DAVID BANKS

An Introduction to Thermogeology

GROUND SOURCE HEATING AND COOLING

2ND EDITION

WILEY-BLACKWELL

An Introduction to Thermogeology: Ground Source Heating and Cooling

For Jenny 'the Bean'

An Introduction to Thermogeology: Ground Source Heating and Cooling

2nd Edition

David Banks
Holymoor Consultancy Ltd
UK

WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

This edition first published 2012

© 2008 David Banks
© 2012 John Wiley & Sons, Ltd

Wiley-Blackwell is an imprint of John Wiley & Sons, formed by the merger of Wiley's global Scientific, Technical and Medical business with Blackwell Publishing.

Registered office:
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices:
9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
2121 State Avenue, Ames, Iowa 50014-8300, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

The right of the author to be identified as the author of this work has been asserted in accordance with the UK Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

Banks, David, 1961–
An introduction to thermogeology : ground source heating and cooling / David Banks. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-67034-7 (hardcover : alk. paper)
1. Ground source heat pump systems. I. Title.
TH7638.B36 2012
697'.7–dc23

2011045231

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image:
Main photo: Coils of heat exchange pipe can be installed in natural lakes. They can be mounted in a steel frame, rowed out, filled and sunk to the base of the lake. Photo by kind permission of Geowarmth Heat Pumps Ltd. of Newcastle-upon-Tyne.

Top inset photo: Staff of the Geological Survey of Norway carry out a thermal response test on a closed loop heat exchange borehole drilled into greenstone rocks in Trondheim. Photo by David Banks.

Bottom inset photo: An underground house in Matmata, Tunisia. The rocks store 'coolth' from winter and night-time, such that the underground is much cooler than the surface at the height of summer. Photo by David Banks.

Cover design by Edge Creative

Set in 10/13 pt Trump Mediaeval by Toppan Best-set Premedia Limited

1 2012

Contents

About the Author xi
Preface to the First Edition xiii
Preface to the Second Edition xv
Acknowledgements xvii

1 An Introduction 1

1.1 Who should read this book? 2
1.2 What will this book do and not do? 2
1.3 Why should you read this book? 3
1.4 Thermogeology and hydrogeology 6

2 Geothermal Energy 11

2.1 Geothermal energy and ground source heat 11
2.2 Lord Kelvin's conducting, cooling earth 12
2.3 Geothermal gradient, heat flux and the structure of the earth 14
2.4 Internal heat generation in the crust 16
2.5 The convecting earth? 17
2.6 Geothermal anomalies 19
2.7 Types of geothermal system 27
2.8 Use of geothermal energy to produce electricity by steam turbines 28
2.9 Binary systems 28
2.10 Direct use 30
2.11 Cascading use 30
2.12 Hot dry rock systems [a.k.a. 'enhanced geothermal systems (EGS)'] 32
2.13 The 'sustainability' of geothermal energy and its environmental impact 35
2.14 And if we do not live in Iceland? 38

3 The Subsurface as a Heat Storage Reservoir 40

3.1 Specific heat capacity: the ability to store heat 41
3.2 Movement of heat 45
3.3 The temperature of the ground 51
3.4 Insolation and atmospheric radiation 55
3.5 Cyclical temperature signals in the ground 59

	3.6	Geothermal gradient	61
	3.7	Human sources of heat in the ground	65
	3.8	Geochemical energy	69
	3.9	The heat energy budget of our subsurface reservoir	70
	3.10	Cyclical storage of heat	72
	3.11	Manipulating the ground heat reservoir	74
4	**What Is a Heat Pump?**		**79**
	4.1	Engines	81
	4.2	Pumps	84
	4.3	Heat pumps	85
	4.4	The rude mechanics of the heat pump	88
	4.5	Absorption heat pumps	91
	4.6	Heat pumps for space heating	91
	4.7	The efficiency of heat pumps	93
	4.8	Air-sourced heat pumps	96
	4.9	Ground source heat pumps	98
	4.10	Seasonal performance factor (SPF)	99
	4.11	GSHPs for cooling	100
	4.12	Other environmental sources of heat	100
	4.13	The benefits of GSHPs	101
	4.14	Capital cost	104
	4.15	Other practical considerations	107
	4.16	The challenge of delivering efficient GSHP systems	108
	4.17	Challenges: the future	109
	4.18	Summary	112
5	**Heat Pumps and Thermogeology: A Brief History and International Perspective**		**114**
	5.1	Refrigeration before the heat pump	115
	5.2	The overseas ice trade	117
	5.3	Artificial refrigeration: who invented the heat pump?	119
	5.4	The history of the GSHP	121
	5.5	The global energy budget: how significant are GSHPs?	129
	5.6	Ground source heat: a competitor in energy markets?	132
6	**Ground Source Cooling**		**133**
	6.1	Our cooling needs in space	133
	6.2	Scale effects and our cooling needs in time	134
	6.3	Traditional cooling	135
	6.4	Dry coolers	136
	6.5	Evaporation	138
	6.6	Chillers/heat pumps	141

6.7 Absorption heat pumps 143
6.8 Delivery of cooling in large buildings 144
6.9 Dehumidification 145
6.10 Passive cooling using the ground 145
6.11 Active ground source cooling 147
6.12 An example of open-loop groundwater cooling 148

7 Options and Applications for Ground Source Heat Pumps 150

7.1 How much heat do I need? 150
7.2 Sizing a GSHP 156
7.3 Open-loop ground source heat systems 161
7.4 Closed-loop systems 173
7.5 Domestic hot water by ground source heat pumps? 191
7.6 Heating and cooling delivery in complex systems 195
7.7 Heat from ice 201

8 The Design of Groundwater-Based Open-Loop Systems 202

8.1 Common design flaws of open-loop groundwater systems 203
8.2 Aquifers, aquitards and fractures 203
8.3 Transmissivity 205
8.4 Confined and unconfined aquifers 206
8.5 Abstraction well design in confined and unconfined aquifers 208
8.6 Design yield, depth and drawdown 210
8.7 Real wells and real aquifers 215
8.8 Sources of information 217
8.9 Multiple wells in a wellfield 222
8.10 Hydraulic feedback in a well doublet 227
8.11 Heat migration in the groundwater environment 234
8.12 The importance of three-dimensionality 240
8.13 Mathematical reversibility 242
8.14 Sustainability: thermally balanced systems and seasonal reversal 243
8.15 Groundwater modelling 244
8.16 Examples of open-loop heating/cooling schemes 245
8.17 Further reading 246

9 Pipes, Pumps and the Hydraulics of Closed-Loop Systems 248

9.1 Our overall objective 251
9.2 Hydraulic resistance of the heat exchanger 252
9.3 The hydraulic resistance of pipes 253
9.4 Acceptable hydraulic losses 255
9.5 Hydraulic resistances in series and parallel 255
9.6 An example 256
9.7 Selecting pumps 262

9.8 Carrier fluids 265
9.9 Manifolds 271
9.10 Hydraulic testing of closed loops 275
9.11 Equipping a ground loop 277

10 Subsurface Heat Conduction and the Design of Borehole-Based Closed-Loop Systems 279

10.1 Rules of thumb? 279
10.2 Common design flaws 282
10.3 Subsurface heat conduction 283
10.4 Analogy between heat flow and groundwater flow 286
10.5 Carslaw, Ingersoll, Zobel, Claesson and Eskilson's solutions 289
10.6 Real closed-loop boreholes 294
10.7 Application of theory – an example 304
10.8 Multiple borehole arrays 313
10.9 Simulating cooling loads 321
10.10 Simulation time 322
10.11 Stop press 323

11 Horizontal Closed-Loop Systems 325

11.1 Principles of operation and important parameters 326
11.2 Depth of burial 327
11.3 Loop materials and carrier fluids 328
11.4 Ground conditions 329
11.5 Areal constraints 333
11.6 Geometry of installation 333
11.7 Modelling horizontal ground exchange systems 344
11.8 Earth tubes: air as a carrier fluid 351

12 Pond- and Lake-Based Ground Source Heat Systems 353

12.1 The physics of lakes 354
12.2 Some rules of thumb 356
12.3 The heat balance of a lake 357
12.4 Open-loop lake systems 365
12.5 Closed-loop surface water systems 367
12.6 Closed-loop systems – environmental considerations 371

13 Standing Column Wells 372

13.1 'Standing column' systems 372
13.2 The maths 376
13.3 The cost of SCWs 377
13.4 SCW systems in practice 379
13.5 A brief case study: Grindon Camping Barn 379
13.6 A final twist – the Jacob doublet well 381

14 Thinking Big: Large-Scale Heat Storage and Transfer 383

14.1 The thermal capacity of a building footprint 384
14.2 Simulating closed-loop arrays with balanced loads 385
14.3 A case study of a balanced scheme: car showroom, Bucharest 390
14.4 Balancing loads 392
14.5 Deliberate thermal energy storage – closed-loop borehole thermal energy storage (BTES) 395
14.6 Aquifer thermal energy storage (ATES) 398
14.7 UTES and heat pumps 403
14.8 Regional transfer and storage of heat 403

15 Thermal Response Testing 410

15.1 Sources of thermogeological data 410
15.2 Laboratory determination of thermal conductivity 411
15.3 The thermal response test (TRT) 412
15.4 The practicalities: the test rig 417
15.5 Test procedure 420
15.6 Sources of uncertainty 425
15.7 Non-uniform geology 426
15.8 Non-constant power input 426
15.9 Groundwater flow 427
15.10 Analogies with hydrogeology 428
15.11 Thermal response testing for horizontal closed loops 429

16 Environmental Impact, Regulation and Geohazards 432

16.1 The regulatory framework 432
16.2 Thermal risks 437
16.3 Hydraulic risks 444
16.4 Geotechnical risks 449
16.5 Contamination risks 451
16.6 Geochemical risks 453
16.7 Microbiological risks 454
16.8 Excavation and drilling risks 455
16.9 Decommissioning of boreholes 458
16.10 Promoting technology: subsidy 459
16.11 The final word 460

References 463
Study Question Answers 493
Symbols 503
Glossary 509
Units 515
Index 518

About the Author

David BANKS was born in Bishop Auckland in 1961. He is a hydrogeologist with 26 years experience of investigating groundwater-related issues. He started his career with the Thames Water Authority in southern England, then moved across the North Sea to the Geological Survey of Norway, where he eventually headed the Section for Geochemistry and Hydrogeology. Since returning to the United Kingdom in 1998, he has worked as a consultant from a base in Chesterfield, sandwiched between the gritstone of the Peak District National Park and the abandoned mines of Britain's largest coalfield. He has international experience from locations as diverse as Afghanistan, the Bolivian Altiplano, Somalia, Western Siberia, Darfur and Huddersfield. During the past 10 years, his attention has turned to the emerging science of thermogeology: he has worked closely with the ground source heat industry and has also enjoyed spells as a Senior Research Associate in Thermogeology at the University of Newcastle-upon-Tyne. Most recently, he was employed by Newcastle University to provide input to the European Union 'GeoTrainet' program of geothermal education.

In his spare time, Dave enjoys music. With his chum Bjørn Frengstad, he has formed almost one half of the sporadically active acoustic lo-fi stunt duo 'The Sedatives'. They have murdered songs by their musical heroes (who include Jarvis Cocker, Benny Andersen, Richard Thompson and Katherine Williams) in a variety of seedy locations.

Reviews of 'An Introduction to Thermogeology'

> '. . . it is seldom that one needs to use superlatives when talking about a book . . . this book should be a bible for all who would like to gain insight into the nature of the earth's heat, and how we can exploit it in practice'.
>
> Inga Sørensen, writing in Geologisk Nyt, Denmark, August 2009

Other books by the same author

With Bruce Misstear and Lewis Clark, Dave Banks has previously co-authored 'Water Wells and Boreholes', currently available from Wiley.

> 'The book is fulsome. It is a complete counterbalance to the common, but naïve, notion that if you want a new water well "you just go out and get yourself a driller." This book

explains how to do it properly. . . . It is an important achievement. I expect that it will become a "Bible" that will be on the desk or in the field with every practical hydrogeologist . . .'.

David Ball, writing in the Geological Survey of Ireland Newsletter

'. . . it far outshines most other volumes with which it might otherwise be compared. . . . I would recommend every aspiring and practising hydrogeologist to buy it and thumb it to pieces'.

Paul Younger, writing in the Quarterly Journal of Engineering Geology and Hydrogeology

Preface to the First Edition

In the late 1990s, I was working for the Norwegian Geological Survey's Section for Hydrogeology and Geochemistry. Despite the Section being choc-a-bloc with brainy research scientists, one of my most innovative colleagues was an engineer who called me, on what seemed a weekly basis, brimming with enthusiasm for some wizard new idea. One day, he started telling me all about something called *grunnvarme* or ground source heat, which was, apparently, very big in Sweden. Initially, it seemed to me to be something akin to perpetual motion – space heating from Norwegian rock at 6°C? – and in violation of the second law of thermodynamics to boot. Nevertheless, he persuaded me that it really did have a sound physical basis. In fact, my chum went on to almost single-handedly sell the concept of ground source heat to a Norwegian market that was on the brink of an energy crisis. A subsequent dry summer that pulled the plug on Norway's cheap hydroelectric supplies and sent prices soaring was the trigger that ground source heat needed to take off. So, firstly, a big thank you to Helge Skarphagen (for it was he!), who first got me interested in ground source heat.

On my return to England in 1998, I tried to bore anyone who gave the appearance of listening about the virtues of ground source heat (I was by no means the first to try this – John Sumner and Robin Curtis, among others, had been evangelists for the technology much earlier). It was not until around 2003, however, that interest in ground source heat was awakened in Britain and I was lucky enough to fall in with a group of entrepreneurs with an eye for turning it into a business. So, secondly, many thanks to GeoWarmth of Hexham (now based at Newcastle) for the pleasure of working with you, and especially to Dave Spearman, Jonathan Steven, Braid and Charlie Aitken, Nick Smith and John Withers.

Oh, and by the way, Jenny, I don't know what you've been up to while I've been locked in the attic writing this book, but normal parental service will shortly be resumed!

David Banks
Chesterfield, Derbyshire, 2007

Preface to the Second Edition

This book is written for an international audience. It aims to aid professionals in conceptualising the ground – heat exchanger – building linkages at the heart of ground-coupled heat exchange systems. Forgive me, therefore, if I focus for a few moments on my own recent British experiences in this Preface.

At the time of writing the first edition of this book, the ground source heating and cooling industry in the United Kingdom was in its infancy and growing fast. Four years later, the profession is much larger but is still regrettably immature.

British ground source heat pump meetings abound with grey-suited salesmen (and they are invariably men) warning us to be on our guard against 'cowboys', who will drag our profession into disrepute by their ignorance. Quite who these 'cowboys' are is never fully explained . . . probably due to the fact that the speaker himself is a 'cowboy', as are most of the audience. The hard truth is that almost all ground source heat practitioners (with a few honourable exceptions) in the United Kingdom are relatively new to the science and are still learning fast. Indeed, I will myself admit to being just such a 'cowboy'. But, hey, being a cowboy can be fun – cowboys are pioneers, blazing a trail in unknown terrain. Cowboys can be rough and ready and can make mistakes but, with time and experience, they will form the backbone of a new frontier community. Westward ho and wagons roll!

The UK ground source heat pump market is still reported to be the fastest growing in the world (Lund, 2010). However, I trust that the time is approaching when the cowboys are beginning to settle, to form professional communities and to get a real grasp of their tools and terrain. We should be reaching a stage where we are not merely building ground source heat systems that work, but ones that work really efficiently. At the time of writing, the industry is still reeling from the implications of a report by the Energy Saving Trust (2010), which found that the system performance factors of UK ground source heat pump systems were typically as low as between 2 and 3. Such low efficiencies risk not only that the system fails to save the owner any money in operational costs, but also that it ultimately releases more atmospheric CO_2 than a conventional mains gas boiler. This is very bad news for the industry. The UK industry has, in response, forced out new standards designed to promote significantly more efficient systems (GSHPA, 2011; MIS, 2011a,b,c).

I feel that the time is ripe for a second edition of this book. This edition will not merely cover the thermophysics of subsurface heat transfer and the conceptualisation of a ground heat exchange system. It will also address many of the key issues involved in designing efficient systems: the impact of design loop temperatures and hydraulics,

the impact of client pressure to cut capital costs, the influence of building (load side) heat delivery decisions and the importance of energy storage. It will attempt to stress the importance of considering system design, not merely in terms of thermogeological variables, but also in the light of your nation's physical climate and energy/carbon economy.

David Banks

Acknowledgements

I would like to thank the following for taking the time to review the various chapters in the 1st Edition and for their invaluable comments:

- Cat Oakley and Madeleine Metcalfe of Wiley-Blackwell Publishing
- Professor Paul Younger of the University of Newcastle-upon-Tyne
- Professor Keith Tovey of the University of East Anglia in Norwich
- Karl Drage of Geothermal International in Coventry
- Helge Skarphagen, formerly of the Norwegian Water Research Institute (NIVA), now with Gether AS in Oslo
- James Dodds of Envireau Ltd in Draycott
- Jonathan Steven and Charlie Aitken, formerly of Geowarmth Ltd, Hexham
- Professor Göran Hellström of Lund Technical University, Sweden
- Dr Simon Rees of De Montfort University, Leicester
- Dr Robin Curtis, now with Mimer Energy Ltd in Falmouth
- Marius Greaves of the Environment Agency of England and Wales

The lyrics from *First & Second Law* from *At the Drop of Another Hat* by Flanders & Swann © 1963 are reproduced in Chapter 4 by kind permission of the Estates of Michael Flanders & Donald Swann. The administrator of The Flanders & Swann Estates, Leon Berger (leonberger@donaldswann.co.uk) was good enough to facilitate this permission. Additionally, I would like to thank the London Canal Museum for sourcing historical photos of the ice trade, and would wholeheartedly recommend a visit to anyone who has a few hours to spend in the Kings Cross area of London and who wants to view a genuine 'ice well'.

I am grateful to all those who have provided materials, case studies, inspiration, diagrams, photos and more – Pablo Fernández Alonso, Hannah Russell, Johan Claesson, Richard Freeborn of Kensa Engineering, Bjørn Frengstad of the fabulous 'Sedatives', the International Ground Source Heat Pump Association (IGSHPA), the Geotrainet team, Ben Lawson and Paul Younger of Newcastle University, John Lund and the Geo-Heat Centre in Oregon, Jim Martin, John Parker, Umberto Puppini of ESI Italia, Kevin Rafferty, Randi Kalskin Ramstad of Asplan VIAK, Igor Serëdkin, Chris Underwood of Northumbria University and many more. I'd like to thank John Vaughan of Chesterfield Borough Council, Doug Chapman of Annfield Plain, Les Gibson of Grindon Camping Barn and Lionel Hehir of the Hebburn Eco-Centre for permission to use their buildings as case studies. Janet Giles was heroic in assisting with administration and printing. Lastly, Ardal O'Hanlon has unwittingly provided

me with the alter ego of *Thermoman*, which I have occasionally assumed while lecturing. While I have tried to contact all copyright holders of materials reproduced in this book, in one or two cases you have proved very elusive! If you are affected by any such omission, please do not hesitate to contact me, via Wiley, and we will do our utmost to ensure that the situation is rectified for any future editions of this book.

1

An Introduction

> 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.
© 2012 John Wiley & Sons, Ltd. Published 2012 by John Wiley & Sons, Ltd.

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.

---

[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 $\mathrm{Btu\,ft^{-1}\,°F^{-1}}$, 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 $[M][L][T]^{-2}$. Thus, work and energy have the same dimensionality $[M][L]^2[T]^{-2}$ and $1\,J = 1\,kg\,m^2\,s^{-2}$.

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

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

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 ($J\,s^{-1} = W$),
λ = thermal conductivity of the material ($W\,m^{-1}\,K^{-1}$),
A = cross-sectional area of the block of material under consideration (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 ($K\,m^{-1}$).

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.

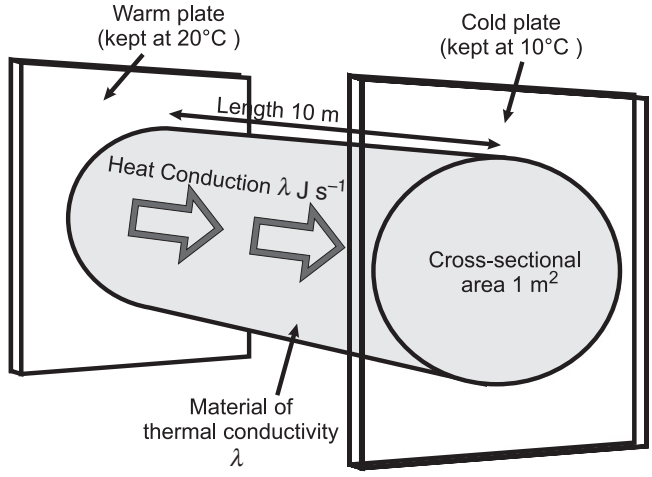

Figure 1.2 The principle of Fourier's law. Consider an insulated bar of material of cross-sectional area 1 m^2 and length 10 m. If one end is kept at 20°C and the other end at 10°C, the temperature gradient is 10 K per 10 m, or 1 $K m^{-1}$. Fourier's law predicts that heat will be conducted from the 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 $Z = -KA\frac{dh}{dx}$	Fourier's law (conduction only) $Q = -\lambda A\frac{d\theta}{dx}$
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 $s = \frac{Z}{4\pi T}W\left(\frac{r^2 S}{4Tt}\right)$	Carslaw's equation $\theta_o - \theta = \frac{q}{4\pi\lambda}W\left(\frac{r^2 S_{VC}}{4\lambda t}\right)$
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

[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 $3 \times 10^{-4}\,m\,s^{-1}$ 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 $3.1\,W\,m^{-1}\,K^{-1}$, 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.