *Georgics, Liber II*) and Marcus Cicero (in *Aratea*) used the term *aestifer* astronomically to describe (respectively) the dog-star Sirius and the constellation Cancer as the harbingers of summer's heat. Lucretius used the word in around 60 BC in his work "De Rerum Natura" to describe the heat-bearing nature of the sun's radiation (Possanza 2001).

STUDY QUESTIONS

1.1 An aquifer is composed of sand with a hydraulic conductivity of $3 \times 10^{-4}\,\mathrm{m\,s^{-1}}$ and is 30 m thick. It is fully saturated with water, and the groundwater head declines by 8 m every 1 km from north to south. Estimate the total groundwater flow through 1 km width of the aquifer every year.

1.2 A small, insulated core of granite, with a thermal conductivity of $3.1\,\mathrm{W\,m^{-1}\,K^{-1}}$, a diameter of 30 mm and a length of 55 mm is placed between two metal plates. One of the plates is kept at 22°C, while the other is heated to 28°C. What is the flow of heat through the core of rock?

1.3 Think about the following sentences:

A stream of water, flowing from high topographic elevation to low elevation is able to turn a water wheel, which can perform mechanical work.

We can use mechanical energy (work) to power a pump, which can lift water from a well up to a water tower.

Try to construct analogous sentences for the concept of heat flow, rather than water flow. Take a look at Sections 4.1 and 4.2 if you get into trouble.