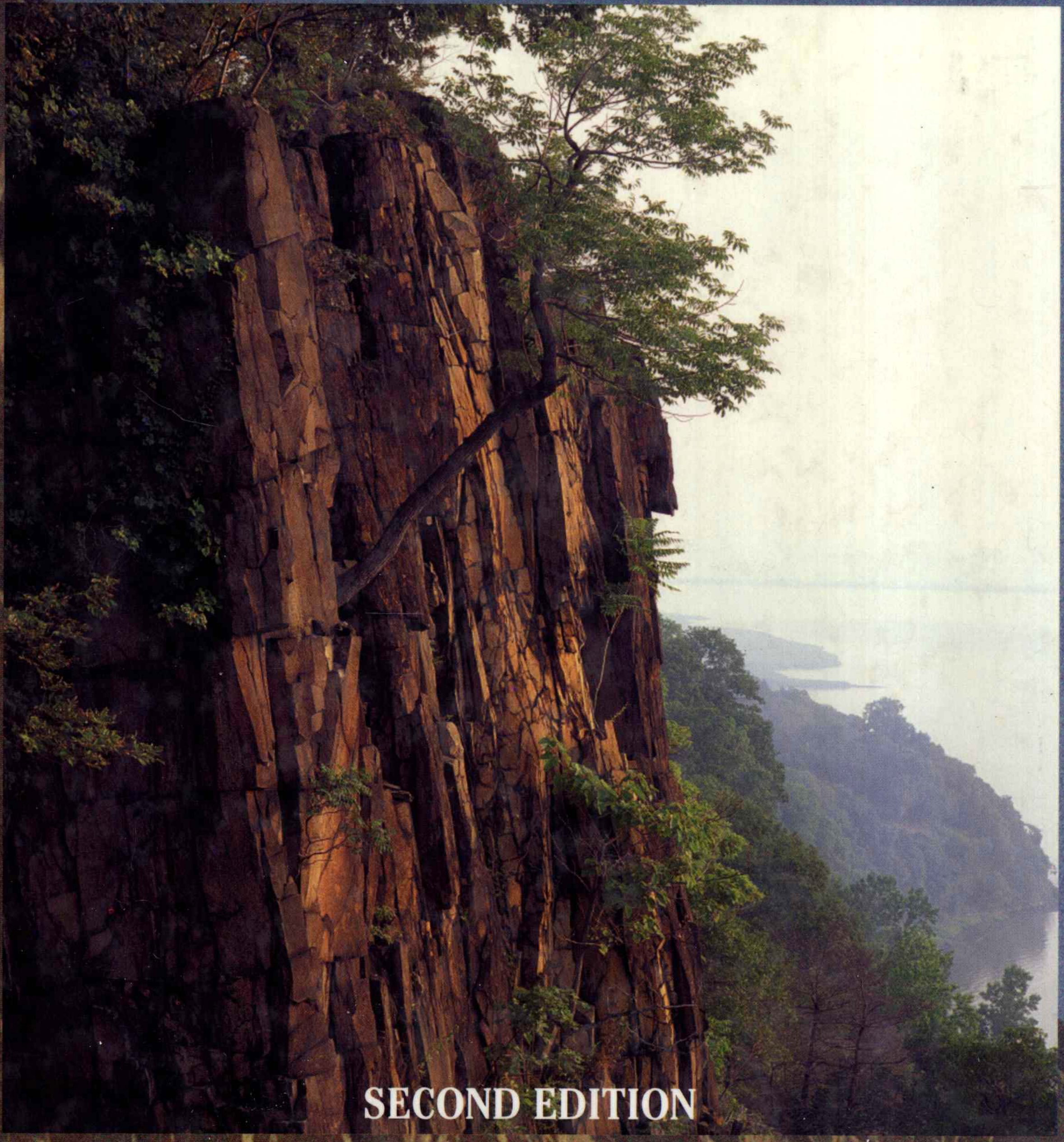
HARVEY BLATT ROBERT J. TRACY

PETROLOGY

IGNEOUS, SEDIMENTARY, AND METAMORPHIC



SECOND EDITION

PETROLOGY

Igneous, Sedimentary, and Metamorphic

Second Edition

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W. H. Freeman and Company
New York

About the cover: The inset image shows the dramatic igneous rock structures of the Palisades Interstate Park that cascade down to the Hudson River, north of New York City. The background image shows the contrast of the sedimentary rock cliffs falling into the Pacific Ocean at Torrey Pines State Park, Del Mar, California.

Photographs by Joshua Sheldon.

Library of Congress Cataloging-in-Publication Data

Blatt, Harvey.

Petrology: igneous, sedimentary, and metamorphic/ Harvey Blatt, Robert Tracy.

p. cm.

Includes index.

ISBN 0-7167-2438-3 (hardcover)

1. Petrology. I. Tracy, Robert J. II. Title.

QE431.2B57 1995

552—dc20 95-35545

CIP

Printed in the United States of America

First printing 1995, VB

PREFACE

The preface to the first edition of this book was written almost 15 years ago. It pointed out that the subject of petrology had undergone a revolution during the previous decade (1970–1980), largely as a result of increasing awareness by geologists that plate tectonics has played a key role in the genesis and distribution of rocks. In the years since then, the ferment over plate tectonics has subsided; it has become standard theory, and petrology has firmly entered a consolidation phase. More than ever before, petrologists are interacting with earth scientists in other fields, notably geochemistry, geophysics, and structural geology, to document how petrologic processes and products fit into a tectonic framework.

The most striking aspect of the change in petrology since 1982 lies in the evolutionary, rather than revolutionary, quantification of techniques for the study of rocks—an evolution sparked by gradual improvements in techniques for indirect measurement of temperatures and pressures of formation, ages, and chemical and physical processes of petrogenesis. These techniques include elemental and isotopic chemical analyses, spectroscopy, and the ready availability of powerful computers to students and researchers. (Note that the explosion in personal computing postdates the writing of the first edition of this book!)

Petrology has long been one of the more quantitative of earth science fields, but the last 15 years have seen an acceleration of mathematical approaches, especially modeling of magmatic and metamorphic processes. Throughout this period, igneous, sedimentary, and metamorphic petrology have increasingly diverged in their fundamental approaches. Igneous petrologists now focus most strongly on geochemical studies of petrogenesis, on the physics of magmas, and on magmatism as a planetary process. Sedimentary petrologists examine the geochemistry of sediment formation and diagenesis, the details of the relationship of sedimentation patterns to plate tectonic regimes, and the use of sedimentary rocks in documenting long-term climatic patterns on the earth. In turn, metamorphic petrologists emphasize the refinement and application of thermodynamic databases for calculation of phase equilibria, the development of more precise techniques for characterization of temperature-pressure-time paths during metamorphism, and the complex processes of fluid-rock interactions in the crust.

This broad diversity within the description of petrology and the rapidly increasing store of information about rocks and rock-forming processes have made writing this book a challenging task. Our goal has been as much to enable readers as to inform them. The book is aimed at giving undergraduate students an appreciation of the current fundamental intellectual approaches to the study of rocks, as well as the basic tools and information they need to make a start on reading and understanding the literature of petrology. We have not attempted the obviously impossible feat of creating an encyclopedic volume about rocks. Rather, we introduce readers to the way petrologists go about doing their work. Study exercises at the end of each chapter give students a way to test their understanding of the material, and the references and additional readings provide a pathway into a deeper pursuit of each topic. We have written the book as a text for a first course in petrology, at a level appropriate to college sophomores or juniors, and have assumed a basic understanding of elementary chemistry and mineralogy. We hope that all student readers will have an opportunity to work with thin sections and petrographic microscopes, and thus gain a greater appreciation for the inner workings of rocks.

We gratefully acknowledge the contributions of all the scientists whose work we have cited in this book and who have given us permission to reproduce their materials. In addition, we would especially like to thank colleagues who have inspired us as mentors, fellow teachers, or students and who in some cases have provided critical reviews or special materials; these include R. A. Badger, J. M. Christie, W. G. Ernst, R. L. Folk, R. A. Heimlich, P. C. Hess, D. A. Hewitt, J. F. Hogan, T. N. Irvine, D. M. Kerrick, John Longhi, the late H. O. A. Meyer, S. A. Morse, B. J. Munn, Peter Robinson, A. B. Thompson, J. B. Thompson, and E. W. Wolfe.

CONTENTS

Introduction

WHY STUDY PETROLOGY?

Leaving aside the atmosphere and hydrosphere, rocks are the stuff of which the earth is made. Because of this, the study of rocks, petrology (from the Greek *petra*, "rock," and *logos*, "discourse or explanation"), occupies a central position among the earth sciences. The study of rocks is the source of virtually all of our ideas about the history of Earth. Knowledge about rocks, their origin and ages, and their distribution is potentially capable of contributing to the solution of a wide variety of problems that run the gamut of geological interests.

1. Most evolutionary biologists believe that living matter evolved from nonliving matter more than 3 billion years ago in a reducing atmosphere, because it is thought that primitive cells would have been defenseless against oxidation. This suggestion implies that there was little or no oxygen in the atmosphere of the early earth, a theory supported by the absence of free oxygen in the atmospheres of other planets in our solar system. However, early Precambrian (Archean) iron ores contain oxidized iron, in the form of magnetite, a fact that might be interpreted to mean that the early atmosphere contained substantial oxygen. Similarly, Precambrian weathering zones or soils have a red appearance caused by oxidized (hematitic) iron. Did these ores and soils contain magnetite or hematite from the beginning, or was more reduced iron gradually oxidized as free oxygen increased in the atmosphere in the later Precambrian and after? Can we use these rocks to infer how much oxygen was present in the early atmosphere?

2. The relative abundance of different sedimentary materials forming at present is drastically different from rock abundances found in the geologic record.

- **a.** Dolostone is three times as abundant as limestone in Precambrian rocks. At present, formation of dolostone is rare, restricted to unusual environments such as the Persian Gulf or the Netherlands Antilles.
- **b.** The Middle Precambrian stratigraphic column (about 2.5 billion years old) contains about 15 percent fine-grained silica in the form of chert. At present, chert formation is trivial outside the deep ocean basins.
- **c.** Evaporites are extremely rare in the Precambrian as compared to more recent times. Why? Has the composition of seawater changed during the last 2.5 billion years? Has the proportion of rocks exposed to weathering, and thus the composition of material supplied to the oceans, changed since the Precambrian?

3. Igneous rocks have a wide variety of textures and compositions—in particular, a range in silica content from less than 45 to about 75 percent. Yet the great bulk of igneous rocks consists of either coarse-grained granitoid rocks (silica content of about 65 to 75 percent) or fine-grained basaltic rocks (silica content of 45 to 52 percent). What does this tell us about formation and evolution of magmas and about crust-forming processes?

4. Metamorphic rocks of identical chemical composition in different tectonic settings and at different crustal depths can consist of widely differing mineral assemblages. How, exactly, does this relate to metamorphic reactions and to different rates of temperature and pressure change during orogeny?

5. Some sandstones contain only quartz; others, 30 percent feldspar; and still others 90 percent volcanic rock fragments. Can these data be used to infer the types and proportions of rocks exposed on the earth's surface at different times and in different geographic locations? Can similar sedimentary rock types be identified as the precursors for metamorphic rocks in orogenic belts? Is the precise mineral composition of sandstones and other clastic rocks related to tectonic processes and crustal evolution—and, if so, how?

6. Geologic studies of the lunar surface and satellite studies of the Martian surface have given us a preliminary understanding of the early stages of planetary evolution in bodies that have been geologically inactive for billions of years. Can we use our developing understanding of other planetary bodies to interpret the much sparser information on the early earth preserved in rare, very old rocks that have survived later geologic activity and recycling?

THE MAJOR ROCK TYPES

Rocks are naturally occurring, mechanically coherent aggregates of minerals or mineraloids (coal, glass, opal), and most rocks consist of several different minerals. Rocks are traditionally divided into three groups: igneous, sedimentary, and metamorphic. In most outcrops and hand specimens, it is not difficult to apply these categories, and they serve the useful purpose of sorting rocks on the basis of observable characteristics that depend on the conditions of initial formation. The American Geological Institute's *Glossary of Geology* defines each group as follows:

Igneous rock: A rock that solidified from a molten or partially molten material, that is, from a magma.

Sedimentary rock: A rock resulting from the consolidation of loose sediment that has accumulated in layers. A clastic rock consisting of mechanically formed fragments of older rock transported from their source and deposited in water or from air or ice; or a chemical rock formed by precipitation from solution; or an organic rock consisting of the remains or secretions of plants and animals are examples.

Metamorphic rock: Any rock derived from preexisting rocks by mineralogical, chemical, and structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the earth's crust; that is, below the zones of weathering and cementation.

This fundamental classification scheme, as is true of all classification schemes, contains a flaw. Nature is a continuum; it is not segregated into discrete parts for our convenience. Hence, borderline or transitional rocks exist and end up in one or another of the categories because of historical precedence or the bias or whim of the classifier. For example, volcanic tuffs are rocks that originate in volcanoes. After explosive ejection as rock, mineral, or glass fragments into the atmosphere, they settle on land surfaces or in the water. They may even be transported some distance by water or wind. If they settle into layers (as is common), should they be classified as sedimentary or igneous? In most classification schemes, these rocks are classified as igneous. Another example is serpentinite, a rock mainly composed of minerals of the serpentine group. Many serpentinites are thought to originate as ultramafic magmatic rocks in small, shallow magma chambers near a mid-ocean ridge. During cooling, they undergo hydration from surrounding water-rich sediments that transforms most or all of the crystals into serpentine. Should this rock be classified as igneous or metamorphic? Most petrologists would classify it as metamorphic. A third example is migmatite, an outcrop-scale mixture of light and dark rocks thought to represent the onset of melting in the crust. Thus, migmatite is partly metamorphic and partly igneous.

In fact, the necessity of classifying rocks commonly forces petrologists into making critical observations and interpretations that aid in assessing the process of formation of rocks. In this book we discuss many of these observations and interpretations. Additional subdivisions within each of the major categories are introduced and discussed. Subdivision of rocks into the three general categories can be based to some extent on actual observation of processes of formation, particularly for sedimentary and volcanic rocks. For intrusive igneous rocks and metamorphic rocks, it is obviously impossible to observe their formation directly, and therefore indirect and inferential methods are required.

Table I-1 is designed to facilitate the subdivision of rocks into one or another of the major categories. The table lists some of the outcrop characteristics and structures, followed by textures and characteristic minerals. Note that any single characteristic may not be sufficient to categorize the rock but, rather, a number of such features may have to be used. Unfamiliar and technical terms that we use now or later are either defined in the text or found in the Glossary. Glossary terms are indicated by bold print in the text.

RELATIVE SURFACE AND CRUSTAL ABUNDANCES OF ROCK TYPES

The earliest geologic maps date from about 1800, and most parts of the earth have now been mapped either in detail or at a reconnaissance scale. Using such maps and related literature, we can determine the relative abundances of igneous, sedimentary, and metamorphic rocks on the continents. The method used to obtain the data is to generate random latitudes and longitudes by computer and then examine existing maps to determine the frequency of igneous, sedimentary, and metamorphic outcrops. Results indicate that Earth's surface is 66 percent sedimentary rocks and 34 percent igneous and metamorphic rocks. The bulk of the 34 percent is probably igneous, but large parts of some continents are mapped as "undifferentiated igneous and metamorphic rocks," so exact percentages are uncertain. As detailed geologic mapping proceeds worldwide, a better estimate may be possible.