

## Principles of Igneous and Metamorphic Petrology Second Edition

This textbook provides a basic understanding of the formative processes of igneous and metamorphic rocks through quantitative applications of simple physical and chemical principles. The book encourages a deeper comprehension of the subject by explaining the petrologic principles rather than simply presenting the student with petrologic facts and terminology. Assuming knowledge of only introductory college-level courses in physics, chemistry, and calculus, it lucidly outlines mathematical derivations fully and at an elementary level, and is ideal for intermediate and advanced courses in igneous and metamorphic petrology.

The end-of-chapter quantitative problem sets facilitate student learning by working through simple applications. They also introduce several widely used thermodynamic software programs for calculating igneous and metamorphic phase equilibria and image analysis software. With over 500 illustrations, this revised edition contains valuable new material on the structure of the Earth's mantle and core, the properties and behavior of magmas, recent results from satellite imaging, and more.

ANTHONY PHILPOTTS is a visiting fellow at Yale University and an adjunct professor at the University of Massachusetts, and has had over 40 years of teaching experience. He has worked on Precambrian massif type anorthosites, pseudotachylites, alkaline rocks, liquid immiscibility in Fe–Ti oxide systems and in tholeiitic magmas. He has been awarded the Peacock Memorial Prize of the Walker Mineralogical Club of Toronto and the Hawley Award of the Mineralogical Association of Canada. He has served as an editor for the *Canadian Mineralogist* and the *Journal of the Canadian Institute of Mining and Metallurgy*.

JAY AGUE is a Professor at Yale University and has been teaching for more than 20 years. He studies fluid flow, chemical reactions, mass transfer, and heat transfer in Earth's crust, focusing on the metamorphic and igneous rocks comprising the deep roots of mountain belts. He was the Senior Editor of the *American Journal of Science* from 1998 to 2008, and has served on the editorial board of the journal *Geology*. He is also Curator of Mineralogy at the Yale Peabody Museum of Natural History.



Gray Ordovician Trenton limestone intruded by aphanitic basalt at the margin of the Cretaceous alkaline gabbro intrusion in Montreal, Quebec, Canada. The intrusion of the network of small basaltic dikes caused brittle failure of the limestone, with fragments frozen in the act of detaching from the walls to form xenoliths in the basalt. Surrounding the igneous rock is a prominent contact metamorphic halo of white marble, where hydrocarbons in the gray limestone were converted to minute crystals of graphite (black specks) in recrystallized calcite. Width of field, 8 cm.

Cambridge University Press  
978-0-521-88006-0 - Principles of Igneous and Metamorphic Petrology: Second Edition  
Anthony R. Philpotts and Jay J. Ague  
Frontmatter  
[More information](#)

---

# Principles of Igneous and Metamorphic Petrology

Second Edition

ANTHONY R. PHILPOTTS

*Yale University*

JAY J. AGUE

*Yale University*



**CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press  
978-0-521-88006-0 - Principles of Igneous and Metamorphic Petrology: Second Edition  
Anthony R. Philpotts and Jay J. Ague  
Frontmatter  
[More information](#)

CAMBRIDGE  
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University’s mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)  
Information on this title: [www.cambridge.org/9780521880060](http://www.cambridge.org/9780521880060)

© Prentice-Hall Inc., now known as Pearson Education Inc., 1990  
© A. R. Philpotts and J. J. Ague 2009

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published by Prentice-Hall Inc. 1990  
Second edition 2009  
8th printing 2015

Printed in the United Kingdom by TJ International Ltd, Padstow, Cornwall

*A catalog record for this publication is available from the British Library*

*Library of Congress Cataloging in Publication data*  
Philpotts, Anthony R. (Anthony Robert), 1938–  
Principles of igneous and metamorphic petrology / Anthony R. Philpotts, Jay J. Ague.  
p. cm.  
ISBN 978-0-521-88006-0  
1. Rocks, Igneous. 2. Rocks, Metamorphic. 3. Petrology. I. Ague, Jay J. II. Title.  
QE461.P572 2009  
552'.1–dc22

2008040943

ISBN 978-0-521-88006-0 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press  
978-0-521-88006-0 - Principles of Igneous and Metamorphic Petrology: Second Edition  
Anthony R. Philpotts and Jay J. Ague  
Frontmatter  
[More information](#)

Anthony Philpotts dedicates this book to his wife, Doreen,  
who in the meantime learned to play the piano.

Jay Ague dedicates this book to his family for making everything possible.

Cambridge University Press  
978-0-521-88006-0 - Principles of Igneous and Metamorphic Petrology: Second Edition  
Anthony R. Philpotts and Jay J. Ague  
Frontmatter  
[More information](#)

Contents

<i>Preface</i>	<i>page</i> xiii
<i>Acknowledgments</i>	xvi
<i>List of units</i>	xvii
<b>1 Introduction</b>	<b>1</b>
1.1 Petrology and its scope	1
1.2 Major structural units of the Earth	2
1.3 Pressure distribution within the Earth	4
1.4 Temperature gradients and heat flow in the lithosphere	6
1.5 Heat sources in the Earth	10
1.6 Temperatures in the lithosphere: the steady-state geotherm	11
1.7 General outline of the origin of igneous and metamorphic rocks	13
1.8 Problems	17
<b>2 Physical properties of magma</b>	<b>19</b>
2.1 Introduction	19
2.2 Magmatic temperatures	19
2.3 Magma densities	21
2.4 Magma viscosities	23
2.5 Problems	26
<b>3 Intrusion of magma</b>	<b>28</b>
3.1 Introduction	28
3.2 Buoyant rise of magma	28
3.3 Volume expansion on melting	32
3.4 Vesiculation	33
3.5 Tectonic pressure on magma	35
3.6 Intrusion rates of Newtonian magma in laminar flow	35
3.7 Flow rate of a Bingham magma	39
3.8 Intrusion rates of turbulent magma	41
3.9 Flow through a porous medium	41
3.10 Channel flow	43
3.11 Diapiric intrusion of magma	45
3.12 Factors in source affecting the supply of magma	47
3.13 Evidence of flow in rocks	48
3.14 Problems	50
<b>4 Forms of igneous bodies</b>	<b>52</b>
4.1 Introduction	52
<i>Extrusive bodies</i>	52
4.2 Flood basalts	52
4.3 Central volcanoes	59
4.4 Pyroclastic deposits and calderas	73
<i>Intrusive bodies</i>	77
4.5 General statement	77
4.6 Volcanic necks	80
	vii

viii Contents

4.7	Dikes and sills	80
4.8	Ring dikes, cone sheets, and caldron subsidence	86
4.9	Diatreme breccia pipes	89
4.10	Laccoliths	93
4.11	Lopoliths and layered intrusions	95
4.12	Stocks	99
4.13	Batholiths	101
4.14	Problems	108
5	Cooling of igneous bodies and other diffusion processes	111
5.1	Introduction	111
5.2	General theory of heat conduction	112
5.3	Heat conduction across a plane contact	113
5.4	Numerical analysis	117
5.5	Cooling by radiation	121
5.6	Diffusion	123
5.7	Problems	128
6	Classification of igneous rocks	130
6.1	Introduction	130
6.2	Mode and norm	133
6.3	CIPW norm calculation	134
6.4	MELTS program and normative minerals	136
6.5	General classification terms	137
6.6	IUGS classification of plutonic igneous rocks	137
6.7	IUGS classification of volcanic and hypabyssal rocks	139
6.8	The Irvine–Baragar classification of volcanic rocks	143
6.9	Igneous rock names	146
6.10	Chemical discriminants of rock types	147
6.11	Problems	148
7	Introduction to thermodynamics	149
7.1	Introduction	149
7.2	Energy in the form of heat and work	149
7.3	First law of thermodynamics	151
7.4	Standard heats of formation	152
7.5	Second law of thermodynamics	156
7.6	Entropy	157
7.7	Third law of thermodynamics and the measurement of entropy	158
7.8	Gibbs equation: thermodynamic potentials	159
7.9	Free energy of formation at any temperature and pressure	161
7.10	Problems	162
8	Free energy and phase equilibria	164
8.1	Introduction	164
8.2	Free energy surface in $G$ – $T$ – $P$ space	164
8.3	Plotting univariant lines in $P$ – $T$ diagrams	166
8.4	Schreinemakers rules for intersecting surfaces in $G$ – $T$ – $P$ space	168
8.5	Schreinemakers rules applied to multicomponent systems	170
8.6	Degenerate systems	176
8.7	Summary and conclusions	176
8.8	Problems	177
9	Thermodynamics of solutions	179
9.1	Introduction	179
9.2	Conservative and nonconservative components of a solution	179
9.3	Free energy of solutions	180



9.4	Free energy of ideal solutions	181
9.5	Free energy of nonideal solutions	184
9.6	Nonideal solution: the regular solution model	185
9.7	Unmixing of nonideal solutions: exsolution	187
9.8	Equilibrium constant of a reaction	189
9.9	Problems	193
10	<b>Phase equilibria in igneous systems</b>	194
10.1	Introduction	194
10.2	Two-component systems	194
10.3	Lever rule	197
10.4	Simple binary systems with no solid solution	197
10.5	Phase rule	200
10.6	Binary systems with binary compounds	201
10.7	Binary systems with liquid immiscibility	205
10.8	Complex binary systems with no solid solution	207
10.9	Binary systems with complete solid solution	208
10.10	Polymorphism in binary solid solutions	210
10.11	Binary systems exhibiting partial solid solution	211
10.12	Binary systems with liquidus passing through a minimum	212
10.13	Ternary systems	215
10.14	Simple ternary systems with congruently melting phases with no solid solution	218
10.15	Ternary systems with congruently melting binary phases	220
10.16	Ternary systems with an incongruent-melting binary phase	220
10.17	Ternary systems with liquid immiscibility	223
10.18	Ternary systems with one binary solid solution without a minimum	224
10.19	Ternary systems with one binary solid solution with a minimum	226
10.20	Ternary systems with more than one solid solution series	228
10.21	Ternary systems with binary and ternary compounds	233
10.22	Quaternary systems	233
10.23	Adiabatic phase relations	236
10.24	Computer-generated phase relations	239
10.25	Problems	240
11	<b>Effects of volatiles on melt equilibria</b>	243
11.1	Introduction: composition of volcanic gases	243
11.2	Solubility of H <sub>2</sub> O in silicate melts	244
11.3	Solubility of CO <sub>2</sub> in silicate melts	246
11.4	Solubility of sulfur in silicate melts	247
11.5	Effect of H <sub>2</sub> O on melting in silicate systems	250
11.6	Fractional crystallization of hydrous magma	254
11.7	Effect of CO <sub>2</sub> on melting in silicate systems	259
11.8	Role of oxygen fugacity in phase equilibria	261
11.9	Problems	265
12	<b>Crystal growth</b>	268
12.1	Introduction	268
12.2	Nucleation	268
12.3	Crystal growth rates	271
12.4	Crystal morphology determined by rate-determining growth processes	274
12.5	Crystal size distribution	281
12.6	Equilibrium shape of crystals	286
12.7	Surface free energy and wetting of crystals by magma	291
12.8	Problems	294

13	Isotope geochemistry related to petrology	295
13.1	Introduction	295
13.2	Radioactive decay schemes	295
13.3	Rate of radioactive decay	296
13.4	Evolution of isotopic reservoirs in the Earth	304
13.5	Stable isotopes	312
13.6	Problems	315
14	Magmatic processes	316
14.1	Introduction	316
14.2	Compositional variation in suites of volcanic rocks	317
14.3	Crystal settling in magma	321
14.4	Magma convection	323
14.5	Crystal-mush compaction	328
14.6	Igneous cumulates	332
14.7	Liquid immiscibility	340
14.8	Diffusion processes: Soret effect	345
14.9	Pneumatolitic action	346
14.10	Magmatic assimilation and assimilation and fractional crystallization (AFC)	347
14.11	Mixing of magmas	350
14.12	Trace element fractionation by magmas	356
14.13	Problems	361
15	Igneous rock associations	365
15.1	Introduction	365
15.2	Igneous rocks of oceanic regions	365
15.3	Igneous rocks associated with convergent plate boundaries	374
15.4	Continental flood basalts and large igneous provinces	380
15.5	Large layered igneous complexes	384
15.6	Continental alkaline rocks	390
15.7	Ultra-alkaline and silica-poor alkaline rocks	394
15.8	Special Precambrian associations	397
15.9	Meteorite-impact-generated rocks	405
15.10	Problems	411
16	Metamorphism and metamorphic facies	414
16.1	Introduction	414
16.2	Metamorphic volatiles	415
16.3	Metamorphic grade	417
16.4	Metamorphic facies	419
16.5	Petrogenetic grids	424
16.6	Ultrahigh-pressure and ultrahigh-temperature metamorphism	425
16.7	Problems	427
17	Deformation and textures of metamorphic rocks	428
17.1	Introduction	428
17.2	Metamorphic foliation	428
17.3	Porphyroblasts	435
17.4	Interpretation of porphyroblast–inclusion relations	436
17.5	Metamorphic textures in shear zones	440
17.6	Problems	444
18	Graphical analysis of metamorphic mineral assemblages	447
18.1	Introduction	447
18.2	Model metamorphic terrane	447

	Contents	xi
18.3	Interpretation and representation of mineral assemblages	448
18.4	Metamorphic mineral assemblages	451
18.5	Simple petrogenetic grid	452
18.6	<i>ACF</i> and <i>AKF</i> diagrams	454
18.7	Representation of solid solutions	457
18.8	Graphical representation of mineral assemblages in systems of four or more components	457
18.9	Variance in metapelitic mineral assemblages	460
18.10	Isograds in metapelitic rocks	462
18.11	Effect of <i>P</i> and <i>T</i> on reactions among solid solution phases	465
18.12	Petrogenetic grid for metapelitic rocks	467
18.13	Application: regional pressure estimation	469
18.14	Problems	470
19	Geothermometry, geobarometry, and mineral reactions among solid solutions	473
19.1	Introduction	473
19.2	Solid solutions and thermobarometry	473
19.3	Thermobarometry and multiple reactions	476
19.4	Trace element thermometry	478
19.5	Solvus thermometry	478
19.6	Oxygen isotope thermometry	479
19.7	Mineral zoning and thermobarometry	480
19.8	Introduction to pseudosections	482
19.9	Field examples	485
19.10	Problems	487
20	Mineral reactions involving H <sub>2</sub> O and CO <sub>2</sub>	490
20.1	Introduction	490
20.2	<i>P–V–T</i> behavior of fluids	490
20.3	Carbonaceous organic matter	493
20.4	Metamorphosed siliceous carbonate rocks	493
20.5	Thermodynamics of mineral reactions with H <sub>2</sub> O–CO <sub>2</sub> fluids	497
20.6	Reaction progress and fluid infiltration	504
20.7	Problems	508
21	Material transport during metamorphism	511
21.1	Introduction	511
21.2	Porosity	512
21.3	Fluid flow	514
21.4	Diffusion	517
21.5	Mechanical dispersion	518
21.6	Dissolution of minerals in supercritical H <sub>2</sub> O	519
21.7	Mass transfer mechanisms at a metamorphic isograd	521
21.8	Metasomatic zonation	522
21.9	Estimating fluid fluxes during metamorphism using geochemical fronts	525
21.10	Fluid fluxes along gradients in temperature and pressure	530
21.11	Reaction kinetics	533
21.12	Multidimensional transport and reaction	540
21.13	Determining changes in composition and volume using mass balance	550
21.14	Regional fluid transport through the crust	555
21.15	Problems	556
22	Pressure–temperature–time paths and heat transfer during metamorphism	560
22.1	Introduction	560
22.2	Preservation of metamorphic mineral assemblages	560

xii Contents

22.3	Metamorphic field gradients	562
22.4	Calculation of pressure–temperature–time paths	563
22.5	Heat advection by fluids and magmas	569
22.6	Effects of reaction	574
22.7	Observed $P$ – $T$ – $t$ paths	575
22.8	Problems	580
23	Origin of rocks	584
23.1	Introduction	584
23.2	Advective heat transfer in the Earth	585
23.3	Conditions necessary for rock generation	591
23.4	Generation and accumulation of melts	599
23.5	Composition of the source of magmas	601
23.6	Partial melting in the source region	604
23.7	Summary and conclusions	612
23.8	Problems	612
	<i>Answers to selected numerical problems</i>	615
	<i>References</i>	618
	<i>Index</i>	645

## Preface

The second edition of *Principles of Igneous and Metamorphic Petrology* follows the same general approach as the first edition. The book is designed to introduce igneous and metamorphic petrology to those who have completed introductory college-level courses in physics, chemistry, and calculus. Its emphasis is on principles and understanding rather than on facts and memorization. With this approach, it is hoped that students will not only gain a sound understanding of petrology but will develop skills that can be applied to the analysis of problems in many other fields of Earth Science.

Anthony Philpotts took many years to write the first edition of the book, and the thought of preparing a revision was daunting. He was therefore grateful when Jay Ague agreed to share the challenge of producing the revised edition. We both share the same approach to the teaching of petrology, and consequently the new edition retains the flavor of the original while benefiting from the dual authorship.

The first edition of the book was written during the 1980s (published 1990). Since then, the field of petrology has seen significant changes due to both increased knowledge of our planet and new research techniques. In preparing a book of this scope, one cannot help but reflect on the status of petrology as a field of scientific endeavor, especially in light of the trend at many universities to give only survey courses in petrology that are geared toward the environmental science student. From our perspective, the science is still growing and, indeed, the rate of growth of petrologic knowledge and new ideas appears to be increasing. In preparing the book, it was often difficult to decide where to draw the line on what new material to include and what to exclude. We are certain that many readers will find some favorite topic that we have omitted or short-changed. Our goal, however, was to cover the principles of petrology rather than to survey all of petrologic research.

How we study the Earth at both the macro and micro scales has changed dramatically since the 1980s. The whole Earth is now monitored almost continuously. Seismic networks track the motion of tectonic plates while tomography reveals the temperature distributions at depth. Satellites provide almost daily information about surface temperatures, composition of the atmosphere, and minor changes in elevation, which can be used, for example, to forecast volcanic eruptions, even in remote areas. At the other end of the scale, microanalytical techniques now provide isotopic and chemical analyses with micron or even submicron resolution. This has revolutionized the absolute dating of zoned crystals, and chemical gradients in crystals can now be used to investigate the kinetics of petrologic processes. Computers continue to change dramatically the way we investigate rocks. They have made it possible to access petrologic and thermodynamic databases and to use them to solve petrologic problems. The MELTS program, for example, allows one to appreciate an igneous rock in a way that was never previously possible. Similarly, programs such as THERMOCALC allow us to investigate the complexities of possible metamorphic reactions. No longer is a petrographic microscope the only way of examining rocks microscopically. Now, high-resolution images can be used with image analysis software to extract quantitative data about the textures of rocks.

An enormous amount of petrologic information is now available on the Web. At the end of this preface there is a list of web sites of general petrologic interest. Web sites referring to specific topics are given in the text.

As with the first edition, the book is arranged so that it can be used in a two-semester course, or a one-semester course on either igneous or metamorphic petrology. Although it covers both igneous and metamorphic petrology, the contents of chapters allow the text to

be used for courses dealing with either of these groups of rocks separately. Such a division, however, is somewhat arbitrary because the principles involved in the formation of these rocks are so similar. Moreover, in the upper mantle, where many petrologic processes have their origins, igneous and metamorphic processes are so interdependent that one cannot be treated without the other. If the book is used for just one of these groups of rocks, cross-references will lead the reader to relevant material covered elsewhere in the text.

The order in which topics are presented in the new edition is essentially the same as in the first, except that diffusion is now treated in Chapter 5 along with heat flow and the chapter on isotopes has been moved from its penultimate position to the middle of the text. The new edition also contains many more illustrations of field relations and photomicrographs, all of which are available in color on the text's web site ([www.cambridge.org/philpotts](http://www.cambridge.org/philpotts)). However, no attempt was made to present a comprehensive treatment of petrography. A companion book, *Petrography of Igneous and Metamorphic Rocks* by A. R. Philpotts ([www.waveland.com/Titles/Philpotts.htm](http://www.waveland.com/Titles/Philpotts.htm)), gives the optical properties of all the common rock-forming minerals and the textures of igneous and metamorphic rocks, illustrated in color on a CD-ROM accompanying that book.

As with the first edition, the end-of-chapter problems are an important part of the new edition. Considerable effort has gone into making the problems as instructive as possible. We believe that if users of the book learn as much about petrology in answering the problems as the authors did in creating them, they will be richly rewarded. The book, however, can be used without problems. We would recommend doing as many problems as possible. From our experience, students who have an aversion to mathematics may actually start to enjoy the subject when given the chance to apply it to geological problems. Deserving of special recognition are the students who, over the years, have struggled with these problems; their efforts have allowed us to clarify many of the questions.

#### Web sites of general petrologic interest

Early history (1565–1835) of ideas on volcanoes, basalt, and geologic time:  
[www.lhl.lib.mo.us/events\\_exhib/exhibit/exhibits/vulcan/index.shtml](http://www.lhl.lib.mo.us/events_exhib/exhibit/exhibits/vulcan/index.shtml)

NASA Earth Observatory: [www.visibleearth.nasa.gov](http://www.visibleearth.nasa.gov)

World map of volcanoes, earthquakes, impact craters, and plate tectonics:  
[www.minerals.si.edu/tdpmap](http://www.minerals.si.edu/tdpmap)

Earthquakes, near-real time display of earthquakes worldwide: [www.iris.edu/seismon](http://www.iris.edu/seismon)

Heat flow from Earth: [www.geo.lsa.umich.edu/IHFC](http://www.geo.lsa.umich.edu/IHFC)

#### *Mineral data*

Mineralogical Society of America: [www.minsocam.org](http://www.minsocam.org)

Material Properties at High Pressure: [www.compres.us](http://www.compres.us)

Pegmatites: [www.minsocam.org/msa/special/Pig](http://www.minsocam.org/msa/special/Pig)

#### *Volcanoes*

Smithsonian Institution Global Volcanism Program: [www.volcano.si.edu](http://www.volcano.si.edu)

Smithsonian's list of volcanoes as an overlay on Google Earth:  
[www.volcano.si.edu/world/globalists.cfm?listpage=googleearth](http://www.volcano.si.edu/world/globalists.cfm?listpage=googleearth)

Volcano textbook by Robert I. Tilling: <http://pubs.usgs.gov/gip/volc>

Volcanoworld: <http://volcano.und.edu>

#### *Volcano hazards*

U.S. Geological Survey: [www.usgs.gov/hazards/volcanoes](http://www.usgs.gov/hazards/volcanoes)  
<http://volcanoes.usgs.gov>

Thermal map of Earth: <http://modis.higp.hawaii.edu>

SO<sub>2</sub> map of Earth: <http://aura.gsfc.nasa.gov>

*Image analysis*  
NIH Image: <http://rsb.info.nih.gov/ij>  
USGS CIPW norm: [http://volcanoes.usgs.gov/staff/jlowenstern/other/software\\_jbl.html](http://volcanoes.usgs.gov/staff/jlowenstern/other/software_jbl.html)

*Thermodynamic calculations and phase equilibria*  
MELTS: <http://melts.ofm-research.org>  
THERMOCALC: [www.earthsci.unimelb.edu.au/tpg/thermocalc](http://www.earthsci.unimelb.edu.au/tpg/thermocalc)  
winTWQ: [http://gsc.nrcan.gc.ca/sw/twq\\_e.php](http://gsc.nrcan.gc.ca/sw/twq_e.php)  
Phase equilibria: <http://ees2.geo.rpi.edu/MetaPetaRen/Software/Software.html>  
[http://serc.carlton.edu/research\\_education/equilibria/index.html](http://serc.carlton.edu/research_education/equilibria/index.html)  
<http://titan.minpet.unibas.ch/minpet/theriak/theruser.html>

## Acknowledgments

We would like to thank the many users of the first edition of the book who convinced us to prepare a second edition. Without their encouragement, it would not have happened. We would also like to express our gratitude to Cambridge University Press who suggested that they publish the second edition. It has been a pleasure working with a publisher who has not requested that the mathematics be removed from our presentation to make it more palatable.

We cannot possibly acknowledge all of the colleagues who have played important roles in developing our interests in petrology and who have contributed in so many ways to completing this textbook. Anthony Philpotts owes a special debt of gratitude to the following professors who influenced him early in his career: E. H. Kranck of McGill University, and C. E. Tilley, W. A. Deer, I. D. Muir, S. R. Nockolds, and S. O. Agrell of the University of Cambridge.

Jay Ague would like to thank his Ph.D. advisor G. H. Brimhall (U.C. Berkeley), his M.S. thesis advisor A. P. Morris (Wayne State University), and his undergraduate advisor S. J. Birnbaum (also at Wayne), for their tireless and inspirational mentoring. Faculty colleagues at Yale have been a constant wellspring of scientific ideas and support, and Ague would especially like to acknowledge D. M. Rye, B. J. Skinner, M. T. Brandon, J. J. Park, and K. K. Turekian in this regard. Discussions and collaborations with research scientists J. O. Eckert and E. W. Bolton are also much appreciated. Numerous undergraduates, graduate students, and post docs have contributed in countless ways to the material presented in this book, including E. F. Baxter, C. M. Breeding, C. J. Carson, R. L. Masters, J. L. M. van Haren, and D. E. Wilbur. In addition, students C. E. Bucholz, X. Du, T. V. Lyubetskaya, and S. H. Vorhies read draft chapters and made numerous suggestions for improvement. R. W. White (Mainz) provided valuable help with THERMOCALC. Finally, Ague would like to gratefully acknowledge the National Science Foundation, the Department of Energy, and Yale University for research support.

We would both like to thank our families who have been totally neglected while we prepared this edition. Without their support, the second edition of *Principles of Igneous and Metamorphic Petrology* would never have been completed.



List of units

Basic Units

This text uses units of the <i>Système International</i> (SI). The basic units are		
Length		meter (m)
Mass		kilogram (kg)
Time		seconds (s)
Temperature		kelvin (K)

Prefixes

For convenience these units can be preceded by the following prefixes:		
pico (p)	$10^{-12}$	
nano (n)	$10^{-9}$	
micro ( $\mu$ )	$10^{-6}$	
milli (m)	$10^{-3}$	
kilo (k)	$10^3$	
mega (M)	$10^6$	
giga (G)	$10^9$	
tera (T)	$10^{12}$	

Derived Units

Quantity	Unit	Equivalent
Force	newton (N)	$\text{kg m s}^{-2}$
Pressure	pascal (Pa)	$\text{N m}^{-2}$
Energy	joule (J)	N m
	joule (J)	$\text{Pa m}^3$
Power	watt (W)	$\text{J s}^{-1}$
Viscosity		Pa s
Kinematic viscosity		$\text{m}^2 \text{s}^{-1}$

Other Common Units		
Length	centimeter (cm)	$10^{-2}$ m
	angstrom (Å)	10 nm
Mass	gram (g)	$10^{-3}$ kg
Force	dyne	$\text{g cm s}^{-2}$
Heat Flow Unit (HFU)		$10^{-6}$ cal $\text{cm}^2 \text{s}^{-1}$
		41.84 mW $\text{m}^{-2}$
Heat Generation Unit (HGU)		$10^{-13}$ cal $\text{cm}^{-3} \text{s}^{-1}$
		0.4184 $\mu\text{W m}^{-3}$
Pressure	bar (b)	$10^6 \text{dyne cm}^{-2}$ ( $10^5$ Pa)
	atmosphere (atm)	1.013 25 bar ( $\sim 10^5$ Pa)
Energy	calorie (cal)	4.184 J
Parts per million (ppm)		kg/ $10^6$ kg

Commonly Used Constants		
Gas constant	( <i>R</i> )	8.3144 J $\text{mol}^{-1} \text{K}^{-1}$ (1.9872 cal $\text{mol}^{-1} \text{K}^{-1}$ )
Avogadro’s number	( <i>N</i> <sub>0</sub> )	$6.022 \times 10^{23} \text{mol}^{-1}$
Stefan–Boltzmann constant	( <i>σ</i> )	$5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4}$
Boltzmann’s constant	( <i>k</i> )	$1.3806 \times 10^{-23} \text{J K}^{-1}$
Acceleration of gravity at Earth’s surface		$\sim 9.8 \text{m s}^{-2}$