CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Minerals

Their Constitution and Origin

Second edition

The new edition of this popular textbook once again provides an indispensable guide for the next generation of mineralogists.

Minerals is an authoritative and comprehensive study of modern mineralogy, designed for use on one- or two-semester courses, for undergraduate and graduate students in the fields of geology, materials science, and environmental science.

This second edition has been thoughtfully reorganized, making it more accessible to students, whilst still being suitable for an advanced mineralogy course. Fully updated and revised, important additions include expanded introductions to many chapters, a new introductory chapter on crystal chemistry, revised figures, and an extended color plates section containing beautiful color photographs. Text boxes include historical background and case studies to engage students, and end-of-chapter questions help them reinforce concepts. With new online resources provided to support learning and teaching, including laboratory exercises, PowerPoint slides, useful web links, and mineral identification tables, this is a sound investment for students and a valuable reference for researchers, collectors, and anyone interested in minerals.

Hans-Rudolf Wenk is Professor of the Graduate School in the Department of Earth and Planetary Science at the University of California, Berkeley. Since joining the Berkeley faculty, he has been engaged in teaching and research, covering a wide field of mineralogy, from feldspars to carbonates, metamorphic rocks to shales, and from the Earth's surface to the inner core. His particular focus has been on microstructures, investigated using electron microscopy and synchrotron X-rays.

Andrey Bulakh is Professor in the Department of Mineralogy at St. Petersburg State University. He is a specialist in mineralogy, geochemistry, and the origin of alkaline rocks and carbonatites. More recently, he has studied the history of ornamental stones in architecture. He has written several books that are widely used at Russian universities, and was a long-time member of the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Minerals

Their Constitution and Origin

Second Edition

Hans-Rudolf Wenk
University of California, Berkeley, USA

Andrey Bulakh
St. Petersburg State University, Russia

CAMBRIDGE
UNIVERSITY PRESS

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, 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 Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107514041

© Hans-Rudolf Wenk and Andrey Bulakh 2016

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 & Assessment.

First published 2004
Second edition 2016

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

Library of Congress Cataloging-in-Publication data
Names: Wenk, Hans–Rudolf, 1941– author. | Bulakh, A. G. (Andrey Glebovich), author.
Title: Minerals : their constitution and origin / Hans-Rudolf Wenk, Andrey Bulakh.
Description: Second edition. | Cambridge : Cambridge University Press, 2016. | Includes bibliographical references and index.
Identifiers: LCCN 2015042018| ISBN 9781107106260 (hardback : alk. paper) | ISBN 9781107514041 (pbk. : alk. paper)
Subjects: LCSH: Mineralogy.
Classification: LCC QE363.2 .W46 2016 | DDC 549–dc23 LC record available at http://lccn.loc.gov/2015042018

ISBN 978-1-107-10626-0 Hardback
ISBN 978-1-107-51404-1 Paperback

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

Cambridge University Press & Assessment 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
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Contents

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

© in this web service Cambridge University Press & Assessment www.cambridge.org

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Color plates section is found between pp. 314 and 315

© in this web service Cambridge University Press & Assessment www.cambridge.org

Preface

Minerals: Their Constitution and Origin is an introduction to mineralogy for undergraduate and graduate students in the fields of geology, materials science, and environmental science. It has been designed as a textbook for use in a one- or two-semester course but gives students a broader view and covers all aspects of mineralogy in a modern and integrated way. It provides detailed references to important publications on principles of crystallography and mineralogy. The book is not only descriptive but for interested readers derives basic principles such as aspects of symmetry theory, background on stereographic projection, X-ray diffraction and thermodynamics, based on general background from mathematics, physics and chemistry. The overall goal is to emphasize concepts and to minimize nomenclature. The text includes appendices covering identification of hand specimens and optical properties. With the broad approach, the book is not only a textbook for students but also a reference for teachers, researchers, collectors and anyone interested in minerals. The book is written in a modular fashion that permits instructors to select or omit some parts, depending on the level of the course, without compromising the continuity.

Today mineralogy is not just part of a geology curriculum. The importance of mineralogy has broadened to a wide variety of disciplines, from igneous petrology to soils science, from archaeology to cement engineering, from materials science to structural geology. Our book provides an alternative to existing texts by focusing more tightly on concepts, at the expense of completeness, and by integrating geological processes and applications more closely with the discussions of systematic mineralogy.

The book is divided into six parts:

Part I deals with general concepts of crystal chemistry, bonding, chemical formulas, mineral classification and hand specimen identification.

Part II introduces concepts of symmetry expressed in the morphology and structure of crystals. It then explores defects in crystal structures and the diversity of features observed during crystal growth.

Part III centers on the physics of minerals. First it shows how to use X-ray diffraction to determine the structural features introduced in Part II. A chapter on physical properties is optional but is significant for modern mineral physics and geophysics. We introduce optical properties and the use of the petrographic microscope because most mineralogists need to have this background before mineral systems are discussed in detail. The chapter on mineral identification with a microscope relies on access to relevant laboratory equipment. If there is no such access to microscopes, or if a separate course in optical mineralogy is available, chapters on optical mineralogy can be skipped. Part III concludes with a discussion of advanced analytical techniques, introducing equipment that may be encountered in modern mineralogical research laboratories.

Part IV discusses the wide range of mineral formation. It also provides some background in thermodynamics for understanding mineral equilibria in geological environments and phase transformations. Later chapters include applications of thermodynamics to sedimentary, hydrothermal, metamorphic, and igneous processes to demonstrate its relevancy.

Part V is a systematic treatment of mineral groups and about 200 of the most important minerals. Each chapter combines mineral characteristics with a discussion of a mineral-forming environment particularly linked to this mineral group, and information about mineral origin and mineral-forming processes. Part V starts with the most common minerals in the crust, quartz and feldspars, and ends with an overview of rare organic minerals like mellite.

Part VI on applied mineralogy deals with topics such as metal deposits, gems, cement, and human health, and explores how minerals form in the universe and were active components at each stage of the evolution of the Earth. We now have a much better understanding of minerals in the deep Earth, thanks largely to progress in seismology and experiments at ultra-high pressure and temperature. This part is largely independent from the rest of the book and these chapters can be used as reading assignments and form good starting points for term projects. The chapters should illustrate to students that mineralogy is not just complicated formulas, strange names,

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Miller indices, and point-groups, but has practical significance.

Appendices contain determinative tables and important technical terms are defined in a glossary.

There are many excellent mineralogy textbooks, ranging from the early Niggli (1920) monograph (which still contains much of the information that is needed), to modern books such as Hibbard (2002), Klein and Dutrow (2007), Nesse (2011) and Klein and Philpotts (2012). Our book has a different emphasis. The goal is to be selective in including material rather than all inclusive, yet trying to remain quantitative, scientifically sound, and avoiding superficiality. It is well known that many students are frightened of mathematical expressions. We are using some equations here and there, but they can be skipped, without losing the thread, if students do not have the necessary background. But since most geology programs require mathematics and physics courses, it seems only reasonable to show students that this material is useful and to show some quantitative relationships; for example, how trigonometry can be used to calculate interfacial angles; how X-ray diffraction patterns are linked to lattice parameters; basic thermodynamics to understand a boundary in a phase diagram; simple linear algebra to appreciate why a second-rank tensor, such as the optical indicatrix, has the shape of an ellipsoid; or how complex numbers can be used to add waves more easily analytically than graphically to obtain diffraction intensities. We also have not shied away from referring to important references, including the classic studies of von Laue (1913) on X-ray diffraction, van't Hoff (1912) on the geochemistry of salt deposits, Bowen (1915) on experimental petrology, and also recent discoveries such as the structure of the lower mantle (e.g. Lekic *et al.*, 2012), mineral identification on Mars (e.g. Bish *et al.*, 2013) or isotope analyses at the atomic scale (e.g. Valley *et al.*, 2014). This provides links to follow up on details about some of the milestones in mineralogy for readers who are interested.

The origin of this book goes back to 1993, when Dasha Sinitsyna, a student from (then) Leningrad, visited Berkeley on an exchange program and brought a little red book on mineralogy, written by her professor, Andrey Bulakh (1989), which caught Rudy Wenk's attention because it was an inspiring brief introduction to mineralogy. Over the following years we established further contact, in part through the exchange of another student, Anton Chakmouradyan. After reciprocal visits to St Petersburg and Berkeley, sponsored by the University of California Education Abroad Program, the authors decided to attempt to produce an English mineralogy book, in the spirit of the Russian version but expanded it considerably.

The different backgrounds of the authors guarantee a broad view: Andrey Bulakh is a specialist on alkaline rocks and minerals and geochemistry and has written several books that are widely used at Russian universities, including the latest (Bulakh, 2011). Rudy Wenk's earlier research focused on metamorphic rocks, deformation fabrics, and investigations of microstructures in feldspars and carbonates with electron microscopes. More recently it has emphasized minerals at high pressure, stress and temperature with aspects such as anisotropy in the deep Earth (see http://eps.berkeley.edu/people/hans-rudolf-wenk). Both have taught introductory mineralogy at major universities for a long time. In this book we have tried to unite our expertise.

The first edition was published 12 years ago. Why have we prepared a new edition? The basic concepts of mineralogy and crystallography have not changed and a lot still relies on investigations with the petrographic microscope, introduced almost 200 years ago, and X-ray diffraction, celebrating in 2014 its hundredth anniversary with the UNESCO Year of Crystallography. But in 12 years a few things have happened: 1000 new minerals were added to the 4000 in 2002, but none of those are the subject of the book. Important is the shift in mineral production. South Africa is no longer the leading supplier of diamonds and China has become by far the main producer of steel. Particularly it manufactures a whopping 60% of the world's cement.

In 12 years the internet has also made profound changes. If you want to know the density of olivine, or the price of gold, you no longer go to a library but to Wikipedia. The new edition takes this into account by referring not only to books for "Further reading" but also recommends webpages with important mineral information. Appendices on mineral properties are provided not only in printed format but as digital files as well. And we added digital materials that may be useful for instructors: PowerPoint files from which teachers can select slides, and sample laboratory exercises based on a one-semester Berkeley mineralogy course. A Kindle edition is also available.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Compared with the first edition we have reorganized the content to make it easier to use for teaching. Part I starts with crystal chemistry and connects students with what they learnt in chemistry lectures, then links it to mineral classification which is mainly based on chemical composition, and introduces hand-specimen identification to bring students early in contact with actual minerals. With such a background it makes it easier to advance in Part II to the more abstract but important concepts of symmetry principles as well as graphic representations of crystal forms such as the stereographic projection. In Part V we have added a brief chapter on organic minerals, though rare but very interesting to make readers aware of different types of bonding and crystal structures.

The book has benefited from the help of many colleagues. Some generously contributed illustrations, others reviewed parts of the manuscript and provided valuable input in discussions. Foremost our thanks go to students who, over many years, taught us what for them is important in mineralogy, made us appreciate the difficult subjects, and guided us to topics of most interest.

There are different acknowledgements: One is to obtain permissions from publishers which we appreciate greatly and will give details in the next section.

Another is to appreciate people who have become friends. In alphabetical order we acknowledge first those who share some of their outstanding images, Joszef Arnoth (Naturhistorisches Museum, Basel, e.g., Arnoth, 1986); Mark Bailey (Asbestos TEM Laboratory, Berkeley); Regine Buxtorf (Basel); John Christensen (LBNL, Berkeley); Frank de Wit (Terhorst Nl, www.strahlen.org); Ken Finger (UCMP, Berkeley); Andreas Freund (ESRF, Grenoble); Walter Gabriel (Münchenstein-CH); John Grimsich (Berkeley CA); Gustaaf Hallegraeff (IMAS, University of Tasmania, Hobart); Henry Hänni (University of Basel-CH); Gregory Ivanyuk (Apatiti); Ray Joesten (University of Connecticut); Deborah Kelley (University of Washington, Seattle); Steven Kesler (University of Michigan, Ann Arbor); E.C. Klatt (Mercer University, Florida); Maya Kopylova (University of British Columbia Vancouver); George Kourounis (Toronto, http://www.stormchaser.ca/Stormchaser.html); Rob Lavinski (Richardson TX, The Arkenstone, http://www.irocks.com); Wayne and Dona Leicht (Laguna Beach CA, http://www.Kristalle.com); Wendy Mao (Stanford University CA); Andreas Massanek (Technical University of Freiberg, e.g., Hofmann and Massanek, 1998); Remo Maurizio (Vicosoprano, e.g., Bedogné *et al.*, 1995); Olaf Medenbach (Ruhr University, Bochum, e.g., Medenbach and Wilk, 1986; Medenbach and Medenbach, 2001); Terry Mitchell (Los Alamos National Laboratory); Hans-Ude Nissen (ETH Zurich); Janet Oldak (UCSC, Los Angeles CA); Michael Queen (Carlsbad); Colin Robinson (University of Leeds, UK); Thomas Schüpbach (Digital Studio, Ipsach-CH); Jeffrey Scovil (Phoenix, scovilphotography.com; e.g., Pough, 1996; Scovil, 1996); Tim Teague (UC Berkeley); Erica and Harold Van Pelt (Los Angeles, e.g., Keller, 1990; Sofianides and Harlow, 1990); Gustaaf Van Tendeloo (University of Antwerp); Mark Thompson (Lunenburg MA; Mark Thompson Information Service, http://mtinfopage.com/minerals.htm); Alexander Van Driessche (Vrije Universiteit, Brussel); Max Weibel (ETH Zurich, e.g., Weibel, 1973); Dan and Diana Weinrich (Weinrich Minerals, Inc., Grover MO, http://danweinrich.com); Elizabeth Wenk (Macquarie University, Sydney); Roland Wessicken (ETH Zurich); and a collective of the Museum of Geology at Beijing (e.g., Gao Zhen-xi, 1980). All are enthusiastic mineralogists. Two of them even have a mineral named after them: medenbachite and lavinskiite. Two appear in photographs as scale: Frank de Wit next to a giant halite crystal (Figure 10.12b) and George Kourounis in a sulfur fumarole (Plate 19d).

For other figures, data, reviews of book chapters, and comments we appreciate help from Jill Banfield (UC Berkeley), Dmitriy Belakovskiy (Fersman Museum, Moscow), David Bish (University of Indiana), David Blake (NASA, Ames CA), Douglas Bock (CSIRO, Sydney), Evelyn Denzin (Athens, Georgia), Robert Downs (University of Arizona, Tucson), Edward Garnero (Arizona State University, Tempe), A. Filippenko (UC Berkeley), Valeriy Ivanikov, Catherine McCammon (Bayerisches Geoinstitut), Wolfgang Müller (T.U. Darmstadt), Barbara Romanowicz (UC Berkeley), Masha Sitnikova (BRD, Hannover), Alan Stern (SwRI, Boulder CO); Roman Vasin (JINR, Dubna), and Sergei and Vladimir Krivovichev, Igor Pekov, S. Petov, Eugeniy Treivus, and Anatoly Zolotarev (St. Petersburg State University). Rudy Wenk is particularly indebted to his wife Julia for her meticulous review that discovered many embarrassing errors.

To interact with these people has been the most rewarding experience and we appreciate their

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

enthusiasm and support. It is like a great family of mineral enthusiasts which started with Theophrastus and Pliny, included Stensen, Goethe (a dedicated mineral collector; visit his house in Weimar), and then of course Dana who created systematic mineralogy.

Last but not least we are grateful to the staff at Cambridge University Press for their dedication and patience. Of course blame for all remaining deficiencies, omissions, and errors in content rests with the authors and we continue to appreciate the input from readers who suggest corrections. We can make corrections in future printings and do not have to wait for another edition; so do not hesitate to contact us to report errors and make suggestions. We dedicate the book to our wives, Julia Wenk and Victoria Kondratieva.

H.-R. Wenk
A. Bulakh

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE

Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Figure credits

For more details see also captions and references.

The authors are grateful to the following publishers, institutions, and individuals for permission to reproduce material:

Cambridge University Press

Figure 16.31: Putnis, A. (1992). *Introduction to Mineral Sciences*. Cambridge University Press, Cambridge. Fig. 4.35.

Figure 38.3: Fowler, C. M. R. (2005). *The Solid Earth. An Introduction to Global Geophysics*, 2nd edn. Cambridge University Press, Cambridge. Fig. 8.17.

Dover Publications

Figure 7.8b: Haeckel, E. (1904). *Kunstformen der Natur*. Bibliografische Institut, Leipzig. English translation (1974): *Art Forms in Nature*, Dover Publications, New York.

Figure 10.10a,b: Bentley, W. A. and Humphreys, W. J. (1962). *Snow Crystals*. Paperback edn. Dover Publications, New York.

Elsevier

Books

Figure 1.5a: Baikow, V. E. (1967). *Manufacture and Refining of Raw Cane Sugar*. Elsevier, Amsterdam. Fig. 17.1. Copyright 1967 with permission from Elsevier.

Figure 10.8a: Verma, A. R. (1953). *Crystal Growth and Dislocations*. Academic Press, New York. Fig. 56. Copyright 1953 with permission from Elsevier.

Figure 12.19: Dillon, F. J. (1963). Domains and domain walls. In *Magnetism*, *Volume 3*, ed. G. T. Rado and H. Suhl, pp. 415–464. Academic Press, New York. Fig. 13. Copyright 1963 with permission from Elsevier.

Journals

Figure 17.7b: Barber, D. J. and Wenk, H.-R. (1979). On geological aspects of calcite microstructure. *Tectonophysics*, **54**, 45–60. Fig. 9. Copyright 1979 with permission from Elsevier.

Figure 33.6: Cann, J. R., Strens, M. R. and Rice, A. (1985). A simple magma-driven thermal balance model for the formation of volcanogenic massive sulfides. *Earth Planet. Sci. Lett*., **76**, 123–134. Fig. 4. Copyright 1985 with permission from Elsevier.

Figure 37.6: Daulton, T. L., Eisenhour, D. D., Bernatowicz, T. J., Lewis, R. S. and Buseck, P. R. (1996). Genesis of presolar diamonds: comparative high-resolution transmission electron microscope study of meteoritic and terrestrial nano-diamonds. *Geochim. Cosmochim. Acta*, **60**, 4853–4872. Fig. 7. Copyright 1996 with permission from Elsevier.

Figure 37.7: Wood, J. A. and Hashimoto, A. (1993). Mineral equilibrium in fractionated nebular systems. *Geochim. Cosmochim. Acta*, **57**, 2377–2388. Fig. 5. Copyright 1993 with permission from Elsevier.

International Union of Crystallography

Figure 7.7c: MacGillavry, C. H. (1976). *Symmetry Aspects of M. C. Escher's Periodic Drawings*, 2nd edn. International Union of Crystallography. Fig. 10.

Figure 11.3a,b: Ewald, P. P. (1962). *Fifty Years of X-ray Diffraction*. International Union of Crystallography, Utrecht. Figs. 4.4-1 and 4.4-3.

Figure 32.6: Gerkin, R. E., Lundstedt, A. P. and Reppart, W. J. (1984). Structure of fluorene $C_{13}H_{10}$, at 159K. *Acta Cryst. C*, **40**, 1892–1894. Fig. 2.

Figure 32.9: Swaminathan, S., Craven, B. M. and McMullan, R. K. (1984). The crystal structure and molecular thermal motion of urea at 12, 60 and 123 K from neutron diffraction. *Acta Cryst. B*, **40**, 300–306. Fig. 1.

Geological Society of America

Figures 9.6 and 29.12: Page, R. H. and Wenk, H.-R. (1979). Phyllosilicate alteration of plagioclase studied by transmission electron microscopy. *Geology*, **7**, 393–397. Figs. 2C and 2F.

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Iraq

Figure 7.7a: Mallowan, M. E. L. and Cruikshank, R. J. (1933). Excavations at Tel Arpachiyah. *Iraq*, **2**, 1–178.

Maxwell Museum of Anthropology, University of New Mexico

Figure 7.7b: Courtesy of the Maxwell Museum of Anthropology, University of New Mexico. Photographer: C. Baudoin.

Mineralogical Association of Canada

Figure 32.5: Echigo, T. and Kimata, M. (2010). Crystal chemistry and genesis of organic minerals: A review of oxalate and polycyclic aromatic hydrocarbon minerals. *Can. Mineral.*, **48**, 1329–1358. Fig. 13, p. 1343.
Figure 32.8: Echigo, T. and Kimata, M. (2010). Crystal chemistry and genesis of organic minerals: a review of oxalate and polycyclic aromatic hydrocarbon minerals. *Can. Mineral.*, **48**, 1329–1358. Fig. 8, p. 1339.
Figure 36.3: Wicks, F. J., Kjoller, K. and Henderson, G. S. (1992). Imaging the hydroxyl surface of lizardite at atomic resolution with the atomic force microscope. *Can. Mineral.*, **30**, 83–91. Fig. 8, p. 90.
Figure 36.5: Semkin, R. G. and Kramer, J. R. (1976). Sediment geochemistry of Sudbury area lakes. *Can. Mineral.*, **14**, 73–90. Fig. 13, p. 83.

Mineralogical Society of America

Figure 4.2: Sriramadas, A. (1957). Diagrams for the correlation of unit cell edges and refractive indices with the chemical composition of garnets. *Am. Mineral.*, **42**, 294–298. Fig. 1, p. 295.
Figures 9.15 and 16.2: Meisheng, Hu, Wenk, H.-R. and Sinitsyna, D. (1992). Microstructures in natural perovskites. *Am. Mineral.*, **77**, 359–373. Fig. 10, p. 367; Fig. 15, p. 370.
Figure 10.12a,b: Rickwood, P. C. (1981). The largest crystals. *Am. Mineral.*, **66**, 885–907. Figs. 10 and 11, p. 903.
Figure 16.28: Bischoff, W. D., Sharma, S. K. and MacKenzie, F. T. (1985). Carbonate ion disorder in synthetic and biogenic magnesian calcites: a Raman spectral study. *Am. Mineral.*, **70**, 581–589. Fig. 2, p. 583.
Figure 16.32: McKeown, D. A. and Post, D. A. (2001). Characterization of manganese oxide mineralogy in rock varnish and dendrites using X-ray absorption spectroscopy. *Am. Mineral.*, **86**, 701–713. Fig. 2, p. 39.
Figure 16.35: Phillips, B. L. (2000). NMR spectroscopy of phase transitions in minerals. In *Transformation Processes in Minerals*. Reviews in Mineralogy, vol. 39, Mineralogical Society of America, pp. 203–240. p. 223.
Figure 16.37: McCammon, C. A. (2000). Insights into phase transformations from Mössbauer spectroscopy. In *Transformation Processes in Minerals*. Reviews in Mineralogy, vol. 39, Mineralogical Society of America, pp. 241–257. p. 251.
Figure 21.13: Steiger, R. H. and Hart, S. R. (1967). The microcline–orthoclase transition within a contact aureole. *Am. Mineral.*, **52**, 87–116. Fig. 2, p. 91.
Figure 21.23: Barron, L. M. (1972). Thermodynamic multicomponent silicate equilibrium phase calculations. *Am. Mineral.*, **57**, 809–823.
Figure 25.9: Devouard, B., Posfai, M., Hua, X., Bazylinski, D. A., Frankel, R. B. and Buseck, P. R. (1997). Magnetite from magnetotactic bacteria: size distributions and twinning. *Am. Mineral.*, **83**, 1387–1398. Fig. 12, p. 389.
Figure 30.12: Veblen, D. R. and Buseck, P. (1980). Microstructures and reaction mechanisms in biopyriboles. *Am. Mineral.*, **65**, 599–623. Fig. 5, p. 608.
Figure 30.25: Greenwood, H. J. (1967). Wollastonite: stability in H_2O–CO_2 mixtures and occurrence in a contact-metamorphic aureole near Salmo, British Columbia, Canada. *Am. Mineral.*, **52**, 1669–1680.
Figure 36.2: Guthrie, G. D. and Mossman, B. T. (1993). *Health Effects of Mineral Dust*. Reviews in Mineralogy, vol. 28. p. 1 and p. 231. RA1231.M55 H424 Public Health.

Mineralogical Magazine

Figure 30.20: Joesten, R. (1986). The role of magmatic reaction, diffusion and annealing in the evolution of coronitic microstructure in troctolitic gabbro from Risör, Norway. *Mineral. Mag.*, **50**, 441–467.

Oxford University Press

Figure 36.1: Stanton, M. F., Layard, M., Tegeris, A., Miller, E., May, M., Morgan, E. and Smith, A. (1981). Relation of particle dimension to

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

carcinogenicity in amphibole asbestoses and other fibrous materials. *J. Natl. Cancer Inst.*, **67**, 965–975, by permission of Oxford University Press.

Royal Geological Society of Cornwall

Figure 26.12: Hosking, K. F. G. (1951). Primary ore deposition in Cornwall. *Trans. Roy. Geol. Soc. Cornwall*, **18**, 309–356.

Schweizerische Mineralogische und Petrographische Gesellschaft

Figure 28.10: Wenk, H.-R., Wenk, E. and Wallace, J. H. (1974). Metamorphic mineral assemblages in pelitic rocks of the Bergell Alps. *Schweiz. Mineral. Petrog. Mitt.*, **54**, 507–554.

Figure 30.26: Trommsdorff, V. (1966). Progressive Metamorphose kieseliger Karbonatgesteine in den Zentralalpen zwischen Bernina und Simplon. *Schweiz. Mineral. Petrog. Mitt.*, **46**, 431–460.

Schweizer Strahler

Figures 18.8 and 18.9: Mullis, J. (1991). Bergkristall. *Schweizer Strahler*, **9**, 127–161. Figs. 2 and 5.

Society of Economic Geologists

Figure 18.2: Fournier, R. O. (1985). The behavior of silica in hydrothermal solutions. In *Geology and Geochemistry of Epithermal Systems*, ed. B. R. Berger and P. M. Bethke. Reviews in Geology, vol. 2, pp. 63–79. Society of Economists and Geologists, Chelsea, MI.

Figure 26.10: Sillitoe, R. H. (1973). The tops and bottoms of porphyry copper deposits. *Econ. Geol.*, **68**, 799–815. Fig. 1, p. 800.

Figure 33.7: Carr, H. W., Groves, D. I. and Cawthorne, R. G. (1994). The importance of synmagmatic deformation in the formation of Merensky Reef potholes in the Bushveld complex. *Econ. Geol.*, **89**, 1398–1410. Fig. 1, p. 1399, Fig. 2, p. 1402.

Figure 36.7: Smith, K. S. and Huyck, H. L. O. (1999). An overview of the abundance, relative mobility, bioavailability, and human toxicity of metals. In *The Environmental Geochemistry of Mineral Deposits, Volume A*, ed. G. S. Plumlee and M. J. Logsdon, pp. 29–70. Society of Economic Geologists, Littleton, CO.

Society of Glass Technology

Figure 18.4: Lee, R. W. (1964). On the role of hydroxyl on the diffusion of hydrogen in fused silica. *Phys. Chem. Glasses*, **5**, 35–43.

Springer-Verlag

Books

Figure 9.13: Lally, J. S., Heuer, A. H. and Nord, G. L. (1976). Precipitation in the ilmenite-hematite system. In *Electron Microscopy in Mineralogy*, ed. H.-R. Wenk, pp. 214–219. Springer-Verlag, Berlin. Fig. 1a. Copyright Springer-Verlag 1976.

Figure 18.1: Hoefs, J. (1987). *Stable Isotope Geochemistry*, 3rd edn. Springer-Verlag, Berlin. Fig. 31. Copyright Springer-Verlag 1987.

Figure 22.7: Mitchell, R. H. (1986), *Kimberlites: Mineralogy, Geochemistry and Petrology*. Plenum Press, New York. Fig. 3.1.

Figures 20.8 and 21.17: Champness, P. and Lorimer, G. (1976). Exsolution in silicates. In *Electron Microscopy in Mineralogy*, ed. H.-R. Wenk, pp. 174–204. Springer-Verlag, Berlin. Figs. 9 and 14. Copyright Springer-Verlag 1976.

Figures 21.16 and 21.18: Smith, J. V. and Brown, W. L. (1988). *Feldspar Mineralogy*. Springer-Verlag, Berlin. Figs. 1.4 and 2.4. Copyright Springer-Verlag 1988.

Figure 29.20: Pédro, G. (1997). Clay minerals in weathered rock materials and in soils. In *Soils and Sediments. Mineralogy and Geochemistry*, ed. H. Paquet and N. Clauer, pp. 1–20. Springer-Verlag, Berlin. Fig. 3. Copyright Springer-Verlag 1997.

Figure 30.7: Wenk, H.-R. (ed.) (1976). *Electron Microscopy in Mineralogy*. Springer-Verlag, Berlin. p. 2. Copyright Springer-Verlag 1976.

Figure 30.14: Liebau, F. (1985). *Structural Chemistry of Silicates: Structure, Bonding, Classification*. Springer-Verlag, Berlin. Fig. 10.3. Copyright Springer-Verlag 1985.

Figure 30.23: Winkler, H. G. F. (1979). *Petrogenesis of Metamorphic Rocks*, 5th edn. Springer-Verlag, Berlin. Fig. 5.6. Copyright Springer-Verlag 1979.

Figures 31.6a and 31.6c: Gottardi, G. and Galli, E. (1985). *Natural Zeolites*. Springer-Verlag, Berlin. Figs. 2.1E and 6.1. Copyright Springer-Verlag 1985.

Figures 37.10 and 37.11: Ringwood, A. E. (1979). *Origin of the Earth and Moon*. Springer-Verlag,

© in this web service Cambridge University Press & Assessment www.cambridge.org

CAMBRIDGE
Cambridge University Press & Assessment
978-1-107-51404-1 — Minerals
2nd Edition
Hans-Rudolf Wenk , Andrey Bulakh
Frontmatter
More Information

Berlin. Figs. 2.1 and 12.1. Copyright Springer-Verlag 1979.

Journals

Figures 9.5 and 17.7b: Barber, D. J., Heard, H. C. and Wenk, H.-R. (1981). Deformation of dolomite single crystals from 20–800C. *Phys. Chem. Miner.*, **7**, 271–286. Fig. 3a,b. Copyright Springer-Verlag 1981.

Figures 16.3 and 12.10: Wenk, H.-R., Hu, M., Lindsey, T. and Morris, W. (1991). Superstructures in ankerite and calcite. *Phys. Chem. Mineral.*, **17**, 527–539. Fig. 3c. Copyright Springer-Verlag 1991.

Figures 16.30 and 12.29: Aines, R. D., Kirby, S. H. and Rossman, G. R. (1984). Hydrogen speciation in synthetic quartz. *Phys. Chem. Mineral.*, **11**, 204–212. Fig. 1. Copyright Springer-Verlag 1984.

Figures 19.15b and 21.15b: Müller, W. F., Wenk, H. R. and Thomas G. (1972). Structural variations in anorthites. *Contrib. Mineral. Petrol.*, **34**, 304–314. Copyright Springer-Verlag 1976.

Taylor and Francis Group

Figure 17.7a: Westmacott, K. H., Barnes, R. S. and Smallman, R. E. (1962). The observation of dislocation "climb" source. *Phil. Mag.*, **7** (ser. 8), 1585–1613. Fig. 2.

University of Chicago Press

Figure 21.24: Bowen, N. L. and Tuttle, O. F. (1950). The system $NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O. *J. Geol.*, **58**, 498–511. Fig. 3.

Figure 24.6: Goldsmith, J. R. and Heard, H. C. (1961). Subsolidus phase relations in the system $CaCO_3$–$MgCO_3$. *J. Geol.*, **69**, 45–74. Fig. 4.

Wepf & Co. AG Verlag

Figure 10.15: Stalder *et al.* (1973). Tafel 17c (Figure 5.30). Republished 1998 as *Mineralienlexikon der Schweiz*, Wepf, Basel.

John Wiley & Sons

Books

Figure 26.13: Evans, A. M. (1993). *Ore Geology and Industrial Minerals: An Introduction*, 3rd edn. Blackwell, Oxford. Fig. 4.13.

Figures 2.21 and 34.5: Klein, C. (2002). *Mineral Science*, 22nd edn. Wiley, New York. Copyright 2002 John Wiley & Sons. This material is used by permission of John Wiley & Sons, Inc.

Figure 16.29: Nakamoto, K. (1997). *Infrared and Raman Spectra of Inorganic and Coordination Compounds, Part A: Theory and Applications in Inorganic Chemistry*, 5th edn. Wiley, New York. Copyright 1997 John Wiley & Sons. This material is used by permission of John Wiley & Sons, Inc.

Journals

Figure 12.13: Morris, G. B., Raitt, R. W. and Shor, G. G. (1969). Velocity anisotropy and delay time maps of the mantle near Hawaii. *J. Geophys. Res.*, **74**, 4300–4316. Fig. 12.

Figure 16.9: Vasin, R., Wenk, H.-R., Kanitpanyacharoen, W., Matthies, S. and Wirth, R. (2013). Anisotropy of Kimmeridge shale. *J. Geophys. Res.*, **118**, 1–26, doi:10.1002/jgrb.50259. Fig. 1.

Figure 16.39: McCammon, C. A. (1995). Mössbauer spectroscopy of minerals. In *Mineral Physics and Crystallography. A Handbook of Physical Constants*. American Geophysical Union, Washington, DC, pp. 332–347. Fig. 2.

Figure 38.1: Anderson, D. L. and Hart, R. S. (1976). An earth model based on free oscillations and body waves. *J. Geophys. Res.*, **81**, 1461–1475.

Figure 38.6: Shen, G., Mao, H.-K., Hemley, R. J., Duffy, T. S. and Rivers, M. L. (1998). Melting and crystal structures of iron at high pressures and temperatures. *Geophys. Res. Lett.*, **25**, 373–376. Fig. 3.

Yale University Press

Figure 24.12: Garrels, R. M., Thompson, M. E. and Siever, R. (1960). Stability of some carbonates at 25 °C and one atmosphere total pressure. *Am. J. Sci.*, **258**, 402–418. Fig. 5.

© in this web service Cambridge University Press & Assessment www.cambridge.org

Praise for the first edition

"I think this book represents a sound undergraduate investment – a textbook that an undergraduate could visit and revisit throughout their degree program, to remind them of the basics and, by following up the references, to provide a deeper understanding of the subjects covered."

Chemistry World

". . . the book provides a good coverage of minerals, with clear diagrams and photographs to supplement the text. . . . there is much of value in this book. . . . the text is clear; and deeper treatments can be skipped, while still gaining knowledge of the wider range of mineralogy."

OUGS Newsletter

"Wenk and Bulakh's *Minerals* is both authoritative and accessible, providing a thorough grounding in many aspects of modern mineralogy in a first-rate text."

New Scientist

". . . this is a refreshing new mineral textbook and is a wonderful resource to freshen up an undergraduate course. Every lecturer who teaches mineralogy and every Earth Sciences library should get a copy. . . . Very highly recommended."

Geological Magazine

© in this web service Cambridge University Press & Assessment www.cambridge.org