Principles of Igneous and Metamorphic Petrology
Third Edition

Building upon the award-winning second edition, this comprehensive textbook provides a fundamental understanding of the formative processes of igneous and metamorphic rocks. Encouraging a deeper comprehension of the subject by explaining the petrologic principles, and assuming knowledge of only introductory college-level courses in physics, chemistry, and calculus, it lucidly outlines mathematical derivations fully and at an elementary level, making this the ideal resource for intermediate and advanced courses in igneous and metamorphic petrology. With over 500 illustrations, many in color, this revised edition contains valuable new material and strengthened pedagogy, including boxed mathematical derivations allowing for a more accessible explanation of concepts, and more qualitative end-of-chapter questions to encourage discussion. With a new introductory chapter outlining the "bigger picture," this fully updated resource will guide students to an even greater mastery of petrology.

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From reviews of previous editions:

"The real quality of this book lies in its authoritative character and depth of coverage ... a volume which will likely be well thumbed and littered with 'stickies' and other place markers by students and professors alike ... one of the excellent aspects of the book is the clever integration of different aspects of petrology ... a 'must-have' for any self-respecting petrologist."

Jon Davidson, *Elements*

"I will choose the second edition of Philpotts and Ague's *Principles of Igneous and Metamorphic Petrology* because of its forward-looking coverage."

John M. Ferry, *American Journal of Science*

"This is a book to read and a book to keep as a reference. It is a must-have for every student of tectonics."

Michael L. Williams, *EOS*

From reviews of this third edition:

"The third edition of *Principles of Igneous and Metamorphic Petrology* follows in the footsteps of its previous editions. It not only covers the fundamentals of igneous and metamorphic petrology, but delves into many petrological aspects in great detail and thoroughness. The authors are to be commended on their outstanding quantitative treatment of petrological processes, supported by explanatory boxes of mathematical formulations. Clearly structured and richly illustrated with field and thin section photographs as well as sketches and diagrams, the book provides a comprehensive resource for those keen on acquiring an in-depth understanding of igneous and metamorphic processes."

Ralf Halama, Keele University

"This third edition of Philpotts and Ague builds upon an excellent record of textbooks focusing on igneous and metamorphic petrology. The book is comprehensive in its coverage of the processes involved in the petrogenesis of igneous and metamorphic rocks and the implications of these processes, is well illustrated with excellent diagrams and images throughout, and will be useful for a range of geoscientists from upper-level undergraduate students to graduate students and faculty, for both teaching and research. This edition is well supplemented by online resources that are ideally suited for teaching, including all of the figures in the textbook in digital format and a solutions manual for instructors. Overall, I highly recommend this book and strongly suspect well-thumbed versions will end up on the shelves of many geologists worldwide."

Simon Jowitt, University of Nevada

"The third edition of *Principles of Igneous and Metamorphic Petrology* is a detailed and well-illustrated textbook that lays out analytical petrologic methods in a clear, comprehensive manner. Extensive examples are given throughout to thoroughly elucidate complex topics and mathematical formulations. One standout feature that sets this textbook apart from others is the end-of-chapter questions. These questions are divided into quantitative and broad topics, facilitating multiple levels of student mastery and allowing for the text to be used at both the undergraduate and graduate levels. Much as I still regularly consult my copy of the first edition of this book, many years after using it as an undergraduate, the third edition ... should be a mainstay of every petrology student's bookshelf."

Molly McCanta, University of Tennessee

"This is the definitive textbook on igneous and metamorphic petrology. Philpotts and Ague have found the perfect balance between ensuring that the content is accessible to students while avoiding oversimplification. I will continue to use this textbook in my online and campus courses."

Alasdair Skelton, Stockholm University

Principles of Igneous and Metamorphic Petrology

Third Edition

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Additional resources for this publication at www.cambridge.org/philpotts3

Anthony Philpotts dedicates the third edition of this book to his wife, Doreen, who provided such a beautiful *five-foot-two* (1.57 m) scale for so many of its photographs and provided life support while he became a hermit for three years working on the book. Her piano playing improved significantly during this period.

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

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Preface

Principles of Igneous and Metamorphic Petrology is now in its third edition. The authors undertook this revision because of the positive response that the earlier two editions received. Anthony Philpotts took many years to write the first edition (1990) and was only too pleased when Jay Ague agreed to coauthor the second edition (2009). We share the same approach to the teaching of petrology, and consequently the partnership has worked well.

The third edition follows the same general approach as the first two editions. The book is designed to introduce igneous and metamorphic petrology to those who have completed introductory college-level courses in geology, mineralogy, 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 also develop skills that can be applied to problems in many other fields of earth science.

The book's main focus is on the principles of petrology. These have not changed significantly since publication of the second edition, but their application has grown substantially, especially as a result of technological advances at both the macro- and microscales. Seismic networks track the motion of tectonic plates while tomography reveals the temperature distributions at depth in the Earth. 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 such as zircon, and chemical gradients in crystals are now being used to investigate the kinetics of petrologic processes. Computers continue to change dramatically the way in which we investigate rocks. Thermodynamic databases have been improved, and programs such as MELTS for determining the crystallization of magmas and THERMOCALC for analyzing metamorphic reactions have been calibrated so as to be more accurate over a wider range of conditions. Even the standard petrographic polarizing microscope, which is a rather expensive item, is now available for free to download in a virtual form from the Internet. An enormous amount of other petrologic information is available online, a list of some of which is given at the end of this preface. Web sites referring to specific topics are also given in the text.

In preparing a book, authors are continually pressured by editors to restrict its length, and decisions have to be made on what new material to include or exclude. Readers will undoubtedly find some favorite topic that we have omitted or short-changed in the third edition. Our goal, however, was to cover the principles of petrology rather than survey recent petrologic research. Hopefully, these principles will provide the tools with which to appreciate the omitted material.

New to the third edition are illustrations in color. So many geological features, both in the field and in the laboratory, cannot be illustrated properly without color – a petrographic thin section under crossed polarized light or a chemical map of minerals in an electron microprobe image are good examples. New color photographs of outcrops, hand samples, photomicrographs, and electron microprobe chemical maps have been added to illustrate key petrological concepts. All figures are also available in color on the book's web site (www.cambridge.org/philpotts3).

Another new feature is the boxing of some mathematical derivations. In the previous editions, derivations were interwoven with the text. In some cases this resulted in unfortunate, lengthy separations of the introduction of a topic from its conclusion. We still believe these derivations are important, because they indicate the assumptions and boundary conditions involved and illustrate how we tackle geologic problems quantitatively. By placing lengthy derivations in boxes, concepts can be more quickly and clearly expressed while still preserving the derivation. This may also appeal to readers who are less mathematically inclined. The chapters dealing with thermodynamics are, by the nature of the subject, mathematical, and in these chapters most derivations remain interwoven with the text. A number of these derivations have, however, been modified in an effort to make them accessible to a broader audience.

In the previous editions, sets of quantitative questions were given at the end of each chapter. In the new edition these have been supplemented with qualitative questions that provide readers with the opportunity to review and discuss important concepts in the chapter.

The third edition contains a new introductory chapter. A number of professors who used the previous editions in their courses suggested that their students should start by reading the final chapter because of its all-encompassing view of igneous and metamorphic petrology. Because this chapter drew on all the previous material in the book, this initiation to petrology may have been somewhat daunting. Consequently, the new introductory chapter attempts to give the broad picture of what petrology tells us about the Earth, but at a level geared to readers with only an introductory geology background.

At many places in the book mineral names have been abbreviated, as for example in writing reactions and labeling phase diagrams. We have used the recommended abbreviations of Whitney and Evans (2010), unless otherwise noted. A list of these abbreviations is given following the Preface, along with a list of common units and constants.

As with the earlier editions, the new book is arranged so that it can be used in either a one- or two-semester course. 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 very 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 lead the reader to relevant material covered elsewhere in the text. Most petrology courses involve a laboratory component in which rocks are studied under the microscope. Although this book contains many petrographic illustrations, 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 common rock-forming minerals and the textures of igneous and metamorphic rocks, all of which are illustrated in color on a CD-ROM accompanying that book.

Websites of General Petrologic Interest

GeoMapApp is a map-based application for browsing, visualizing, and analyzing a diverse suite of global and regional geoscience data sets covering geophysics, geology, geochemistry, physical oceanography, and climatology (Ryan *et al*. 2009): www.geomapapp.org/index.htm.

NASA Visible Earth is a catalogue of NASA images and animations of planet Earth: https://visibleearth.nasa.gov/.

Earthquakes: a near-real-time display of earthquakes worldwide can be found at: http://ds.iris.edu/seismon/index.phtml

The International Heat Flow Commission presents a map showing heat flow and tectonic plate boundaries: www.geophysik.rwth-aachen.de/IHFC/heatflow.html

Volcanoes:

- The Smithsonian Institution Global Volcanism Program: www.naturalhistory.si.edu/research/mineral-sciences
- The Smithsonian's list of volcanoes as an overlay on Google Earth: https://volcano.si.edu/learn_resources.cfm?p=3
- US Geological Survey's volcano hazards: https://www.usgs.gov/products/data-and-tools/real-time-data/volcanoes

A thermal map of Earth, based on data from an infrared satellite which monitors in essentially real time (<2 hours), shows Earth's surface thermal emissions from volcanic eruptions, wildfires, and anthropogenic heat sources: http://modis.higp.hawaii.edu

Aura: atmospheric chemistry from NASA: https://aura.gsfc.nasa.gov/science/index.html

Mineral data from the Mineralogical Society of America: www.minsocam.org

Acknowledgments

We would like to thank the many users of the earlier editions of the book who convinced us to prepare a third 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 a third edition that would include color illustrations.

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. He benefited immensely from coauthoring a book with Cornelis (Kees) Klein titled *Earth Materials* (Cambridge University Press 2012). He would like to thank Grant Cawthorn of the University of the Witwatersrand for carefully reading some of his writing and supplying valuable photographs of the Bushveld Intrusion. He would also like to thank Jean Bédard, Alan Boudreau, Murray Duke, Marian Holness, Sigurjón Jónsson, Peter Kelemen, Brian O'Driscoll, Matej Pec, Mary Rooden-Tice, Aryeh Shimron, Nicholas Tailby, Christian Tegner, Karen Von Damm, Colin Wilkins, Richard Wilson, Tim Wright, and James Zollweg, who all kindly contributed excellent photographs. And finally he would like to thank all of his students over the years, who in a way helped to form how this book presents petrology.

Jay Ague would like to thank his PhD advisor, G. H Brimhall (U.C. Berkeley), his MS 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 he would especially like to acknowledge D. Bercovici, M. T. Brandon, D. A. D. Evans, J. J. Park, N. J. Planavsky, D. M. Rye, B. J. Skinner, and K. K. Turekian in this regard. Discussions and collaborations with research scientists J. O. Eckert, Jr., and E. W. Bolton and Yale Peabody Museum Collection Manager S. Nicolescu are also greatly appreciated. He is deeply grateful to all the undergraduates, graduate students, postdoctoral fellows, and visiting scholars who have contributed in countless ways to the material presented in this book, including J. A. Axler, E. F. Baxter, C. E. Bucholz, C. M. Breeding, C. J. Carson, X. Chu, C. A. Cooke, E. L. Donald, L. Dunnington, D. A. D. Evans, S. Emmanuel, A. A. Haws, B. L. Hess, M. E. Holycross, D. S. Keller, T. Kuhn, J.-L. Li, T. V. Lyubetskaya, R. L. Masters, F. Piccoli, E. M. Stewart, S. Tasara, M. Tian, J. L. M. van Haren, S. H. Vorhies, D. E. Wilbur, and D. C. Wyatt. He sincerely appreciated a sabbatical visit to Curtin University arranged and hosted by A. Putnis, during which time a substantial portion of this edition was written. J. M. Ferry made valuable suggestions for figures, and S. C. Penniston-Dorland alerted us to an error in a table. J. M. Rahl generously granted permission to use an excellent field photograph. H. Moritz took the beautiful photographs of metamorphic hand specimens in Figures 17.4, 17.14, and 18.22. R. W. White (University of St. Andrews) provided valuable help with THERMOCALC. Finally, Ague would like to gratefully acknowledge the National Science Foundation, the Department of Energy, the Deep Carbon Observatory, the American Chemical Society, 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 third edition of *Principles of Igneous and Metamorphic Petrology* would never have been completed.

Units

Basic Units	
This text uses units of the Système International (SI). The basic units are:	
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)

Prefixes	
For convenience the basic 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^{-1} 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)	$10^{-13}\ cal\ cm^{-3}\ s^{-1}$
		$0.4184\ \mu W\ m^{-3}$
Pressure	bar (b)	$10^{6}\ dyne\ cm^{-2}$ (10^{5} Pa)
	atmosphere (atm)	1.01325 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 constant	(k)	1.3806 × 10^{-23} J K^{-1}
Acceleration due to gravity at Earth's surface	(g)	~9.8 m s^{-2}

Mineral Abbreviations

This is the list of common minerals and their abbreviations accepted by the International Mineralogical Association (after Whitney & Evans 2010). Where possible, these have been used throughout the book. Formulas and thermodynamic data of the most important minerals are given in Table 8.1.

Mineral name	Abbr.	Mineral name	Abbr.
Actinolite	Act	Chromite	Chr
Aegirine	Aeg	Chrysotile	Ctl
Åkermanite	Ak	Clinoamphibole	Cam
Albite	Ab	Clinochlore	Clc
Alkali feldspar	Afs	Clinoenstatite	Cen
Allanite	Aln	Clinoferrosilite	Cfs
Almandine	Alm	Clinopyroxene	Cpx
Aluminosilicate		Clinozoisite	Czo
Al_2SiO_5 polymorphs	Als	Coesite	Coe
Amphibole	Amp	Cordierite	Crd
Analcime (analcite)	Anl	Corundum	Crn
Anatase	Ant	Covellite	Cv
Andalusite	And	Cristobalite	Crs
Andradite	Adr	Crossite	Crt
Anhydrite	Anh	Cubanite	Cbn
Ankerite	Ank	Cummingtonite	Cum
Annite	Ann	Cuprite	Ppr
Anorthite	An	Datolite	Dat
Anorthoclase	Ano	Diamond	Dia
Anthophyllite	Ath	Diaspore	Dsp
Antigorite	Atg	Diopside	Di
Apatite	Ap	Dolomite	Dol
Apophyllite	Apo	Dravite	Drv
Aragonite	Arg	Edenite	Ed
Arfvedsonite	Arf	Enstatite	En
Arsenopyrite	Apy	Epidote	Ep
Augite	Aug	Eudialite	Eud
Awaruite	Awr	Fayalite	Fa
Axinite	Ax	Feldspar	Fsp
Barite	Brt	Ferrosilite	Fs
Beryl	Brl	Fluorite	Fl
Biotite	Bt	Forsterite	Fo
Bornite	Bn	Galena	Gn
Brookite	Brk	Garnet	Grt
Brucite	Brc	Gedrite	Ged
Bustamite	Bst	Gehlenite	Gh
Calcite	Cal	Gibbsite	Gbs
Cancrinite	Ccn	Glaucophane	Gln
Carbonate	Cb	Goethite	Gth
Cassiterite	Cst	Graphite	Gr
Celadonite	Cel	Grossular	Grs
Celsian	Cls	Grunerite	Gru
Chabazite	Cbz	Gypsum	Gp
Chalcocite	Cct	Halite	Hl
Chalcopyrite	Ccp	Hastingsite	Hst
Chamosite	Chm	Haüyne	Hyn
Chlorite	Chl	Hedenbergite	Hd
Chloritoid	Cld	Hematite	Hem

Mineral name	Abbr.	Mineral name	Abbr.
Hercynite	Hc	Pentalndite	Pn
Heulandite	Hul	Periclase	Per
Hornblende	Hbl	Perovskite	Prv
Hypersthene	Hyp	Phengite	Ph
Illite	Ilt	Phillipsite	Php
Ilmenite	Ilm	Phlogopite	Phl
Jadeite	Jd	Piemontite	Pmt
Kaersutite	Krs	Pigeonite	Pgt
Kalsilite	Kls	Plagioclase	Pl
Kaolinite	Kln	Prehnite	Prh
K-feldspar	Kfs	Pseudobrookite	Psb
Kornerupine	Krn	Pumpellyite	Pmp
Kyanite	Ky	Pyrite	Py
Larnite	Lrn	Pyrochlore	Pcl
Laumontite	Lmt	Pyrope	Prp
Lawsonite	Lws	Pyrophyllite	Prl
Lepidolite	Lpd	Pyrrhotite	Po
Leucite	Lct	Quartz	Qz
Limonite	Lm	Rankinite	Rnk
Magnesite	Mgs	Rhodochrosite	Rds
Magnetite	Mag	Rhodonite	Rdn
Majorite	Maj	Richterite	Rct
Malachite	Mlc	Riebeckite	Rbk
Marcasite	Mrc	Ringwoodite	Rwd
Margarite	Mrg	Rutile	Rt
Melilite	Mll	Sanidine	Sa
Merwinite	Mw	Sapphirine	Spr
Microcline	Mc	Scapolite	Scp
Molybdenite	Mol	Scheelite	Sch
Monazite	Mnz	Schorl	Srl
Monticellite	Mtc	Sericite	Ser
Montmorillonite	Mnt	Serpentine	Srp
Mullite	Mul	Siderite	Sd
Muscovite	Ms	Sillimanite	Sil
Natrolite	Ntr	Sodalite	Sdl
Nepheline	Nph	Spessartine	Sps
Nosean	Nsn	Sphalerite	Sp
Olivine	Ol	Sphene (now titanite)	Spn
Omphacite	Omp	Spinel	Spl
Opal	Opl	Spodumene	Spd
Opaque mineral	Opq	Spurrite	Spu
Orthoamphibole	Oam	Staurolite	St
Orthoclase	Or1	Stilpnomelane	Stp
Orthoenstatite	Oen	Stishovite	Sti
Orthopyroxene	Opx	Talc	Tlc
Osumilite	Osm	Tephroite	Tep
Paragonite	Pg	Thomsonite	Thm
Pargasite	Prg	Tilleyite	Tly

Mineral name	Abbr.	Mineral name	Abbr.
Titanite	Ttn	Troilite	Tro
Topaz	Tpz	Tschermakite	Ts
Tourmaline	Tur	Ulvöspinel	Usp
Tremolite	Tr	Uraninite	Urn
Tridymite	Trd	Uvarovite	Uv

Mineral name	Abbr.	Mineral name	Abbr.
Vermiculite	Vrm	Wüstite	Wu
Vesuvianite	Ves	Xenotime	Xtm
Wadsleyite	Wds	Zeolite	Zeo
Wairakite	Wrk	Zircon	Zrn
Wollastonite	Wo	Zoisite	Zo