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.

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Anthony R. Philpotts and Jay J. Ague
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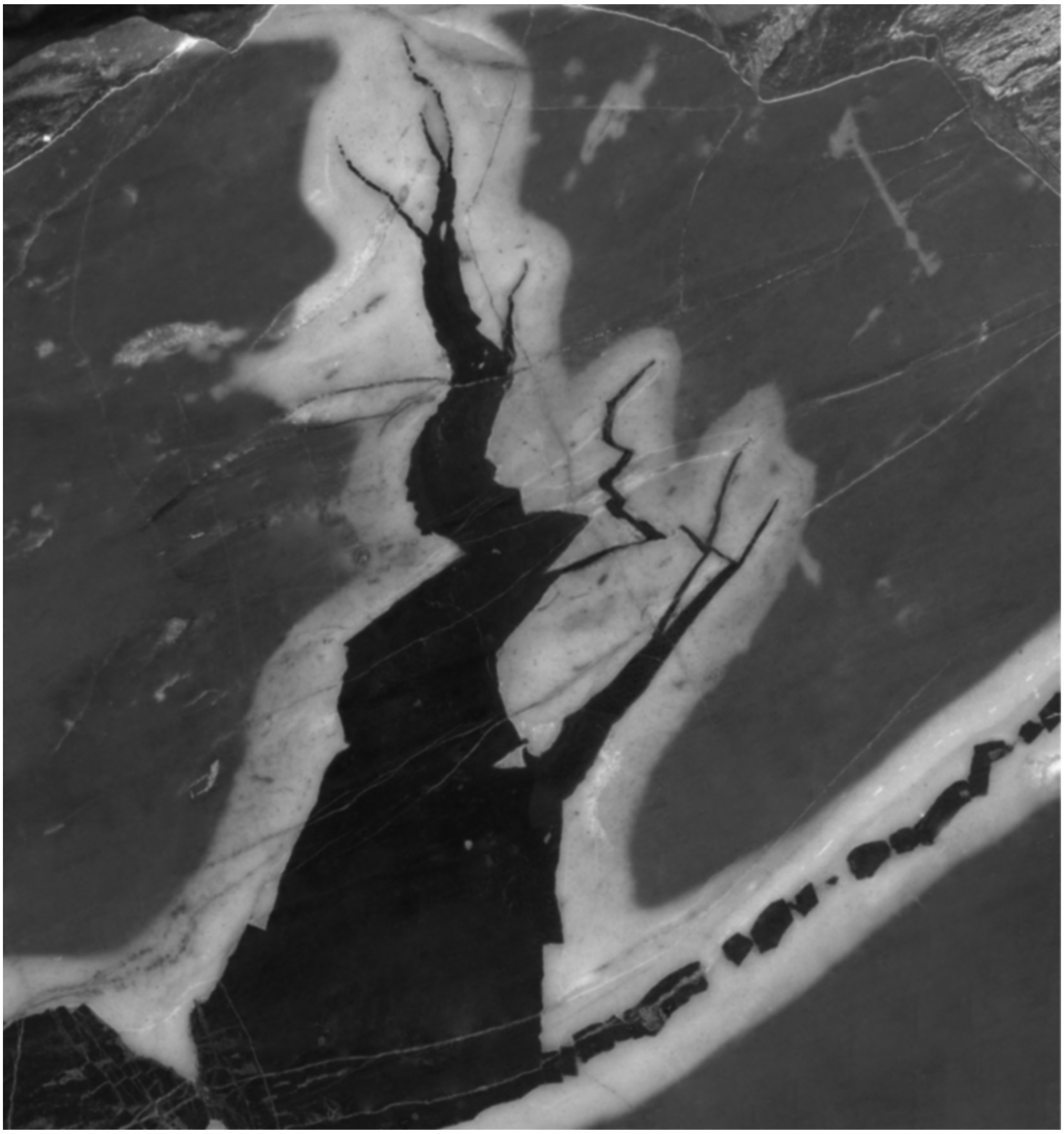

Gray Ordovician Trenton limestone intruded by aphanitic basalt at the margin of the Cretaceous alkaline gabbro intrusion in Montreal, Quebec, Canada. The intrusion of the network of small basaltic dikes caused brittle failure of the limestone, with fragments frozen in the act of detaching from the walls 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.

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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.

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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). 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), 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

NASA Earth Observatory: www.visibleearth.nasa.gov

World map of volcanoes, earthquakes, impact craters, and plate tectonics:
www.minerals.si.edu/tdpmap

Earthquakes, near-real time display of earthquakes worldwide: www.iris.edu/seismon
Heat flow from Earth: www.geo.lsa.umich.edu/IHFC

Mineral data

Mineralogical Society of America: www.minsocam.org

Material Properties at High Pressure: www.compres.us

Pegmatites: www.minsocam.org/msa/special/Pig

Volcanoes

Smithsonian Institution Global Volcanism Program: www.volcano.si.edu

Smithsonian's list of volcanoes as an overlay on Google Earth:
www.volcano.si.edu/world/globallists.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://volcanoes.usgs.gov

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

SO_2 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

Thermodynamic calculations and phase equilibria

MELTS: http://melts.ofm-research.org

THERMOCALC: www.earthsci.unimelb.edu.au/tpg/thermocalc

winTWQ: 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://titan.minpet.unibas.ch/minpet/theriak/theruser.html

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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.

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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 *Système International* (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 (μ)	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)	kg m s^{-2}
Pressure	pascal (Pa)	N m^{-2}
Energy	joule (J)	N m
	joule (J)	Pa m^3
Power	watt (W)	J s^{-1}
Viscosity		Pa s
Kinematic viscosity		m^2 s^{-1}

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

Commonly Used Constants		
Gas constant	(R)	8.3144 J mol^{-1} K^{-1} (1.9872 cal mol^{-1} K^{-1})
Avogadro's number	(N_0)	6.022×10^{23} mol^{-1}
Stefan–Boltzmann constant	(σ)	5.67×10^{-8} W m^{-2} K^{-4}
Boltzmann's constant	(k)	1.3806×10^{-23} J K^{-1}
Acceleration of gravity at Earth's surface		~9.8 m s^{-2}