

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.

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Their Constitution and Origin

Second Edition

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CAMBRIDGE
UNIVERSITY PRESS

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



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

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www.cambridge.org

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

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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://lcn.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

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Contents

Preface	<i>page</i> xiii
Figure credits	xvii
Praise for the first edition	xxi
Part I Minerals as chemical compounds	1
1 Subject and history of mineralogy	3
1.1 What is mineralogy?	3
1.2 History	3
1.3 Major directions of investigation	8
1.4 Some preliminary advice	9
1.5 Definition of crystal and mineral	10
1.6 Summary	10
2 Elements, bonding, simple structures, and ionic radii	12
2.1 Chemical elements	12
2.2 Bonding	15
2.3 Ionic radii	22
2.4 Radius ratio and coordination polyhedra	24
2.5 Some general rules concerning ionic structures	29
2.6 Summary	29
3 Isomorphism, solid solutions, and polymorphism	31
3.1 Isomorphism and solid solutions	31
3.2 Polymorphism and phase transitions	32
3.3 Summary	36
4. Chemical formulas of minerals	37
4.1 Ideal formulas	37
4.2 Empirical formulas	37
4.3 Calculation of chemical formulas from weight percentage of oxides	37
4.4 Simplified formulas	38
4.5 How to use ternary diagrams	39
4.6 Summary	41
5 Chemical classification and names of minerals	42
5.1 Minerals, mineral species, and mineral varieties	42
5.2 Chemical classification of minerals	42
5.3 Mineral names	47
5.4 Summary	47
6 Mineral identification of hand specimens	49
6.1 Different scales	49
6.2 State of aggregation (including crystallographic form and habit)	49

6.3	Color, streak, and luster	50
6.4	Mechanical properties	51
6.5	Density and specific gravity	54
6.6	Other properties	54
6.7	Associations of minerals	54
6.8	Some directions for practical mineral identification	54
6.9	Summary	56
Part II Symmetry expressed in crystal structures and morphology		59
7	The concept of a lattice and description of crystal structures	61
7.1	Discovery of the lattice	61
7.2	Symmetry considerations	63
7.3	The unit cell as the basic building block of a crystal	64
7.4	Representation of lattice lines and planes with rational indices	72
7.5	Relations between lattice planes and lattice lines	76
7.6	Crystal structure	78
7.7	Summary	80
8	Crystal symmetries: point-groups and space-groups	81
8.1	Introduction	81
8.2	Spherical representations of morphology	81
8.3	Point-group symmetry	89
8.4	Crystallographic forms	100
8.5	Some comments on space-groups	102
8.6	Summary	106
9	Crystalline defects	108
9.1	Types of defects	108
9.2	Point defects	108
9.3	Dislocations (line defects)	108
9.4	Planar defects during growth	110
9.5	Planar defects during phase transformations	111
9.6	Quasicrystals	116
9.7	Radiation defects and radioactive decay	116
9.8	Summary	117
10	Crystal growth and aggregation	118
10.1	Crystal habit	118
10.2	Nucleation and growth	120
10.3	Various growth effects	125
10.4	Aggregation	127
10.5	Summary	128
Part III Physical investigation and properties of minerals		131
11	X-ray diffraction	133
11.1	Basic concepts	133
11.2	Brief discussion of waves	136
11.3	Laue and Bragg equations	137
11.4	The powder method	141

11.5	Crystal identification with the powder method	143
11.6	X-rays and crystal structure	143
11.7	Additional atomic scattering considerations	146
11.8	Summary	146
12	Physical properties	149
12.1	Vectors and tensors: general issues	149
12.2	Symmetry considerations	151
12.3	Tensors of different ranks	152
12.4	Density	152
12.5	Thermal conductivity, thermal expansion, and specific heat	154
12.6	Elastic properties	155
12.7	Piezoelectricity and pyroelectricity	159
12.8	Magnetic properties	160
12.9	Summary	164
13	Optical properties	166
13.1	Some physical background	166
13.2	Refractive index and optical applications	168
13.3	Polarization and birefringence	173
13.4	The optical indicatrix	180
13.5	Dispersion	185
13.6	Pleochroism	186
13.7	Summary	187
14	Mineral identification with the petrographic microscope	189
14.1	Sample preparation	189
14.2	Microscope alignment	190
14.3	Determination of the refractive index	191
14.4	Use of interference colors	191
14.5	Observation of interference figures with convergent light	196
14.6	Characteristics of important rock-forming minerals	202
14.7	Summary	215
15	Color	217
15.1	Overview	217
15.2	Absorption	217
15.3	Fluorescence and phosphorescence	221
15.4	Dispersion	222
15.5	Luster	222
15.6	Microstructure	222
15.7	Summary	223
16	Advanced analytical methods	225
16.1	Overview	225
16.2	High-resolution imaging	226
16.3	Diffraction	234
16.4	Spectroscopic methods	238
16.5	Summary	248

viii	Contents
17 Mechanical properties and deformation	251
17.1 Stress–strain	251
17.2 Deformation by slip	252
17.3 Dislocation microstructures	254
17.4 Mechanical twinning	254
17.5 Polycrystal plasticity	256
17.6 Summary	256
Part IV Mineral-forming processes	259
18 Mineral genesis	261
18.1 Overview	261
18.2 Mineral-forming environments	261
18.3 Types of mineral crystallization	264
18.4 Types of mineral deposits	265
18.5 Multistage processes, generations, and parageneses	267
18.6 Typomorphism of minerals	267
18.7 Summary	269
19 Considerations of thermodynamics	270
19.1 Background	270
19.2 Energy minimum in a system	271
19.3 The simplest thermodynamic calculations and diagrams	272
19.4 Electrolytes and Eh–pH phase diagrams	278
19.5 Phase rule	282
19.6 Summary	283
20 Phase diagrams	284
20.1 Introduction	284
20.2 Diagrams for crystallization from a melt	284
20.3 Pressure–temperature phase diagrams and implications for the Earth mantle	285
20.4 Melting behavior of solid solutions	286
20.5 Exsolution	289
20.6 Summary	290
Part V A systematic look at mineral groups	293
21 Important information about silica minerals and feldspars. Their occurrence in granites and pegmatites	295
21.1 Silica minerals	295
21.2 Feldspars	299
21.3 Brief description of silica minerals	307
21.4 Brief description of feldspars	309
21.5 The origin of granite	311
21.6 Pegmatites	315
21.7 Summary	315
22 Simple compounds. Unusual mineral occurrences	317
22.1 Background about metals and intermetallics	317
22.2 Crystal structures and relationships to morphology and physical properties	317
22.3 Brief description of important minerals of the native elements	321

22.4	Unusual conditions of formation	323
22.5	Summary	324
23	Halides. Evaporite deposits	325
23.1	Common compositional and structural features of halides	325
23.2	Brief description of halide minerals	327
23.3	Origin of halide minerals	327
23.4	Commercial deposits	334
23.5	Summary	334
24	Carbonates and other minerals with triangular anion groups. Sedimentary origins	336
24.1	Characteristic features of composition and crystal chemistry of carbonates and borates	336
24.2	Morphology and properties of carbonates	340
24.3	Brief description of important carbonate minerals	340
24.4	Formation conditions of carbonates	342
24.5	Carbonates in sedimentary rocks: chemical and biological origins	344
24.6	Summary	349
25	Phosphates, sulfates, and related minerals. Apatite as a biogenic mineral	350
25.1	Phosphates, arsenates, and vanadates	350
25.2	Brief description of important phosphate minerals	350
25.3	Sulfates and tungstates	352
25.4	Brief description of important sulfate and tungstate minerals	352
25.5	Biogenic processes	356
25.6	Summary	360
26	Sulfides and related minerals. Hydrothermal processes	361
26.1	Crystal chemistry	361
26.2	Brief description of important sulfide minerals	365
26.3	Sulfide genesis and hydrothermal deposits	368
26.4	Weathering and oxidation of sulfides	374
26.5	Summary	375
27	Oxides and hydroxides. Review of ionic crystals	377
27.1	Overview	377
27.2	Ionic crystal structures	377
27.3	More complex oxide structures	382
27.4	Brief description of important oxide and hydroxide minerals	385
27.5	Summary	394
28	Orthosilicates and ring silicates. Metamorphic mineral assemblages	396
28.1	General comments on silicates	396
28.2	Orthosilicates	399
28.3	Brief description of important orthosilicate minerals	405
28.4	Ring silicates	409
28.5	Brief description of important ring silicate minerals	409
28.6	Metamorphic minerals	410
28.7	Summary	417

29	Sheet silicates. Weathering of silicate rocks	418
29.1	Basic structural features	418
29.2	Polytypism	423
29.3	Structure of clay minerals	425
29.4	Brief description of important sheet silicate minerals	426
29.5	Formation conditions for sheet silicates and weathering of silicate rocks	431
29.6	Clay minerals in soils	431
29.7	Summary	435
30	Chain silicates. Discussion of some igneous and metamorphic processes	437
30.1	Structural and chemical features	437
30.2	Brief description of important chain silicate minerals	445
30.3	Crystallization of igneous rocks	450
30.4	Metamorphic reactions in siliceous limestones	456
30.5	Summary	460
31	Framework silicates. Zeolites and ion exchange properties of minerals	462
31.1	The framework structure	462
31.2	Morphology and physical properties	464
31.3	Brief description of important framework silicate minerals	468
31.4	Ion exchange properties of some minerals	469
31.5	Summary	471
32	Organic minerals	473
32.1	Organic compounds	473
32.2	Chemical classes and some structures of organic minerals	474
32.3	Brief descriptions of some organic minerals	475
32.4	Summary	477
	Part VI Applied mineralogy	479
33	Metalliferous mineral deposits	481
33.1	Applied mineralogy	481
33.2	Economically important minerals	482
33.3	Geological setting of metal deposits	482
33.4	Metal production around the world	489
33.5	Reserves	498
33.6	Summary	500
34	Gemstones	501
34.1	General comments about gems	501
34.2	Instruments used by gemologists	504
34.3	Important gems	507
34.4	Gemstone enhancements	510
34.5	Crystal synthesis	512
34.6	Summary	517
35	Cement minerals	518
35.1	Significance of cement	518
35.2	Some features of nonhydraulic cements	519
35.3	Portland cement	519

35.4	Some problems with concrete	522
35.5	Summary	524
36	Minerals and human health	526
36.1	Mineral-like materials in the human body	526
36.2	Minerals in nutrition	526
36.3	Minerals as health hazards	529
36.4	Summary	535
37	Mineral composition of the solar system	536
37.1	Elements in the universe	536
37.2	Minerals of meteorites	538
37.3	Minerals of the planets	542
37.4	Minerals of the Moon	546
37.5	Summary	549
38	Mineral composition of the Earth	551
38.1	Chemical composition of the Earth	551
38.2	Composition of the crust	551
38.3	Composition of the mantle	553
38.4	Composition of the inner core	557
38.5	Atmosphere and hydrosphere	558
38.6	Mineral evolution over Earth's history	558
38.7	Microscopic mineralogy	560
38.8	Summary	561
	Appendices	563
1a.1	Metallic or submetallic luster, no cleavage or poor cleavage, sorted according to hardness	564
1a.2	Metallic or submetallic luster, distinct cleavage, sorted according to hardness	565
1b.1	Nonmetallic luster, no cleavage or poor cleavage, sorted according to hardness	566
1b.2	Nonmetallic luster, single cleavage (platy), sorted according to hardness	568
1b.3	Nonmetallic luster, polyhedral cleavage (three systems), sorted according to hardness	570
1b.4	Nonmetallic luster, prismatic or fibrous cleavage (two systems), sorted according to hardness	572
2	Minerals that display some distinctive physical properties	574
3	Rock-forming minerals that are colored in thin section	575
4a	Optically isotropic minerals, sorted according to refractive index	576
4b	Minerals with very low birefringence (up to white interference colors in 30 μm thin sections), sorted according to birefringence	577
4c	Minerals with low birefringence (up to first-order red interference colors in 30 μm thin sections), sorted according to birefringence	578
4d	Minerals with high birefringence (second- to fourth-order interference colors in 30 μm thin sections), sorted according to birefringence	579
4e	Minerals with very high birefringence (higher than third-order interference colors in 30 μm thin sections), sorted according to birefringence	581
	Glossary	582
	References	590
	Index	603

Color plates section is found between pp. 314 and 315

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,

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.

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, Jozsef 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 Hallegraef (IMAS, University of Tasmania, Hobart); Henry Hänni (University of Basel-CH); Gregory Ivanyuk (Apatiti); Ray Joesen (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, Eugeny 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

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.

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Geological Society of America

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Mineralogical Magazine

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Society of Economic Geologists

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University of Chicago Press

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Wepf & Co. AG Verlag

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Journals

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