Earth Materials

Introduction to Mineralogy and Petrology

This concise, accessible, market-leading textbook brings together the wide-ranging fundamentals students need to understand rocks and minerals, and shows them how they relate to the broader Earth, materials and environmental sciences. Designed specifically for one-semester courses, it is beautifully illustrated in full colour to explain the key concepts in mineralogy and petrology. This revision has been fully updated based on classroom experience. Including a completely new chapter providing an elementary introduction to thermodynamics, kinetics, radioactive decay and absolute dating, this new edition also features new mineral descriptions and many new stunning color photographs. A new section on hydraulic fracturing and discussion of some of its most serious potential environmental consequences has also been added. Stunning photos of mineral specimens and rock thin sections help students build a core understanding, whilst close intergration of clear illustrations with engaging text create a highly effective learning experience.

Cornelis ("Kase") Klein was Professor in the Department of Earth and Planetary Sciences at the University of New Mexico, Albuquerque. He received his B.Sc. and M.Sc. in geology from McGill University, Canada, and his Ph.D. from Harvard University, also in geology. He was a member of the Geology faculty at Harvard University, Indiana University, Bloomington, and the University of New Mexico: he taught courses in mineralogy at all these universities. His published books include *Manual of Mineralogy* (19th–21st eds.); *Manual of Mineral Science* (22nd–23rd eds.); and *Minerals and Rocks: Exercises in Crystal and Mineral Chemistry, Crystallography, X-Ray Powder Diffraction, Mineral and Rock Identification, and Ore Mineralogy* (3rd ed., 2008). He received two awards for excellence in teaching from the University of New Mexico.

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Frontispiece: Eruption of Mount Etna, Sicily, December 2015.
Credit: Andrea Savoca Andrea Savoca / EyeEm, source Getty.

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Cover: Polished surface of a deeply weathered breccia with fracture infill of turquoise. Photograph courtesy of David Nufer.

Cornelis Klein *dedicates this book to his two children and their immediate families. His son and daughter-in-law, Marc and Laura Klein, and their two children, Alaxandra and Hugh. And to his daughter and son-in-law, Stephanie and Jack Stahl, and Stephanie's three sons, Max, Miles, and Bo Peponis.*

Anthony R. Philpotts *dedicates this book to his three daughters, Liane, Marlaine, and Alison.*

Contents

Preface

Over the past two decades, many curriculum changes have occurred in geology, Earth science, and environmental science programs in universities. Many of these have involved the compression of separate one-semester courses in mineralogy, optical mineralogy, and petrology into a single-semester offering that combines mineralogy and petrology, commonly called Earth Materials. Such a course is a challenge to the instructor (or a team of instructors) and the students. This is especially so when few, if any, textbooks for such a one-semester course have been available.

This text, *Earth Materials*, is an introduction to mineralogy and petrology in which both subjects are covered with a roughly even balance. To keep this textbook reasonably short and applicable to a one-semester course, we decided against providing a shallow survey of everything and instead concentrated on what we consider the most fundamental aspects of the various subjects.

In the writing of this text, we assumed that the students who enroll in an Earth materials course would have previously taken an introductory physical geology course, as well as a course in college-level chemistry.

Coverage

Basic aspects of mineralogy must precede the coverage of petrology. This sequence is obvious from the chapter headings. After a brief, general introduction in Chapter 1, minerals and rocks are broadly defined in Chapter 2. That is followed by three chapters that relate to various mineralogical aspects and concepts. Chapter 3 covers the identification techniques that students must become familiar with to recognize unknown minerals in the laboratory and in the field. It also includes discussion of two common instrumental techniques: X-ray powder diffraction and electron beam methods. Chapter 4 covers the most fundamental aspects of crystal chemistry, and Chapter 5 is a short introduction to basic aspects of crystallography. Chapter 6 covers optical mineralogy. This subject is included so that instructors who plan to introduce thin sections of rocks in their course can give their students quick access to the fundamentals of optical mineralogy and the optical properties of rock-forming minerals.

The sequencing of subsequent systematic mineralogy chapters is completely different from that most commonly used in mineralogy textbooks. In these chapters, minerals are discussed in groups based first on chemistry (native elements, oxides, silicates, and so on) and, subsequently, for the silicates, on structural features (layer, chain, and framework silicates, and so on). Here, the decision was made to group systematic mineralogy descriptions as part of the three major rock types: igneous, sedimentary, and metamorphic. This allows for the closest possible integration of mineralogy and petrology.

Chapter 7 gives systematic mineralogical data on 29 of the most common igneous minerals, including, in order of decreasing abundance, silicates, oxides, a few sulfides, and a phosphate.

Before discussing igneous, sedimentary, and metamorphic rocks, the second edition of Earth Materials has a new Chapter 8 that introduces thermodynamics and kinetics. Thermodynamics provides an explanation for the direction of all geologic processes but the rate at which these goals are achieved depends on kinetic factors. Although both of these subjects can be highly mathematical, this chapter introduces them in easily understood mathematical terms. This chapter also discusses one of the most important kinetic processes in unraveling Earth history, radioactive decay.

Chapter 9 presents the most fundamental aspects of the formation of igneous rocks, explaining why the normally solid Earth can, on occasion, partly melt to form magma, whose physical and chemical properties control its rise toward the surface where it eventually solidifies. A new section added at the end of this chapter discusses how evolving isotopic reservoirs in the Earth can reveal the source of magmas. This is followed by Chapter 10, which addresses the occurrence of igneous rock types, their classification, and plate tectonic settings.

Chapter 11 gives systematic mineralogical descriptions of 14 common sedimentary minerals as well as phosphorite and soil. (The siliciclastic components of sedimentary rocks are discussed in Chapter 7, which deals with igneous minerals). Chapter 12 deals with the formation, transport, and lithification of sediment, and Chapter 13 discusses sedimentary rock classification, as well as the occurrence and plate tectonic setting of sedimentary rocks.

Chapter 14 gives the systematic mineralogy of 27 of the most common metamorphic minerals, all of which are silicates, except for two, an oxide and an element. Chapter 15 addresses the causes of metamorphism, gives rock classifications, and relates their occurrence to plate tectonic settings.

CRYSTALVIEWER

The atomic structure illustrations, which are static images in this text, can also be viewed as interactive visualizations in CrystalViewer, a crystal structures visualization program for Mac and Windows. CrystalViewer is designed to provide the missing "third dimension" for crystal structure illustrations in the book. Each structure can be rotated and scaled with the computer mouse, and it is hoped that such interactive exploration will lead to an improved visual understanding of the complex three-dimensional atomic arrangements of minerals. The program contains 105 structure illustrations, which are distributed over two files. The first file, with the title "Learning," contains 24 structures that are referenced with figure numbers from Chapters 2, 4, and 5. These 24 structures illustrate basic aspects of crystal chemistry. The other file, entitled "Reference" with 81 crystal structures, is arranged in alphabetical order, by mineral name. This file contains the structures of the rock-forming minerals discussed in Chapters 5, 7, 10, 13, and 15. These structures complement the structure illustrations in the text that show unit cell outlines, space group notation, and legends with atomic site occupancies. The files and the CrystalViewer download are at www.cambridge.org/earthmaterials.

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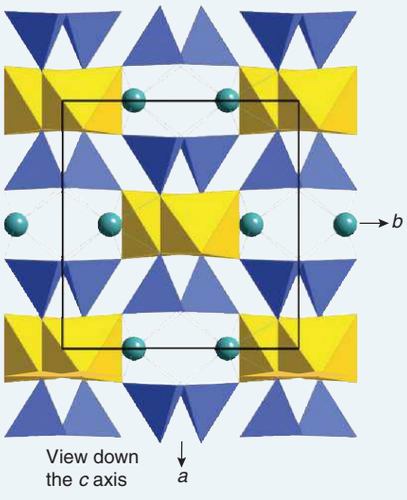

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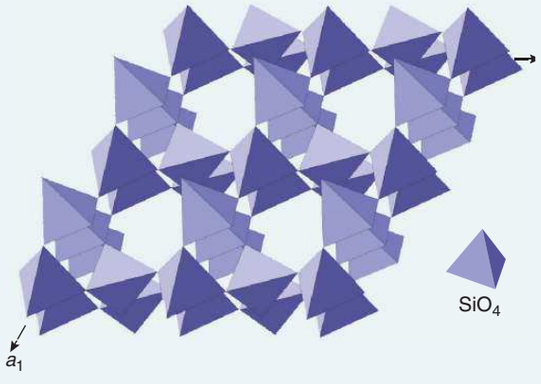

Chapter 16 gives systematic mineralogical descriptions of selected minerals that are of economic importance. Chapter 17 gives a brief overview of some selected resources of Earth materials and has a new section on shale gas, its extraction by hydraulic fracturing (fracking), and its potential environmental impact. Chapter 18 discusses the health effects of several minerals and chemical elements, and the hazards presented by certain rock-forming processes.

In the chapters that deal mainly with systematic mineralogy (Chapters 7, 11, 14, and 16), the main emphasis is on geologic occurrence (paragenesis), chemistry and atomic structure, physical properties that are pertinent to hand specimen identification (in laboratory sessions associated with an Earth materials course), and uses in industry and manufacturing. Hand specimen photographs and atomic structure illustrations are given for each mineral discussed.

This text is meant to be not only a supplement to lectures but also a reference source in the applied laboratory sessions of the course. Basic concepts in crystal chemistry, crystallography, and the origin of various rock types are best presented by the instructor in lectures in the classroom. Mineral and rock identification and classification schemes, however, are best learned in the laboratory with hand specimens and thin sections, using those parts of the book that specifically address the applied aspects.

All chapters begin with a boxed overview of what follows and end with a summary and set of review questions. When a new term is first encountered in the text, it is printed in bold type to signify that its definition is included in the glossary at the end of the text.

Our overall goal was the production of an accessible, highly illustrated and visually attractive, condensed and well-integrated mineralogy-petrology textbook suitable for one-semester Earth materials courses. It is our hope that we have succeeded.

Acknowledgments to First Edition

Cornelis Klein thanks Charles Langmuir, Professor in the Department of Earth and Planetary Sciences at Harvard University, for granting him permission (together with a professional photographer, David Nufer, of David Nufer Photography in Albuquerque, New Mexico) to access and photograph specimens from the Harvard Mineralogy Collections. David and I spent three full days there and with the full-time and very attentive help of Carl Francis (curator of the Harvard Mineralogy Museum and Collections) – whose enormous knowledge of the collections allowed us to locate the most appropriate specimens quickly – we completed all of the necessary hand specimen photography of the minerals for this text. Overnight lodging for our four nights in Cambridge, Massachusetts, was generously provided by Leverett House, one of the college houses of which I had been Allston Burr Senior Tutor between 1966 and 1970. We are most grateful to JoAnn DiSalvo Haas and Lauren Brandt for having provided us with some great student rooms.

Throughout the two-year period devoted to the writing of my sections of this text, many colleagues, be it at the University of New Mexico or elsewhere, have been helpful and generous with their time in reviewing sections of text while still in progress. They appear here in alphabetical order: Adrian Brearley, Jonathan Callender, Brian Davis, Amy Ellwein, Maya Elrick, Dave Gutzler, Rhian Jones, Bruce Loeffler, Matt Nyman, Frans Rietmeijer, Malcolm Ross, Jane Selverstone, and Mary Simmons.

I am grateful to David Palmer of CrystalMaker Software Limited, Yarnton, Oxfordshire, England, for providing expertise and guidance in the design of the crystal structure visualization program that accompanies this textbook.

This book would not have been possible without the support and patient understanding of my wife, Shirley Morrison. The word processing of my part of this text was most efficiently and enthusiastically accomplished by Mabel Chavez of Santo Domingo Pueblo, New Mexico.

Anthony R. Philpotts would like to thank the many reviewers who have painstakingly struggled through what we have written and suggested improvements. We have tried to incorporate as many of these as possible within the limits set by the length of the book. I would particularly like to thank Grant Cawthorn for one of the most thorough reviews I have ever received. His knowledge of igneous rocks and the photographs he provided have greatly benefited the book. Dan Kontak, Tony Morse, Brian Robins, and Jane Selverstone also offered valuable advice, as did numerous anonymous reviewers. I am grateful to all of them.

While writing this book, I have greatly appreciated interactions with many colleagues. Jay Ague, Brian Skinner, and Leo Hickey at Yale University, and Sheila Seaman, Mike Rhodes, and Tony Morse at the University of Massachusetts have all provided me with geological insights. I have also learned a considerable amount about sedimentary rocks from Randy Steinen, formerly of the University of Connecticut, and Paul Olsen, of the Lamont-Dougherty Earth Observatory of Columbia University.

I am grateful to the many petrology students I have had over the years. Their many questions and interests played a big role in how I taught the courses and in no small way have determined what, and how, petrology is presented in this book.

Last, none of my part of this book would have been possible without the support of my wife, who allowed me to disappear into my study for fully two years. She is owed an enormous debt of gratitude, especially in view of the fact that when I finished revising my previous book (*Principles of Igneous and Metamorphic Petrology*), I promised her that it was definitely the last one!

Acknowledgments to Second Edition

Anthony Philpotts wants to express his gratitude for having had the opportunity to work with Kase Klein on both the first and second editions of Earth Materials. On June 1, 2016, Kase suddenly, and unexpectedly, passed away. With his passing, the academic world lost one of the great teachers of mineralogy, but I also lost a very dear friend. We were undergraduates together at McGill University in Montreal, taking the same mineralogy and petrology courses and doing all the things that undergraduates typically do. It seemed only natural that toward the end of our careers we should come back together and pool our efforts in writing a book that introduces what we believed were the essentials of mineralogy and petrology that could be covered in the one-semester courses in Earth materials that have recently become so common. Given the vast scope of mineralogy and petrology, deciding on what should be included, or excluded, was a huge task, and I am so grateful to have had the benefit of Kase's wise council. Fortunately, all revisions for the second edition were completed before his untimely death. This book therefore contains his final contribution to the teaching of mineralogy. From its pages, readers will hopefully glean some of Kase's enthusiasm for mineralogy, and with this introduction possibly go on to delve deeper into the subject, as Kase would have hoped.