Geology of the American Southwest

A Journey through Two Billion Years of Plate-Tectonic History

The processes of geology form our landscape over immeasurable expanses of time, and nowhere is this more self-evident than in the spectacular scenery of the Southwest of the United States of America. Two billion years of Earth history are represented in the rocks and landscape of this region, creating natural wonders such as the Grand Canyon, Monument Valley, the Black Canyon of the Gunnison, and Death Valley.

The Southwest stretches from southern Utah and Nevada in the north, to Arizona, New Mexico, southeastern California, and northern Mexico to the south. This region is considered a geologist's 'dream,' since its rocks provide a slice through a huge range of Earth history, and provide examples of many of the geologic processes shaping the Earth. For this reason, the region attracts a large number of undergraduate field classes and amateur geologists.

Geology of the American Southwest provides the first concise and accessible account of the geology of the region. It relates local geological events to global plate tectonics, and documents complex episodes of sedimentation, mountain building, and crustal stretching, describing events leading to features of the modern landscape. Its broad, chronological approach differs from other books about the geology of the region, which either focus on smaller regions or are organized by travel route. This book will prove invaluable to students studying the geology of the Southwest. It will also appeal to anyone interested in geology and landscape, and is a valuable guide for visitors to the National Parks and Monuments of the region.

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Throughout his thirty-four years of teaching undergraduate students at Hamilton College in Clinton, New York, Donald B. Potter sought to instill in them a love for geology and an appreciation for the importance of science in a liberal arts education. With infectious enthusiasm, he encouraged and guided students to deduce geological relationships from empirical observations, using the field as an outdoor laboratory whenever possible. An impeccable field geologist, researcher, and scholar, Don involved undergraduates in research before it was fashionable to do so. Among the lessons taught by Don were the fundamental importance of critical thinking and writing skills. This book, then, is dedicated to Donald Brandrith Potter, whose commitment to a career of teaching and whose passion for geology helped to educate, motivate, and inspire more than a generation of students.

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Preface

The geologic history of the American Southwest is both fascinating and important, not least because it is openly revealed to both the professional Earth scientist and casual observer alike. The exposures in this arid to semi-arid region are generally superb. This book, then, is intended to present a systematic and comprehensive picture of the geology of the Southwest since the formation of its earliest rocks in subduction zones, through the formation and fragmentation of at least two and possibly additional supercontinents. It will supplement other books, including the popular road guides, presenting more detailed pictures of the geology of the region.

But the real importance of geological studies of this region lies in their broad application to other areas of the Earth. Geological paradigms developed in the Southwest have global import. Thus, a secondary purpose is to highlight the numerous concepts that have grown out of study and research in the Southwest and West and that have bearing elsewhere in the world. Since the geographical and topographical surveys of the middle and latter part of the nineteenth century, the geology of the West has strongly influenced the development of the geological sciences. Examples derived from the American Southwest have been used in the professional training of geologists for over a hundred years. In part, this book will illustrate how concepts derived from study of modern rocks feed back into an understanding of rocks from earlier periods of Earth's history, and vice versa. Many important global geological concepts have emerged from the Southwest. Some of the geological paradigms developed in this region are in the process of being applied in other, less well exposed and studied, regions of the world.

Because of the vigorous and ongoing research activity in the Southwest, part of the approach used here is to highlight research issues and

unsolved problems, and to point out implications for understanding geological problems worldwide. In this manner, the reader may appreciate the ongoing nature of science, which is, after all, a process of exploration. Thus, this approach emphasizes the dynamic, human intellectual endeavor that *is* science and, implicitly at least, the processes by which understanding is arrived at. Presenting some of the limitations of our understanding can be frustrating, because we are reminded of how much is not yet known. At the same time, it is encouraging to be reminded of how much *has* been learned. And major progress continues to be made, as geologists apply new tools and acquire the new data that allow them to choose between alternative hypotheses. Therefore, we can expect that, of the uncertainties highlighted in this book, non-viable hypotheses will eventually be abandoned and successful ones will become accepted, probably in modified form.

The organization of this book differs from that of many devoted to the geological history of parts of the Southwest, or any region for that matter, in two significant respects. First, books on the geologic history of a region typically devote only a few paragraphs or perhaps a chapter to Precambrian time. In diagrammatic time scales, the Precambrian scale is invariably greatly compressed. Yet the Precambrian includes most of geologic time and, in the Southwest, the most important interval of time. For it is during the Precambrian, or more specifically, the Proterozoic (the latter part of the Precambrian) that initial formation of continental crust in the Southwest occurred. Everything else — most of what we see and live on in the Southwest — is built upon this fundament. In the present book, three chapters are invested on the Precambrian. Second, chapters are organized around major geological events that affected the Southwest, rather than by the conventional time-stratigraphic scale, which, when developed in the nineteenth century, reflected events and 'packages' of rock units mainly in Europe. Each chapter of the book begins with a *linear* time scale, with key events referenced.

To minimize interruptions to the text, boxes are used for selected definitions and for detailed discussions of specific features. Some of these are, in a sense, 'mini' papers. In a few instances, figure captions may stand separate from, and augment, discussions in the text. Thus, they constitute 'micro' papers.

This book assumes a familiarity with the terminology and concepts presented in a basic course in physical geology and therefore is directed toward upper level undergraduates and graduate students. Selected terms and concepts that are typically not explained in introductory textbooks on physical geology are discussed in boxes and in the Glossary. It is hoped that this book will be useful as the basis for a course in the geology of the Southwest, especially when supplemented by additional readings from other books and from original literature for in-depth coverage of specific topics. Also, each year many colleges and universities from all over the United States, and in some instances from outside the country, organize field trips to the Southwest, for which this book may serve as a useful introduction.

Finally, because of the tendency in all sciences, and not least in the Earth sciences, toward specialization, it is often difficult to step back and see the broad progress that has been made in understanding a very complex problem. Although many fascinating and important details must be omitted, it is hoped that, through a synthesis of the progress made in studying the geology of the Southwest and in relating the results of relevant studies in other areas and disciplines, the overall paradigm emerges: the geological development of the Southwest.

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Note on the text

In the title of this book I have used the term 'billion' because common parlance in North America is to speak of the age of Earth in billions of years. To Americans and Canadians the term 'billion' means a quantity equal to 10^9, i.e., a thousand million. However, in large parts of Europe the term 'billion' stands for a million million (10^{12}), a quantity which we in North America call a 'trillion.' Therefore, in the remainder of this book I have avoided the term 'billion' and used instead 'thousand million' or appropriate abbreviations (see List of abbreviations).

All references to direction are with respect to *present* coordinates. Present directions are not necessarily the same (in fact, probably are *not* the same) as when the geologic units under discussion were emplaced. Similarly, references to North America, the Southwest, etc., do not imply that these geographic regions were then as they are today. North America did not achieve anything close to its present outline until after the breakup of Pangea, which began in the Triassic period sometime after 248 million years ago, and has continued to change its shape and area even to the present.

Words or phrases introduced in **bold** font refer to definitions and/or explanations in text boxes.

Abbreviations

m.y.	Million years. Used to indicate an interval of time, but not a specific time in the past.
Ma	Million (10^6) years ago. From *mega* (million) and *anni* (years). Used for dates of events in the past.
Myr	Million (10^6) years or million years old. Used for a duration of time or age.
Ga	Thousand million (10^9) years ago. From *giga* (10^9) and *anni* (years). Used for dates of events in the past.
Gyr	Thousand million (10^9) years or thousand million years old. Used for a duration of time or age.
kg/m^3	Unit of density in the widely accepted *Système International d' Unités*, or SI, system. Equivalent to $g/cm^3 \times 1000$ in the cgs system.
km	Kilometer.
cm	Centimeter.
GPa	Gigapascal. Unit of pressure equivalent to 10 kilobars.