

DAVID BANKS



# An Introduction to Thermogeology

GROUND SOURCE HEATING AND COOLING

2<sup>ND</sup> 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**

---

**2<sup>nd</sup> 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](http://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

# Contents

<i>About the Author</i>	xi
<i>Preface to the First Edition</i>	xiii
<i>Preface to the Second Edition</i>	xv
<i>Acknowledgements</i>	xvii
<b>1 An Introduction</b>	<b>1</b>
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
<b>2 Geothermal Energy</b>	<b>11</b>
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
<b>3 The Subsurface as a Heat Storage Reservoir</b>	<b>40</b>
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
<b>4</b>	<b>What Is a Heat Pump?</b>	<b>79</b>
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
<b>5</b>	<b>Heat Pumps and Thermogeology: A Brief History and International Perspective</b>	<b>114</b>
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
<b>6</b>	<b>Ground Source Cooling</b>	<b>133</b>
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
<b>7</b>	<b>Options and Applications for Ground Source Heat Pumps</b>	<b>150</b>
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
<b>8</b>	<b>The Design of Groundwater-Based Open-Loop Systems</b>	<b>202</b>
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
<b>9</b>	<b>Pipes, Pumps and the Hydraulics of Closed-Loop Systems</b>	<b>248</b>
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
<b>10</b>	<b>Subsurface Heat Conduction and the Design of Borehole-Based Closed-Loop Systems</b>	<b>279</b>
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
<b>11</b>	<b>Horizontal Closed-Loop Systems</b>	<b>325</b>
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
<b>12</b>	<b>Pond- and Lake-Based Ground Source Heat Systems</b>	<b>353</b>
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
<b>13</b>	<b>Standing Column Wells</b>	<b>372</b>
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

<b>14</b>	<b>Thinking Big: Large-Scale Heat Storage and Transfer</b>	<b>383</b>
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
<b>15</b>	<b>Thermal Response Testing</b>	<b>410</b>
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
<b>16</b>	<b>Environmental Impact, Regulation and Geohazards</b>	<b>432</b>
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
	<i>References</i>	463
	<i>Study Question Answers</i>	493
	<i>Symbols</i>	503
	<i>Glossary</i>	509
	<i>Units</i>	515
	<i>Index</i>	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