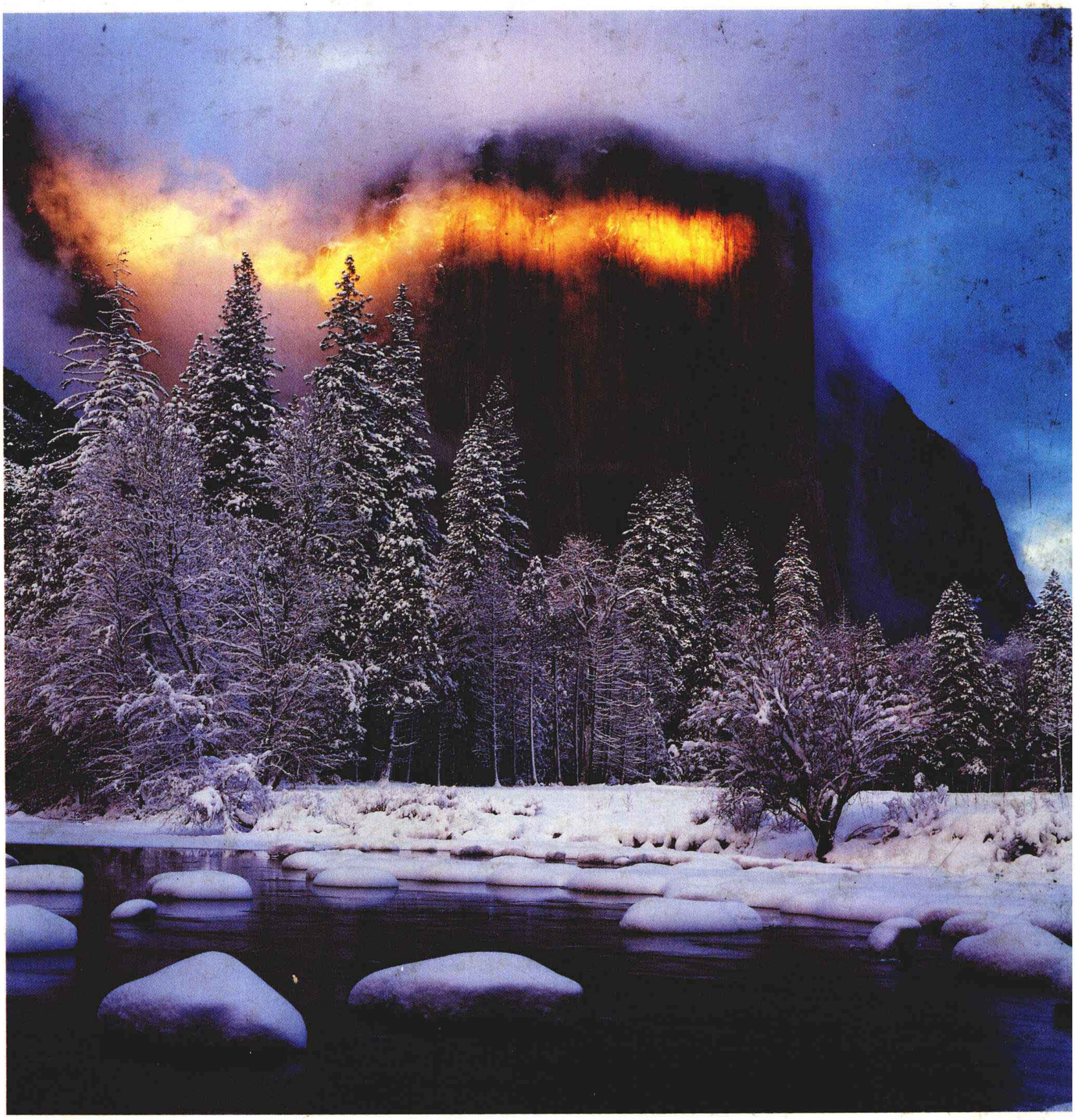
THE EARTH

Third Edition



An Introduction to Physical Geology

Tarbuck · Lutgens

THE EARTH

AN INTRODUCTION TO PHYSICAL GEOLOGY

Third Edition

Edward J. Tarbuck
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ILLINOIS CENTRAL COLLEGE

MERRILL PUBLISHING COMPANY
A Bell & Howell Information Company
Columbus Toronto London Melbourne

Cover and Title Page Photo: Sunrise alpenglow, Yosemite National Park, California. Alpenglow is a meteorological phenomenon in which the sunrise colors precede the regular coloration on a mountain summit. A similar phenomenon occurs at sunset with the reappearance of sunset colors on a mountain summit after the original mountain colors have faded into shadow. Photo by James Randklev/ALLSTOCK.

Published by Merrill Publishing Company
A Bell & Howell Information Company
Columbus, Ohio 43216

This book was set in Garamond

Production Editor: Rex E. Davidson
Text Designer: Cynthia Brunk
Art Coordinator: Raydelle Clement
Photo Coordinator: Gail Meese
Cover Designer: Cathy Watterson
Illustrations by Dennis Tasa, Tasa Graphic Arts, Inc.

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Library of Congress Catalog Card Number: 89–61343
International Standard Book Number: 0–675–21205–7
Printed in the United States of America
1 2 3 4 5 6 7 8 9—94 93 92 91 90

PREFACE

In recent years, media reports have made us increasingly aware of the geological forces at work in our physical environment. News stories graphically portray the violent force of a volcanic eruption, the devastation created by a strong earthquake, and the large numbers left homeless by mudflows and flooding. Such events, and many others as well, are destructive to life and property, and we must be better able to understand and deal with them. However, our natural environment has an even greater importance, for the earth is our home. The earth not only provides the mineral resources so basic to modern society, but it is also the source of most of the ingredients necessary to support life. Therefore, as many members of society as possible should acquire a basic understanding of how the earth works.

With this in mind, we have written a text to help people increase their understanding of our physical environment. We hope this knowledge will encourage some to actively participate in the preservation of the environment, while others may be sufficiently stimulated to pursue a career in the earth sciences. Equally important, however, is our belief that a basic understanding of earth will greatly enhance appreciation of our planet and thereby enrich the reader's life.

The Third Edition of *The Earth: An Introduction to Physical Geology,* like its predecessors, is intended for both science majors and non-majors taking their first course in geology. We have attempted to write a text that is not only informative and timely, but one that is highly usable as well. The language is straightforward and written to be understood by a student with little or no college-level science experience. We have deliberately refrained from using excessive jargon and when new terms are introduced, they are placed in boldface and defined. A list of key terms with page references is found at the end of each chapter, and a glossary is included at the conclusion of the text for easy reference to important terms. Further, review questions conclude each chapter to help the student prepare for exams and quizzes. Useful information on metric conversions, the periodic table of the elements, common minerals, and topographic maps is also provided in the appendices.

In the first two editions of this text special attention was given to the quality of photographs and artwork because geology is a highly visual science. This emphasis has been maintained in the Third Edition. More than 100 new color photographs appear in this revision. The photographs and images were carefully selected to add realism to the subject and to heighten the interest of the reader. Moreover, the already excellent art program of the earlier editions has been strengthened in the Third Edition. Because we believe that carefully planned and executed line art will significantly aid student understanding by making difficult concepts less abstract, more than 110 new and redrawn figures appear in the Third Edition. Once again, the text has benefited greatly from the talents and imaginative production of Dennis Tasa of Tasa Graphic Arts, Inc.

The Third Edition of *The Earth: An Introduction to Physical Geology* represents a thorough revision. Extensive rewriting has made many discussions more timely and more readable. It should be emphasized, however, that the main focus of the Third Edition remains the same as in the first two editions—to foster a basic understanding of physical geology. As much as possible, we have attempted to provide the reader with a sense of the observational techniques and reasoning processes that constitute the discipline of geology. As with other sciences, geology is much more than a mere collection of facts. At its heart are the various methods of probing the earth aimed at uncovering its secrets. These methods involve the collection of the necessary data used to test hypotheses about the nature of the forces that shape our changing planet. In addition to gaining a better understanding of these natural processes, this activity often leads to a re-evaluation of ideas formulated at a time when less information was available. An excellent example of the way geological "truths" are uncovered and reworked is found in Chapter 18. Here we trace the historical formulation and subsequent rejection of the hypothesis that continents drift about the face of the earth and then examine the data that led to the "rebirth" of this idea as part of a more encompassing concept known as plate tectonics.

The organization of the text remains intentionally traditional. Following the overview of geology in the introductory chapter, we turn to a discussion of earth materials and the related processes of volcanism and weathering. Next, a discussion of a most basic topic, geologic time, is followed by an examination of the geological work of gravity, water, wind, and ice in modifying and sculpturing landscapes. After this look at external processes, we examine the earth's internal structure and the processes that deform rocks and give rise to mountains. Finally, the text concludes with chapters on resources and the solar system. This particular organization was selected largely to accommodate the study of minerals and rocks in the laboratory, which usually comes early in the course. Realizing that some instructors may prefer to structure their courses differently, we made each chapter self-contained so that it may be taught in a different sequence. Thus, the instructor who wishes to discuss earthquakes, plate tectonics, and mountain building prior to dealing with erosional processes may do so without difficulty. We also chose to introduce plate tectonics in the first chapter so that this important theory could be incorporated in appropriate places throughout the text. Although plate tectonics is an integral part of this book, we have not included it at the expense of other topics. While it is true that plate tectonics is fascinating and of utmost importance in understanding the dynamics of the earth, other topics are equally worthwhile and interesting to the beginning student. It should also be noted that a separate chapter on environmental problems has not been included. Instead we have incorporated these topics into the text at appropriate places. For example, discussions of the pollution of wells and land subsidence associated with groundwater withdrawal are treated in the chapter on groundwater (Chapter 11) while shoreline erosion problems are taken up in the chapter on shorelines (Chapter 14).

A comparison between this volume and earlier editions would reveal that the number of chapters in the Third Edition has been increased and that the sequence of chapters has been changed slightly. The chapter on geologic time, which was formerly near the end of the text, is now Chapter 8. The authors agreed with many reviewers and users of earlier editions who felt that this important topic needed a more prominent position in the text. The chapter has also been reorganized so that relative dating principles are treated prior to the discussion of radiometric dating. New to the Third Edition is Chapter 15, Crustal Deformation. This chapter is a completely rewritten and expanded treatment of selected topics that were previously part of the chapter on mountain building. Chapter 20, Mountain Building and the Evolution of Continents, is also completely rewritten to make the level compatible with other chapters. Moreover, the treatment of isostasy was expanded and clarified, and the role of the plate tectonics in mountain building was updated to fit current models. Another major addition to the Third Edition is a chapter on mineral and energy resources (Chapter 21). Previously, material pertaining to resources was dispersed throughout the text. Now these sections have been combined, revised, and expanded to create a new chapter. Substantial material has been added, including discussions of renewable and nonrenewable resources, alternative energy sources, and nonmetallic mineral resources. For those who wish to integrate resource topics with other parts of the text, the many sections within the chapter are clearly identified and can be easily assigned as separate readings in any order the instructor desires.

In addition to the changes outlined above, discus-

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sions of many basic topics have also been strengthened in the Third Edition. Expanded and updated coverage of sedimentary rocks, volcanic activity, metamorphism, groundwater environmental problems, deserts, and plate boundaries are just a few examples. New sections on the nature of scientific inquiry (Chapter 1) and types of glaciers (Chapter 12) have also been added.

As with any project of this scope, the contributions of others were very important and too numerous for us to give proper credit to each person involved. The credit for the content must go to our professors, colleagues, and students, who challenged us to search for a deeper understanding. We wish to express our thanks to the many individuals, institutions, and government agencies that provided information, photographs, and illustrations for use in this text. A special debt of gratitude goes to those colleagues who prepared in-depth prerevision reviews of the First Edition and Second Edition of *The Earth:* Larry Agenbroad, Northern Arizona University; Gary Allen, University of New Orleans; Richard W. Arnseth, University of Tennessee; Thomas W. Broadhead, University of Tennessee; Rex Crick, University of Texas; Larry E. Davis, Washington State University; John S. Dickey, Jr., Syracuse University; Joseph F. Donoghue, Florida State University; Tom Freeman, University of Missouri; William D. Gosnold, Jr., University of North Dakota; Dryan Gregor, Wright State University; Bryce M. Hand, Syracuse University; Robert Hatcher, University of South Carolina; Jerry Horne, San Bernardino Valley College; Terence T. Kato, California State University-Chico; David Lageson, Montana State University; John R. Monrad, Eastern Kentucky University; Howard Mooers, University of Minnesota; Michael J. Neilson, University of Alabama, Birmingham; Darlene Richardson, Indiana University of Pennsylvania; Jack Schindler, St. Petersburg Junior College; James R. Snook, Eastern Washington University; William K. Steele, Eastern Washington University; and Daniel A. Sundeen, University of Southern Mississippi. Their critical comments and thoughtful input helped guide our revision and strengthen the text. We thank the following, whose comments from the Second Edition aided the Third Edition: David T. King, Jr., Auburn University; George S. Koch, University of Georgia; Carleton B. Moore, Arizona State University; Mary Jo Richardson, Texas A&M University; Vernon P. Scott, Oklahoma State University; Chris A. Suczek, Western Washington University; Alphonse C. Van Besien, University of Mississippi; and J. M. Wampler, Georgia Institute of Technology.

Our thanks also go to Diane Weber for her unmatched word processing skills and to the fine production team at Merrill Publishing who skillfully transformed our manuscript into a finished product. The expertise and support of Bruce Johnson, Rex Davidson, Cynthia Brunk, Cathy Watterson, and Raydelle Clement is gratefully acknowledged and sincerely appreciated.

EJT
FKL

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The spectacular eruption of a volcano, the terror brought by an earthquake, the magnificent scenery of a mountain valley, and the destruction created by a landslide are all subjects for the geologist (Figure 1.1). The study of geology deals with many fascinating and practical questions about our physical environment. What forces produce mountains? Will there soon be another great earthquake in San Francisco? What was the Ice Age like? Will there be another? What created this cave and the stone icicles hanging from its ceiling? Should we look for water here? Is strip mining practical in this area? Will oil be found if a well is drilled at that location? What if the landfill is located in the old quarry?

The subject of this text is **geology**, a word that literally means "the study of the earth." To understand the earth is not an easy task because our planet is not an unchanging mass of rock but rather a dynamic body with a long and complex history.

The science of geology is traditionally divided into two broad areas—physical and historical. **Physical geology**, which is the primary focus of this book, examines the materials composing the earth and seeks to understand the many processes that operate beneath and upon its surface. The aim of **historical geology**, on the other hand, is to understand the origin of the earth and its development through time. Thus, it strives to establish an orderly chronological ar-

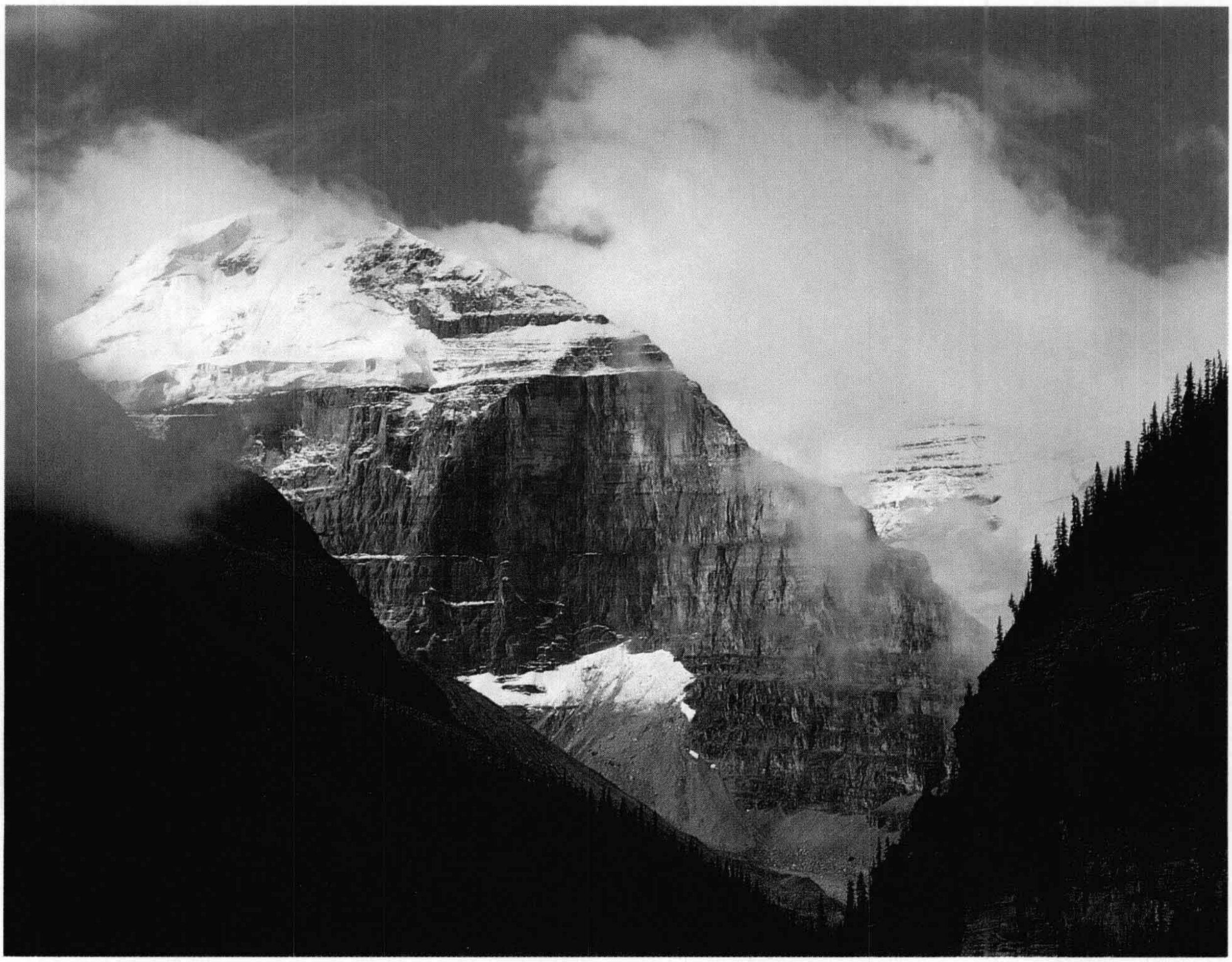


FIGURE 1.1
The study of mountains, including areas such as this in the Canadian Rockies, is just one focus of geology. (Photo by E. J. Tarbuck)

rangement of the multitude of physical and biological changes that have occurred in the geologic past. The study of physical geology logically precedes the study of earth history because we must first understand how the earth works before we attempt to unravel its past.

SOME HISTORICAL NOTES ABOUT GEOLOGY

The nature of our earth—its materials and processes—has been a focus of study for centuries. Writings about such topics as fossils, gems, earthquakes, and volcanoes date back to the early Greeks, more than 2300 years ago. Certainly the most influential Greek philosopher was Aristotle. Unfortunately, Aristotle's explanations about the natural world were not based on keen observations and experiments. Instead they were arbitrary pronouncements. He believed that rocks were created under the "influence" of the stars and that earthquakes occurred when air crowded into the ground, was heated by central fires, and escaped explosively. When confronted with a fossil fish, he explained that "a great many fishes live in the earth motionless and are found when excavations are made." Although Aristotle's explanations may have been adequate for his day, they unfortunately continued to be expounded for many centuries, thus thwarting the acceptance of more up-to-date accounts. Frank D. Adams states in *The Birth and Development of the Geological Sciences* (New York: Dover, 1938) that "throughout the Middle Ages Aristotle was regarded as the head and chief of all philosophers; one whose opinion on any subject was authoritative and final."

Catastrophism

During the seventeenth and eighteenth centuries the doctrine of **catastrophism** strongly influenced the formulation of explanations about the dynamics of the earth. Briefly stated, catastrophists believed that the earth's landscape had been shaped primarily by great catastrophes. Features such as mountains and canyons, which today we know take great periods of time to form, were explained as having been produced by sudden and often worldwide disasters produced by unknowable causes that no longer operate. This philosophy was an attempt to fit the rates of earth processes to the then-current ideas on the age of the earth. In the mid-seventeenth century, James Ussher, Anglican Archbishop of Armagh, Primate of all Ireland, published a major work that had immediate and profound influence. A respected scholar of the Bible, Ussher constructed a chronology of human and earth history in which he determined that the earth was only a few thousands of years old, having been created in 4004 B.C. Ussher's treatise earned widespread acceptance among scientific and religious leaders alike, and his chronology was soon printed in the margins of the Bible itself.

The relationship between catastrophism and the age of the earth has been summarized nicely as follows:

> **That the earth had been through tremendous adventures and had seen mighty changes during its obscure past was plainly evident to every inquiring eye; but to concentrate these changes into a few brief millenniums required a tailor-made philosophy, a philosophy whose basis was sudden and violent change.[1]**

The Birth of Modern Geology

The late eighteenth century is generally regarded as the beginning of modern geology, for it was during this time that James Hutton (Figure 1.2), a Scottish physician and gentleman farmer, published his *Theory of the Earth* in which he put forth a principle that came to be known as the doctrine of **uniformitarianism.** Uniformitarianism is a basic part of modern geology. It simply states that the physical, chemical, and biological laws that operate today have also operated in the geologic past. That is to say that the forces and processes that we observe presently shaping our planet have been at work for a very long time. Thus, to understand ancient rocks, we must first understand present-day processes and their results. This idea is commonly stated by saying "the present is the key to the past."

Prior to Hutton's *Theory of the Earth,* no one had effectively demonstrated that geological processes occur over extremely long periods of time. However, Hutton persuasively argued that forces which appear small could, over long spans of time, produce effects

[1] H. E. Brown, V. E. Monnett, and J. W. Stovall, *Introduction to Geology* (New York: Blaisdell, 1958).

FIGURE 1.2
A contemporary caricature of James Hutton, the eighteenth-century Scottish geologist who is often called the "father of modern geology." The faces scowling at Hutton from the rocky cliff are believed to be profiles of Hutton's most vocal critics. (Courtesy of the Library of Congress)

that were just as great as those resulting from sudden catastrophic events. Unlike his predecessors, Hutton carefully cited verifiable observations to support his ideas. For example, when he argued that mountains are sculptured and ultimately destroyed by weathering and the work of running water, and that their wastes are carried to the oceans by processes that can be observed, Hutton said, "We have a chain of facts which clearly demonstrates . . . that the materials of the wasted mountains have traveled through the rivers"; and further, "There is not one step in all this progress . . . that is not to be actually perceived." He then went on to summarize this thought by asking a question and immediately providing the answer: "What more can we require? Nothing but time."

Since Hutton's literary style was cumbersome and difficult, his work was not widely read nor easily understood. However, that began to change in 1802, when Hutton's friend and colleague, John Playfair, published *Illustrations of the Huttonian Theory,* a volume in which he presented Hutton's ideas in a much clearer and attractive form. The following well-known passage from Playfair's work, which is a restatement of Hutton's basic principle, illustrates this style:

> **Amid all the revolutions of the Globe, the economy of nature has been uniform and her laws are the only things which have resisted the general movement. The rivers and the rocks, the seas and the continents have been changed in all their parts; but the laws which direct those changes, and the rules to which they are subject, have remained invariably the same.**

Although Playfair's book gave impetus to Hutton's ideas and aided the cause of modern geology, it is the English geologist Sir Charles Lyell (Figure 1.3) who is given the most credit for advancing the basic principles of modern geology. Between 1830 and 1872 he produced eleven editions of his great work, *Principles of Geology.* As was customary, Lyell's book had a rather lengthy subtitle that outlined the main theme of the work: *Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes now in Operation.* In the text, he painstakingly illustrated the concept of the uniformity of na-

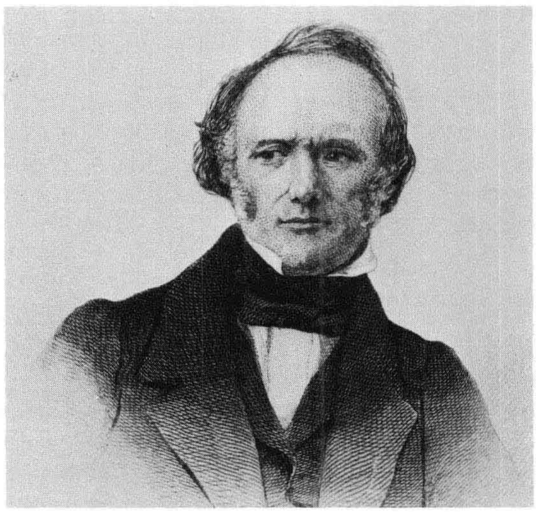


FIGURE 1.3
Charles Lyell. Lyell's book, *Principles of Geology,* did much to advance modern geology. (Courtesy of the Institute of Geological Sciences, London)

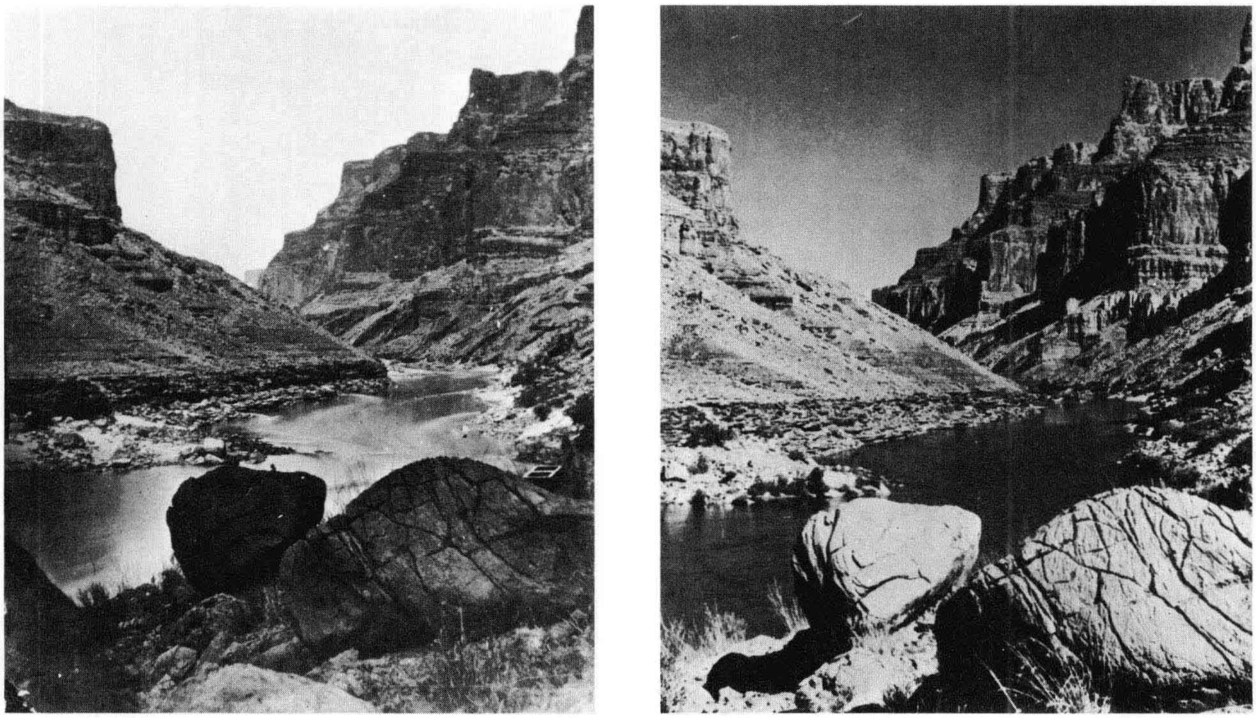
ture through time. He was able to show more convincingly than his predecessors that the geologic processes which are observed today can be assumed to have operated in the past. Although the doctrine of uniformitarianism did not originate with Lyell, a fact that he openly acknowledged, he is the person who was most successful in interpreting and publicizing it for society at large.

Today the basic tenets of uniformitarianism are just as viable as in Lyell's day. Indeed, we realize more strongly than ever that the present gives us insight into the past and that the physical, chemical, and biological laws that govern geological processes remain unchanging through time. However, we also understand that the doctrine should not be taken too literally. To say that geological processes in the past were the same as those occurring today is not to suggest that they always had the same relative importance and operated at precisely the same rate. Although the same processes have prevailed through time, their rates have undoubtedly varied.[1]

The acceptance of uniformitarianism meant the acceptance of a very long history for the earth, for although processes vary in their intensity, they still take a very long time to create or destroy major features of the landscape.

For example, rocks containing fossils of organisms that lived in the sea more than 15 million years ago are now part of mountains that stand 3000 meters (9800 feet) above sea level. This means that the mountains were uplifted 3000 meters in about 15

[1] It should be pointed out that during the earth's formative period, when our planet was very different today, some processes were at work that are no longer operating.



A. B.

FIGURE 1.4

Geologic processes often act so slowly that changes may not be visible during an entire lifetime. These two photographs were taken from the same vantage point nearly one hundred years apart. Photograph A was taken by J. K. Hillers in 1872 and photograph B was taken in 1968 by E. M. Shoemaker. The photos reveal practically no visible signs of erosion. (Photos courtesy of U.S. Geological Survey) million years, which works out to a rate of only 0.2 millimeter per year! Rates of erosion (the processes that wear away land) can be equally slow (Figure 1.4). Estimates indicate that the North American continent is being lowered at a rate of just 3 centimeters per 1000 years. Thus, as you can see, tens of millions of years are required for nature to build mountains and wear them down again. But even these time spans are relatively short on the time scale of earth history, for the rock record contains evidence that shows the earth has experienced many cycles of mountain building and erosion. Concerning the ever-changing nature of the earth through great expanses of geologic time James Hutton made a statement that was to become his most famous. In concluding his classic 1788 paper published in the *Transactions of the Royal Society of Edinburgh,* he stated, "The results, therefore, of our present enquiry is, that we find no vestige of a beginning—no prospect of an end." A quote from William L. Stokes sums up the significance of Hutton's basic concept:

> **In the sense that uniformitarianism implies the operation of timeless, changeless laws or principles, we can say that nothing in our incomplete but extensive knowledge disagrees with it.[1]**

In the chapters that follow, we shall be examining the materials that compose our planet and the processes that modify it. It will be important to remember that although many features of our physical landscape may seem to be unchanging in terms of the tens of years over which we might observe them, they are nevertheless changing, but on time scales of hundreds, thousands, or even many millions of years.

THE NATURE OF SCIENTIFIC INQUIRY

As members of a modern society, we are constantly reminded of the significant benefits derived from scientific investigations. What exactly is the nature of this inquiry?

All science is based on the assumption that the natural world behaves in a consistent and predictable manner. This implies that the physical laws which govern the smallest atomic particles also operate in the largest, most distant galaxies. Evidence for the existence of these underlying patterns can be found in the physical world as well as the biological world. For example, the same biochemical processes and the same genetic codes that are found in bacterial cells are also found in human cells. The overall goal of science is to discover the underlying patterns in the natural world and then to use this knowledge to make predictions about what should or should not be expected to happen given certain facts or circumstances.

The development of new scientific knowledge involves some basic, logical processes that are universally accepted. To determine what is occurring in the natural world, scientists collect scientific *facts* through observation and measurement (Figure 1.5).

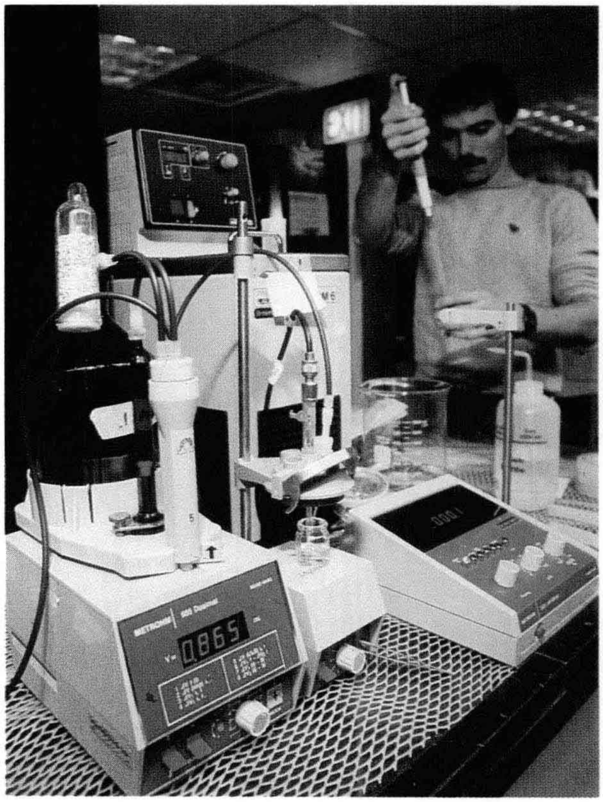


FIGURE 1.5
Scientist analyzing sea-floor samples collected by the drilling ship *JOIDES Resolution.* (Courtesy of Ocean Drilling Program)

[1] *Essentials of Earth History* (Englewood Cliffs, New Jersey: Prentice-Hall, 1966), p. 34.

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