

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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CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

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

Information on this title: www.cambridge.org/highereducation/isbn/9781108492881

DOI: 10.1017/9781108631419

First edition © Prentice-Hall Inc., now known as Pearson Education Inc., 1990

Second edition © A. R. Philpotts and J. J. Ague 2009

Third edition © Anthony R. Philpotts and Jay J. Ague 2022

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First published by Prentice-Hall Inc. 1990

Second edition by Cambridge University Press 2009

Ninth printing 2016

Third edition 2022

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall 2022

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

Library of Congress Cataloging-in-Publication Data

Names: Philpotts, Anthony R. (Anthony Robert), 1938– author. | Ague, Jay J., author.

Title: Principles of igneous and metamorphic petrology / Anthony R. Philpotts, Jay J. Ague.

Description: [Third edition]. | Cambridge, UK ; New York : Cambridge

University Press, 2021. | Includes bibliographical references and index.

Identifiers: LCCN 2021024672 (print) | LCCN 2021024673 (ebook) | ISBN

9781108492881 (hardback) | ISBN 9781108631419 (ebook)

Subjects: LCSH: Igneous rocks. | Metamorphic rocks. | Petrology. | BISAC:

SCIENCE / Earth Sciences / General | SCIENCE / Earth Sciences / General

Classification: LCC QE461 .P572 2021 (print) | LCC QE461 (ebook) | DDC

552/.1–dc23

LC record available at <https://lcn.loc.gov/2021024672>

LC ebook record available at <https://lcn.loc.gov/2021024673>

ISBN 978-1-108-49288-1 Hardback

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

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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.

Cambridge University Press
978-1-108-49288-1 — Principles of Igneous and Metamorphic Petrology
Anthony R. Philpotts , Jay J. Ague
Frontmatter
[More Information](#)

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Cambridge University Press
978-1-108-49288-1 — Principles of Igneous and Metamorphic Petrology
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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.geomapp.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		$\text{m}^2 \text{s}^{-1}$

Other Common Units

Length	centimeter (cm)	10^{-2} m
	angstrom (\AA)	10^{-1} nm
Mass	gram (g)	10^{-3} kg
Force	dyne	g cm s^{-2}
Heat Flow Unit	(HFU)	10^{-6} cal $\text{cm}^2 \text{s}^{-1}$
		41.84 mW 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 dyne cm^{-2} (10^5 Pa)
	atmosphere (atm)	1.01325 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 mol ⁻¹ K ⁻¹ (1.9872 cal mol ⁻¹ K ⁻¹)
Avogadro's number	(<i>N</i> ₀)	6.022 × 10 ²³ mol ⁻¹
Stefan–Boltzmann constant	(<i>σ</i>)	5.67 × 10 ⁻⁸ W m ⁻² K ⁻⁴
Boltzmann constant	(<i>k</i>)	1.3806 × 10 ⁻²³ J K ⁻¹
Acceleration due to gravity at Earth's surface	(<i>g</i>)	~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.	Mineral name	Abbr.	Mineral name	Abbr.
Actinolite	Act	Chromite	Chr	Hercynite	Hc	Pentalndite	Pn
Aegirine	Aeg	Chrysotile	Ctl	Heulandite	Hul	Periclase	Per
Åkermanite	Ak	Clinoamphibole	Cam	Hornblende	Hbl	Perovskite	Prv
Albite	Ab	Clinochlore	Clc	Hypersthene	Hyp	Phengite	Ph
Alkali feldspar	Afs	Clinoenstatite	Cen	Illite	Ilt	Phillipsite	Php
Allanite	Aln	Clinoferrosilite	Cfs	Ilmenite	Ilm	Phlogopite	Phl
Almandine	Alm	Clinopyroxene	Cpx	Jadeite	Jd	Piemontite	Pmt
Aluminosilicate		Clinozoisite	Czo	Kaersutite	Krs	Pigeonite	Pgt
Al ₂ SiO ₅ polymorphs	Als	Coesite	Coe	Kalsilite	Kls	Plagioclase	Pl
Amphibole	Amp	Cordierite	Crd	Kaolinite	Kln	Prehnite	Prh
Analcime (analcite)	Anl	Corundum	Crn	K-feldspar	Kfs	Pseudobrookite	Psb
Anatase	Ant	Covellite	Cv	Kornerupine	Krn	Pumpellyite	Pmp
Andalusite	And	Cristobalite	Crs	Kyanite	Ky	Pyrite	Py
Andradite	Adr	Crossite	Crt	Larnite	Lrn	Pyrochlore	Pcl
Anhydrite	Anh	Cubanite	Cbn	Laumontite	Lmt	Pyrope	Prp
Ankerite	Ank	Cummingtonite	Cum	Lawsonite	Lws	Pyrophyllite	Prl
Annite	Ann	Cuprite	Ppr	Lepidolite	Lpd	Pyrrhotite	Po
Anorthite	An	Datolite	Dat	Leucite	Lct	Quartz	Qz
Anorthoclase	Ano	Diamond	Dia	Limonite	Lm	Rankinite	Rnk
Anthophyllite	Ath	Diaspore	Dsp	Magnesite	Mgs	Rhodochrosite	Rds
Antigorite	Atg	Diopside	Di	Magnetite	Mag	Rhodonite	Rdn
Apatite	Ap	Dolomite	Dol	Majorite	Maj	Richterite	Rct
Apophyllite	Apo	Dravite	Drv	Malachite	Mlc	Riebeckite	Rbk
Aragonite	Arg	Edenite	Ed	Marcasite	Mrc	Ringwoodite	Rwd
Arfvedsonite	Arf	Enstatite	En	Margarite	Mrg	Rutile	Rt
Arsenopyrite	Apy	Epidote	Ep	Melilite	Mll	Sanidine	Sa
Augite	Aug	Eudialite	Eud	Merwinite	Mw	Sapphirine	Spr
Awaruite	Awr	Fayalite	Fa	Microcline	Mc	Scapolite	Scp
Axinite	Ax	Feldspar	Fsp	Molybdenite	Mol	Scheelite	Sch
Barite	Brt	Ferrosilite	Fs	Monazite	Mnz	Schorl	Srl
Beryl	Brl	Fluorite	Fl	Monticellite	Mtc	Sericite	Ser
Biotite	Bt	Forsterite	Fo	Montmorillonite	Mnt	Serpentine	Srp
Bornite	Bn	Galena	Gn	Mullite	Mul	Siderite	Sd
Brookite	Brk	Garnet	Grt	Muscovite	Ms	Sillimanite	Sil
Brucite	Brc	Gedrite	Ged	Natrolite	Ntr	Sodalite	Sdl
Bustamite	Bst	Gehlenite	Gh	Nepheline	Nph	Spessartine	Sps
Calcite	Cal	Gibbsite	Gbs	Nosean	Nsn	Sphalerite	Sp
Cancrinite	Ccn	Glaucophane	Gln	Olivine	OI	Sphene (now titanite)	Spn
Carbonate	Cb	Goethite	Gth	Omphacite	Omp	Spinel	Spl
Cassiterite	Cst	Graphite	Gr	Opal	Opl	Spodumene	Spd
Celadonite	Cel	Grossular	Grs	Opaque mineral	Opq	Spurrite	Spu
Celsian	Cls	Grunerite	Gru	Orthoamphibole	Oam	Staurolite	St
Chabazite	Cbz	Gypsum	Gp	Orthoclase	Orl	Stilpnomelane	Stp
Chalcocite	Cct	Halite	Hl	Orthoenstatite	Oen	Stishovite	Sti
Chalcopyrite	Ccp	Hastingsite	Hst	Orthopyroxene	Opx	Talc	Tlc
Chamosite	Chm	Häüyne	Hyn	Osumilite	Osm	Tephroite	Tep
Chlorite	Chl	Hedenbergite	Hd	Paragonite	Pg	Thomsonite	Thm
Chloritoid	Cld	Hematite	Hem	Pargasite	Prg	Tilleyite	Tly

xxvi List of Mineral Abbreviations

Mineral name	Abbr.	Mineral name	Abbr.	Mineral name	Abbr.	Mineral name	Abbr.
Titanite	Ttn	Troilite	Tro	Vermiculite	Vrm	Wüstite	Wu
Topaz	Tpz	Tschermakite	Ts	Vesuvianite	Ves	Xenotime	Xtm
Tourmaline	Tur	Ulvöspinel	Usp	Wadsleyite	Wds	Zeolite	Zeo
Tremolite	Tr	Uraninite	Urn	Wairakite	Wrk	Zircon	Zrn
Tridymite	Trd	Uvarovite	Uv	Wollastonite	Wo	Zoisite	Zo