Essentials of Igneous and Metamorphic Petrology

Second Edition

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 nearly 300 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 that they have learned and to practice interpreting petrologic data.

B. Ronald Frost is an emeritus 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 120 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*, *Geochimica et Cosmochimica Acta*, and 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 taught mineralogy, petrology, optical mineralogy, and ore deposits for more than 35 years.

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The two authors are unrelated.

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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 concerned mostly with the use of mineral assemblages and textures 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 the iron-enrichment index, the modified alkali–lime index, and the aluminium-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.

The first half of the book is a study of igneous petrology – magmas and the rocks that solidify from magma. Chapters 1–6 describe the fundamentals of igneous petrology. Chapter 1 presents the classification of igneous rocks, and the crystallization of magmas and resulting igneous textures and structures. In Chapter 2, we introduce igneous phase diagrams and how these are used to understand fundamental processes that produce the mineral assemblages, textures, and rock associations that occur in nature. Chapter 3 is an introduction to silicate melts and magmas, including their physical properties and mechanisms that produce differentiated igneous rock suites. Chapter 4 describes how the major- and trace-element chemistry of igneous rocks reflect the processes by which igneous magmas form and differentiate, and Chapter 5 introduces the application of stable and radiogenic isotopes to igneous petrology. This

portion of the text concludes with Chapter 6, in which we explore melt generation from the mantle and the tectonic environments where magmas are generated. Chapters 7–10 examine the igneous rock suites that form in different tectonic environments: the oceanic floor (Chapter 7), convergent margins (Chapter 8), and intracontinental rifting (Chapters 9 and 10). Chapter 11 examines the granitic rock suites that compose the continental crust, and whose mineralogy, geochemistry, and isotopic compositions preserve information about their magma sources and tectonic environment of formation.

The second half of the text concerns metamorphic petrology. Chapter 12 explores how metamorphic petrologists use mineral assemblages to determine the parent, or protolith, of the rock and how metamorphic textures are used to determine whether solid-phase recrystallization took place in a static environment or during deformation. Chapter 13 introduces metamorphic phase diagrams and petrogenetic grids. Chapters 14–17 describe how pressure, temperature, and fluid composition affect the metamorphism of major protoliths, including mafic rocks (Chapter 14), peridotites (Chapter 15), pelitic rocks (Chapter 16), and calc-silicate rocks (Chapter 17). Chapter 18 covers thermobarometry, the quantitative estimation of metamorphic conditions. Finally, Chapter 19 describes the various tectonic environments where igneous and metamorphic rocks are found and the characteristic igneous rock suites and types of metamorphism found in each.

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. Also, 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.

What is New in the Second Edition

To produce this second edition, we have modified the first edition in the following ways:

In response to suggestions from reviewers, we have added a new chapter on application of stable and radiogenic isotopes in petrology. This chapter introduces the concept of isotopic fractionation and the use of stable isotopes in geothermometry and as tracers of magmatic processes. It also describes the process of radioactive decay and the application of radioactive isotopes and their daughter products in geochronology and isotopic petrogenesis.

We have added sections to explain more fully the petrologic significance of phase diagrams, both igneous and metamorphic. Our examples draw explicit connections between the reactions shown on phase diagrams and the mineralogy and textural relations preserved in igneous and metamorphic rocks. Our goal is to demonstrate the usefulness of phase relations of simple systems in predicting and understanding mineral equilibria in natural igneous and metamorphic systems that are chemically more complex.

The second edition places increased emphasis on the connections between igneous and metamorphic rock suites and the tectonic environment in which they form. In addition to new sections throughout the text, we have rewritten the final chapter and present an integrated review of major tectonic environments in which we describe the igneous rock suites and the metamorphic facies typical of each.

The chapter on convergent margin magmatism has been revised to include an updated and more complete description of the origin of arc magmas and mechanisms of magma ascent and emplacement within the crust.

Throughout the text, we have rewritten sections to improve clarity, added new problems, and updated the suggestions for further reading. A new glossary defines bolded terms.