Essentials of Igneous and Metamorphic Petrology

All geoscience students need to understand the origins, environments, and basic processes that produce igneous and metamorphic rocks. This concise textbook, written specifically for one-semester undergraduate courses, provides students with the key information they need to understand these processes. Topics are organized around the types of rocks to expect in a given tectonic environment, rather than around rock classifications: this is much more interesting and engaging for students, as it applies petrology to real geologic environments. This textbook includes more than 250 illustrations and photos, and is supplemented by additional color photomicrographs made freely available online. Application boxes throughout the text encourage students to consider how petrology connects to wider aspects of geology, including economic geology, geologic hazards, and geophysics. End-of-chapter exercises allow students to apply the concepts they have learned and to practice interpreting petrologic data.

B. Ronald Frost is a professor of geology at the University of Wyoming, where he performs wide-ranging research on igneous and metamorphic petrology as well as ore deposits. He has authored more than 110 scientific papers on topics ranging from serpentinization and the metamorphism of serpentinites, ocean floor metamorphism, granulites, thermobarometry, the geochemistry of granites, and melting of sulfide ore deposits. He has conducted extensive field research in the Precambrian basement of Wyoming, as well as in Siberia, Greenland, northern Canada, and the Broken Hill area of Australia. He received the Alexander von Humboldt Research Award from the German government. He has been an associate editor for the *Journal of Metamorphic Geology* and *Geochimica et Cosmochimica Acta*, and he currently serves on the editorial board of the *Journal of Petrology*. He is a member of the American Geophysical Union, the Society of Economic Geologists, and the Geochemical Society and a Fellow of the Mineralogical Society of America. He has taught mineralogy, petrology, optical mineralogy, and ore deposits for more than thirty-five years.

Carol D. Frost is a professor in the Department of Geology and Geophysics at the University of Wyoming. She investigates the origin and evolution of the continental crust, the provenance of clastic sedimentary rocks, and granite petrogenesis, and she applies isotope geology and geochemistry to environmental issues including water coproduced with hydrocarbons and geological sequestration of carbon dioxide. She is the author of more than 120 scientific papers. She is a Fellow of the Mineralogical Society of America and serves as the science editor for the Geological Society of America's journal, *Geosphere*. She was awarded the CASE Wyoming Professor of the Year award in 2001. In 2008, she received her university's highest faculty award, the George Duke Humphrey medal, recognizing teaching effectiveness, distinction in scholarly work, and distinguished service to the university and to the state. She has served in the administration of the University of Wyoming as director of the School of Energy Resources, associate vice president for research and economic development, and vice president for special projects, and associate provost.

The two authors are unrelated.

Advance praise for *Essentials of Igneous and Metamorphic Petrology*

"An authoritative and contemporary petrology textbook that is ideal for today's undergraduate student. Frost and Frost provide a concise petrology textbook that distills the essence of igneous and metamorphic petrology."

– Joshua Schwartz, Department of Geological Sciences, California State University, Northridge

"Frost and Frost present a streamlined view of igneous and metamorphic petrology that is most appropriate for a one-semester undergraduate-level course. The text clearly explains fundamental concepts, which are supplemented by abundant figures. Subjects are structured so as to build on previous concepts and be well suited to work with a laboratory component typically associated with petrology courses."

– Jeffrey M. Byrnes, Boone Pickens School of Geology, Oklahoma State University

"Frost and Frost have produced a soon to be very popular igneous and metamorphic petrology textbook, as it is truly written for the undergraduate geology major with perhaps just a 100-level introductory geology class and mineralogy as their background coursework. However, it is also rich in detail and thoroughly modern. In both the igneous and metamorphic sections, the authors first introduce the needed rock descriptive and theoretical backgrounds to pave the way for students to explore subsequent chapters. Igneous rocks are examined by their tectonic setting and metamorphic rocks by their protolith, which is exactly how I have taught the course for many years. Inserts in each chapter take students to other relevant areas of Earth science. The appendix includes a very useful review of mineralogy. I look forward to adopting this book!"

– Lawford Anderson, Department of Earth and Environment, Boston University

"An introductory textbook that presents the basic principles of the subject matter in a simple and concise manner. Frost and Frost do a good job of linking igneous and metamorphic petrology to basic chemistry and major tectonic processes. Well illustrated with a decent set of problem sets and a nice summary of mineral properties."

– Aley K. El-Shazly, Department of Geology, Marshall University

"*Essentials of Igneous and Metamorphic Petrology* by Frost and Frost succeeds in its stated objective: to convey the essential petrologic information that is needed by all geoscientists, no matter what their eventual specialization. The book meets this objective with a classical mix of fundamental phase relationships, basic geochemical concepts, and field examples, with the bonus of subject boxes that relate petrology to economic mineral deposits. Frost and Frost will provide students with a solid, clearly written, well-illustrated foundation for understanding igneous and metamorphic rocks. I look forward to using this text in my own undergraduate petrology class."

– Calvin G. Barnes, Department of Geosciences, Texas Tech University

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Preface

Petrology, from the Greek words *petra*, meaning rock, and *logos*, system of understanding, is the study of rocks and the conditions in which they form. It includes igneous, metamorphic, and sedimentary petrology. Igneous and metamorphic petrology are commonly taught together because both disciplines depend on the use of chemistry and phase diagrams. In contrast, sedimentary petrology is often combined with stratigraphy because both of these sciences depend on understanding the physical processes that accompany the deposition of sediments. Igneous and metamorphic petrology share common foundations; for example, both use phase diagrams to understand the conditions that control the crystallization of various minerals. However, there are important differences between the disciplines. In igneous petrology, the bulk composition of the rock is important because it gives clues to the tectonic environment in which it formed. Metamorphic petrology is not so much concerned with the bulk chemistry of the rocks as with the use of mineral assemblages to determine the conditions under which the rock crystallized. Because igneous rocks may later be transformed into metamorphic rocks, this book begins with igneous petrology and takes up metamorphic petrology second.

In contrast to many petrology textbooks, which are written for the upper-level undergraduate and graduate student audience, this book is accessible to introductory-level geology students who may have taken few earth science courses beyond physical geology and mineralogy. It aims to convey the essential petrologic information that is needed by all geoscientists no matter what their eventual specialization, be it geophysics, geochemistry, economic geology, geohydrology, or indeed any aspect of the Earth system.

This book focuses on the fundamental principles that govern the mineralogy of igneous and metamorphic rocks. For igneous petrology, this involves an understanding of how the mineralogy of igneous rocks reflects the equilibria that govern the crystallization of minerals from magma and how the geochemistry of a rock reflects its magmatic differentiation. The book uses several major element discrimination diagrams, including Fe-index, modified alkali-lime index, and aluminum saturation index, to compare and contrast magmatic suites that form in different tectonic environments. These simple geochemical parameters effectively highlight the different magmatic processes that create magmatic suites formed at oceanic and continental divergent plate boundaries, in arcs formed at oceanic and continental convergent margins, and in oceanic and continental intraplate tectonic settings.

In metamorphic petrology, the mineral assemblages in metamorphic rocks depend fundamentally upon the protolith of the rock as well as on the mineral reactions that take place at successively higher temperatures and pressures. Starting with mafic and ultramafic protoliths, which are the simplest, the text describes how pressure, temperature, and fluid composition affect the mineral assemblages in progressively more complex systems, including pelitic and calcareous protoliths. This book emphasizes chemographic projections as a way to determine the metamorphic mineral assemblages that occur together at specific metamorphic conditions. In addition, the text discusses the environments where various types of metamorphism are found and the tectonic significance of different types of metamorphic belts.

Throughout the textbook the authors have provided examples of how petrology relates to other areas of geology, including economic geology, geologic hazards, and geophysics. These short vignettes help students make connections between the study of igneous and metamorphic rocks and other fields of geology and illustrate the value of a fundamental understanding of petrology.

Acknowledgments

This textbook is the result of several decades of experience teaching igneous and metamorphic petrology at the University of Wyoming. The authors began writing this material when what had been two separate, semester-long courses in igneous and metamorphic petrology were combined into one and the existing textbooks were more exhaustive than the new course format could accommodate. They would like to acknowledge the hundreds of students who used successive versions of the igneous and metamorphic petrology course packet and provided edits and suggestions. They are especially grateful to those former students who went on to become geoscience faculty members and who have encouraged the authors to convert the course packet into a commercially published textbook.

The authors also wish to thank the external reviewers for their helpful suggestions and the editors and staff at Cambridge University Press for their expertise and patience in seeing the book through to publication. Too, they warmly acknowledge their colleagues at the University of Wyoming and elsewhere for providing a stimulating and rewarding environment in which to pursue petrologic teaching and research. Last, Carol Frost acknowledges with gratitude her family's forbearance while this textbook underwent repeated revision over many evenings, weekends, and holidays.