Petrology

The Study of Igneous Sedimentary & Metamorphic Rocks



SECOND EDITION

Loren A. Raymond

Second Edition

PETROLOGY

The Study of Igneous, Sedimentary and Metamorphic Rocks

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PETROLOGY: THE STUDY OF IGNEOUS, SEDIMENTARY AND METAMORPHIC ROCKS
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Dedicated to
Margaret
whose patience and love during eleven years of
lost vacations,
and whose typing and encouragement
over that time,
helped make this book possible
and to
Matt
who sacrificed significant quality time
while he was growing up.

PREFACE

Petrology is a required subject of study in a majority of geology programs in the United States and is an integral part of geology curricula in Canada and elsewhere in the world. The subject merits this important position because rocks make up much of the Earth. Furthermore, many subdisciplines in geology incorporate petrologic knowledge. Thus, petrology provides the foundation for the study of the Earth and its history.

Available petrology texts designed for middle-level undergraduate students (sophomores and juniors) take a variety of approaches. Some concentrate on principles, others deal only with igneous and metamorphic rocks, and still others tend to emphasize the descriptive aspects of the field (petrography). Only a few books incorporate recent advances in crystal growth studies, isotopic analyses, chemical petrology, sedimentary environmental analysis, and petrotectonics, as well as basic petrographic information.

This text, designed for the middle-level undergraduate geology major, incorporates both fundamentals and information on recent advances in our understanding of igneous, sedimentary, and metamorphic rocks. It provides an overview of the field of petrology and a solid foundation for more advanced studies. For each class of rocks—igneous, sedimentary, and metamorphic—I describe textures, structures, mineralogy, chemistry, and classification as a background to discussing representative occurrences and petrogenesis (rock origins). I have not tried to summarize all occurrences, but the explanatory notes at the end of each chapter provide additional sources the student can use to expand his or her understanding and knowledge.

Advances in petrologic knowledge come about through the efforts of individuals and groups of individuals. Individuals do not operate in a vacuum; rather, they work within a social and political environment. Whether or not an idea is accepted or has an impact on a specific scientific milieu is influenced by the quality of the idea (e.g., its ability to explain phenomena) and the quality of the data that support it; by the social, scientific, and political climate; and by the reputation of the scientist presenting the idea. Certain scientists, more than others, influence the development of a discipline. For this reason, I have chosen to cite, in the text, scientists who have been particularly influential, individuals who have made unique contributions, and a few whose work has advanced or updated earlier contributions of significance. Others who also have made significant contributions or have added to the body of knowledge in a specific area are cited in the notes. Not all of those cited have been correct in their advocacy of particular hypotheses, but each has influenced petrology by contributing major ideas or significant data or by spurring others to prove his or her ideas wrong. In citing a limited number of scientists in the text, my aim has been to make the text more readable while still including sufficient references that may also serve as a model of proper referencing and good scholarship for students.

Igneous rocks are introduced first. Here, as with the other classes of rock, the rock types that are most important volumetrically in the crust are given the greatest emphasis. Because great debates arise from time to time about the origins of these most common rock types (e.g., basalts, andesites, granites), I have chosen to discuss each rock type individually rather than as part of a tectonic association, suite, or clan, as some other texts do. Where it is essential, I do discuss associated rocks.

Conflicting points of view on rock origins are included in many chapters. The inclusion of these controversies is important for two reasons. First, they provide the student with historical background that makes contemporary theory more meaningful. One can see ideas that have come before, see where mistakes have been made (science is a self-correcting enterprise), and see why certain ideas have been abandoned. Some scientists have reinvented the wheel (independently created anew an idea that was formerly evaluated and rejected) because of a lack of knowledge of petrologic history. Second, contemporary controversies reveal that there are many unresolved questions and there is much petrologic work to be done.

Sedimentary rocks are divided into siliciclastic types (mudrocks, sandstones, conglomerates), biochemically and chemically precipitated types (e.g., limestones, cherts), and allochemical types (e.g., limestone conglomerates). Because classifications vary and devotees of one classification or another are often strongly committed to the classification and descriptive practices they follow, various classifications are presented and discussed. Mudrocks and wackes (sandstones), especially turbidites, are given more attention than is common in petrology texts, because of the abundance of mudrocks and the tectonic and economic importance of the wackes. Sedimentary facies analysis is introduced to provide the student with an understanding of the interrelationships among various sedimentary rock types. A chapter on weathering, transportation, and diagenesis links the chapters on sediments and their environments of deposition to those dealing with specific sedimentary rock types.

Metamorphic rocks are presented in the same general fashion as the other classes of rocks, with descriptive aspects preceding chapters detailing the petrogenesis of particular suites of rocks. The facies series concept of Miyashiro is used as a basis for subdividing metamorphic rock suites and for describing the distribution of these suites in metamorphic terranes. Eclogites and cataclasites are given special attention because, although the former are considered to be representative of some mantle rocks and the latter are widely distributed, both are underdescribed in most petrology texts.

The epilogue places all of the rock types into appropriate petrotectonic assemblages representing various plate tectonic sites. Plate tectonics is first discussed in the introduction and is reemphasized in many of the rock chapters where petrogenesis is cast in a plate tectonic framework. Thus, the epilogue synthesizes the broad aspects of petrogenesis.

Important terms are set in bold print in the text where they are first defined and used. Definitions are also provided in a glossary. As a teacher, I subscribe to the view that one must know the vocabulary of a subject in order to be able to effectively communicate in that subject, just as one must know the vocabulary of a foreign language if one desires to communicate in that language. Students are commonly frustrated when they make the transition from texts, which define terminology, to the professional literature, where a knowledge of terminology is assumed. The significant number of defined terms used in this text should help students with this transition.

The language (syntax and word choice) used in the text ranges from simple to moderately complex, with the intent of developing in the student an increased vocabulary and an increased facility with the English language. The presentation of ideas follows a similar (simple to complex) pattern in many of the chapters. In addition, later parts of the text assume an understanding of some earlier parts. A list of Latin words and abbreviations used in the text (e.g., *sensu lato*), as well as other abbreviations appears on page xiv. This too is presented in the hope of increasing the general literacy of students of geology. Also, To the Student on page xiv includes a list of units of measure used in the text.

PREFACE TO SECOND EDITION

Our understanding of petrology continues to change as new data, approaches, and technologies facilitate a greater understanding of petrologic processes and history. One major advance in petrologic understanding over the past few years involves the recognition and petrologic analysis of ultrahigh-pressure (UHP) rocks. Another advance arises out of a better understanding of the roles of fluids in petrologic processes. These and other materials are included in this edition.

This book retains its original purpose—to serve as a first petrology text for upper-level undergraduate students. The focus and the existing length of the book preclude any detailed treatments of optical mineralogy, tectonics, stratigraphy, and the petrology of less common rocks such as lamprophyres, phosphorites, and charnokites. Discussion of these topics is left to more advanced texts and courses.

At the request of some reviewers, colleagues, and students, I have reduced the length of the text slightly. On the other hand, some have suggested the addition of more text on one topic or another. Where possible, I have added a modest amount of new text, while always keeping in mind the need to reduce the overall book length. I hope the changes will please those who requested them and make the book more useful to all.

Loren A. Raymond - August 2000

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FROM THE AUTHOR

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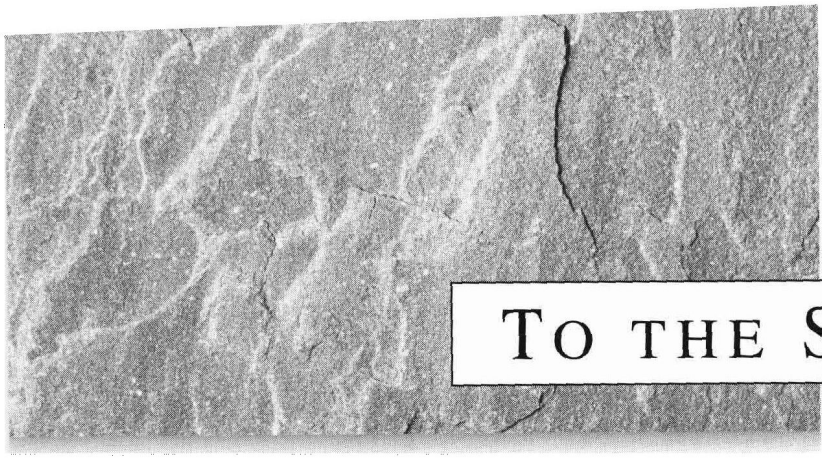
All errors in understanding or knowledge are my own responsibility. A large number of students challenged me during my teaching, discovered sources during their own library research, or otherwise contributed to the successful completion of this project. Among those who provided particular assistance on specific projects were Paul Dahlen, Neil Johnson, Anthony Love, Marjorie McKinney, Vickie Owens, Elizabeth Stevens, Fred Webb, and Susan Wilson. Paul Dahlen assisted with photographic work. Tom Terranova, who prepared the line art for the book, provided inspiration for developing high-quality illustrations. Matt Raymond provided scale in some photographs and gave up much "quality time" over the eight-year period that I was writing the text. Margaret Raymond provided love, support, and many hours of typing time, all of which were of immeasurable help in the completion of this project. To all of the above-named individuals and organizations, I give my heartfelt thanks.

Visit our Instructor's Resources page on the McGraw-Hill GeoScience Supersite at www.mhhe.com/earthsci/geoscience/ for a comprehensive reference list for this text.



To the Student

Units of Measure Used in the Text and Conversion Factors

Pressure (P)

1 Gpa (Gigapascal) = 10^9 Pa (Pascal) = 10 kb (kilobars) = 10^4 bars

Temperature (T)

K (Kelvin) = °C (degrees Celsius) + 273

Length (l)

1 km (kilometer) = 10^3 m (meters) = 10^5 cm (centimeters) = 10^6 mm (millimeters) = 0.6214 miles

Area (A)

1 km^2 (square kilometer) = 10^6 m^2 (square meters) = 10^{10} cm^2 (square centimeters)

Volume (V)

1 km^3 (cubic kilometers) = 10^9 m^3 (cubic meters) = 10^{15} cm^3 (cubic centimeters)

Mass (m)

1 kg (kilogram) = 10^3 grams

Density (ρ) (rho)

1 kg/m^3 (kilograms per cubic meter) = 10^{-3} g/cm^3 (grams per cubic centimeter)

Acceleration of Gravity (g)

0.0098 km/sec^2 = 9.8 m/sec^2 = 980 cm/sec^2

Time (t)

1 b.y. (billion years) = 10^3 m.y. (= 10^3 ma) (million years) = 10^9 years ~ 3.16×10^{16} seconds

Phase Rule and Phase Diagrams

P = number of phases

C = least number of components necessary to define a system

F = the number of degrees of freedom = the variance

X = composition

List of Chemical Symbols Used in Text

Al—aluminum
Ar—argon
B—boron
Ba—barium
Be—beryllium
C—carbon
Ca—calcium
Ce—cerium
Cr—chromium
Cs—cesium
Eu—europium
F—fluorine
Fe—iron
Ga—gallium
Gd—gadollium
H—hydrogen
He—helium
K—potassium
La—lanthanum
Li—lithium
Lu—lutetium
Mg—magnesium
Mn—manganese
Na—sodium
Ni—nickel
Nd—neodymium
O—oxygen
Os—osmium
P—phosphorus
Pb—lead
Pr—praseodymium
Rb—rubidium
Re—rhenium
S—sulfur
Si—silicon
Sm—samarium
Sr—strontium
Ta—tantalum
Ti—titanium
Th—thorium
U—uranium
V—vanadium
W—tungsten
Y—yttrium
Yb—ytterbium
Zr—zirconium

List of Common Abbreviations and Prefixes Used in the Text and Their Meanings

blasto—to bud; to sprout; hence to form anew in a metamorphic rock
cf.—compare to
e.g.—for example
et al.—and others
i.e.—that is
Idem.—In the place cited (above).
in situ—in place
inter—between
intra—within
iso—the same
sensu lato—in the broad sense
sensu stricto—in the strict sense

Figure FM 1 Map showing locations of examples of rock occurrences in North America discussed in the text.

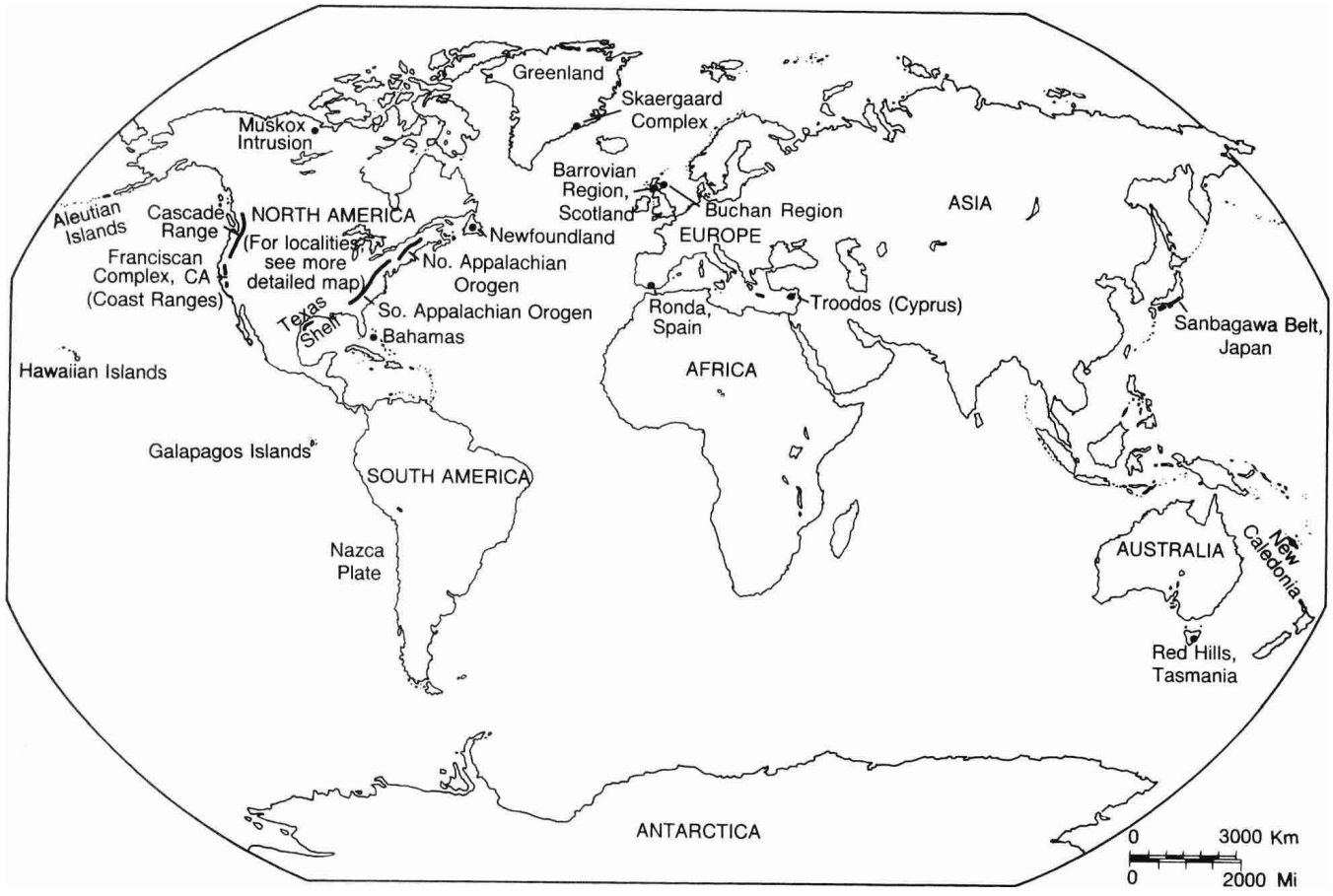
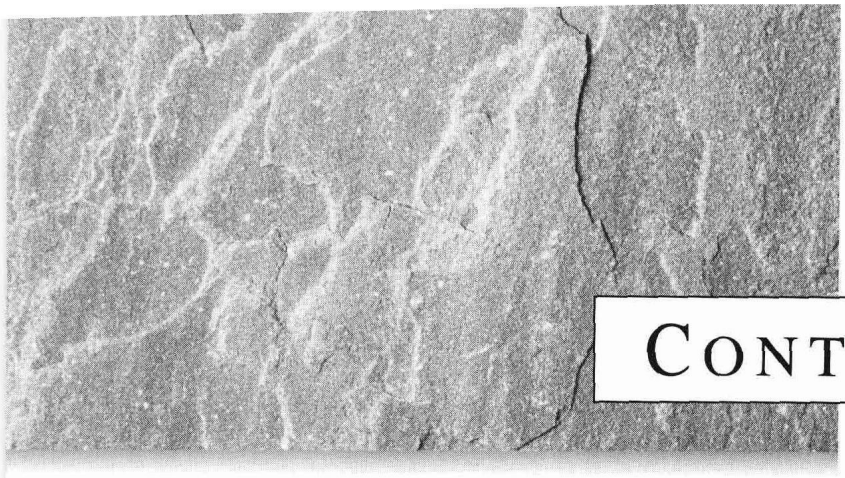


Figure FM 2 Map showing locations of examples of rock occurrences discussed in the text.



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