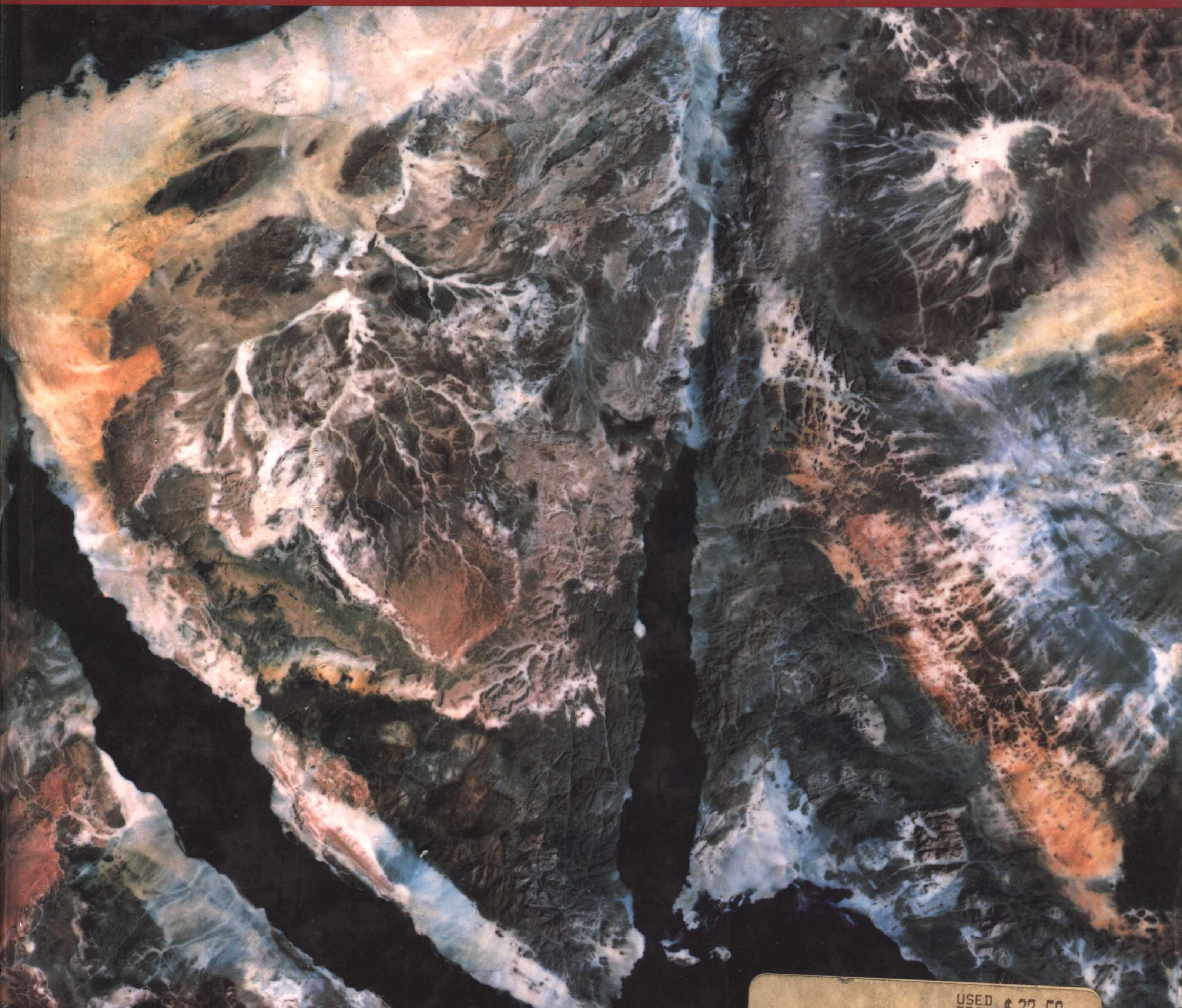
FIFTH EDITION

THE EARTH'S DYNAMIC SYSTEMS



W. KENNETH HAMBLIN

THE EARTH'S DYNAMIC SYSTEMS
A Textbook in Physical Geology

Fifth Edition

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Cover photo: Landsat image shows in a very dramatic way the operations of the two major global systems that operate on the Earth, the hydrologic system and the tectonic system. The Nile River and the Nile delta on the back cover show the operation of the hydrologic system, which comprises the circulation of water from the oceans to the atmosphere, and the surface runoff of the rivers as they empty back into the oceans. The Red Sea Rift illustrates the tectonic system. The movement of tectonic plates splits continents, creates ocean basins, and is ultimately responsible for mountain building, volcanoes, and earthquakes.

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PREFACE

Geology is in a "golden age," a time of new enlightenment, with major discoveries and revolutionary theories, giving us profound new insights into the origin of our planet and how it works. New technological abilities now allow us to see the Earth from space, to compare our planet with other bodies in the solar system, to map the Earth's landforms, "X-ray" its internal structure, measure its magnetic properties, and study the ocean floors.

With this era of enlightenment comes an increased awareness of how the Earth is continually changing, and a fresh awareness of how fragile our planet is. The Earth is a finite sphere and it is impossible for the population and consumption to grow indefinitely. Today's students must understand the facts about energy consumption and diminishing resources. We may find more oil, gas, and coal by improved detection methods, yet nature requires more than a million years to concentrate the oil now consumed in 12 months. We have created nuclear waste, yet are unsure of the effects of its disposal in the geologic system. What can we do about the fact that rivers today transport more agricultural and industrial waste than natural sediment? To live on our planet, we must understand its dynamic systems and how they operate. The fifth edition of The Earth's Dynamic Systems introduces students to how the Earth works and will help them understand and participate in the solution of these problems. It is written for freshmen-level students at both two- and four-year schools who are taking their first course in geology or physical geology for one semester or less.

The Theme of This Book. Beginning geology students commonly suffocate in an avalanche of information without a unifying theme to help them grasp fundamental ideas and important relationships. The core theme in this book is the Earth's dynamic systems, just as the title states. There are two major energy systems that make the Earth a dynamic planet: one is a hydrologic system, the circulation of water over the Earth's surface, which involves the movement of water in the ocean, rivers, underground, and in glaciers. The other is the tectonic system, the movement of material powered by heat from the Earth's interior. This system involves the evolution of continents and ocean basins, and mountain-building. These two systems are the focus of this book and everything discussed in it can be related to these two unifying themes.

New to This Edition. The book remains the same in its overall structure and organization because students consistently find it to be an effective learning tool. However, the revision effort was extensive and resulted in the following improvements:

1. All chapters were updated and checked for accuracy. Some were completely rewritten. Previous users will note we have combined the material in the chapter on matter and energy with the chapter on minerals. We have also developed a new chapter on the hydrologic system. In addition, we have essentially two new chapters covering the most rapidly changing field in geology: plate tectonics. This subject is introduced near the beginning of the book in Chapter 3 in order to serve as a background for all

that follows. It is then treated more fully in Chapter 17 with a discussion on the history of its development and refinements in the concepts that have occurred since the last edition.

2. Equal attention was also given to the illustrations. Our effort was to develop illustrations which would make the book a more effective learning tool in which the line art and photography would support, not overwhelm, the author's message. The publisher and I have been uncompromising in our effort to make each figure support the text. I have traveled over much of North America and many other parts of the world to take photographs specifically for this edition. Our objective was to achieve a new degree of integration of text and illustrations that would help the student understand modern geology and catch a glimpse of some of its splendor. We hope the student will find that reexamining the figures and captions is one useful method of reviewing the content of the chapter.
3. A new element in the fifth edition is the utilization of space photography in chapter openers. With the new high resolution of Landsat images we can view the Earth as never before. By introducing each chapter with a space photo of the subject and discussing what we see in this new perspective, we present the student with a new and up-to-date perspective of the Earth. The twenty-four space images in the book could stand alone as a visual summary of physical geology.
4. We have refined the "Statement" and "Discussion" sections of each chapter with a definite purpose—to state the main ideas and to support them with organized discussion, repetition, and review to enhance and facilitate learning. We have also added an "Examples" section where appropriate.
5. We have introduced guiding questions at the beginning of each topic to stimulate thought and provide a direction for the student's reading.

IN-TEXT LEARNING AIDS

In an effort to make this book more effective and useful to the student, we have designed a number of learning aids and have incorporated them into each chapter.

Outline of Major Concepts. Students taking an introductory course in geology will probably not know enough about geology to identify all key concepts in page after page of text. To help the student focus on the key points of each chapter, we have identified them at the beginning of each chapter under the title of *Major Concepts*.

Guiding Questions. Experience has shown that the most successful students are those who read with a specific purpose—those who read to answer a question. A major pedagogical tool in this edition is the development of guiding questions which are presented at the beginning of each major topic. The questions are intended to guide students in their study and to stimulate their curiosity.

Summary. The major concepts are further reinforced by end-of-chapter summaries that are present in outline form. Students can also use the summary to easily locate pertinent text discussion for more information.

Key Terms. The boldface terms in the text are listed at the end of the chapter after the summary in a section called "Key Terms." These terms are also defined in the glossary at the end of the book.

Review Questions. These discussion questions are intended to reinforce the main concepts and stimulate further investigation by pointing out some of the intriguing questions on which scientists are working.

Additional Reading. A reading list at the end of each chapter includes both periodicals and more general book references to direct the student who would like to learn more about the topic.

Glossary. At the end of the book, the student will find an illustrated glossary including definitions of approximately 800 key terms introduced in the text that are illustrated where appropriate by over 100 full color illustrations. The definition of the terms are in conformance with the latest edition of the Glossary published by the American Geologic Institution.

SUPPLEMENTARY MATERIALS

1. Student Study Guide. In preparing the fifth edition, we have been acutely aware that effective learning involves more than attending lectures and reading textbooks. It involves the student's active participation, with as much one-to-one interaction with the instructor as possible. This is difficult in large introductory courses, but we have solved part of the problem by further developing the new technique of *latent image printing* which we introduced in the fourth edition. This companion workbook—study guide utilizes an instant feedback system which is a form of a personal tutor. The unique aspect of this workbook is that answers are printed next to the questions in invisible ink that can be activated by a special accompanying chemical felt-tip pen. Depending on the student's response, the latent image will give the student instant feedback on their work and provides further guidance for study. The system is similar to that used in many computer-assisted learning programs.

2. Laboratory Manual. The seventh edition of the Laboratory Manual written by Hamblin and Howard is available for laboratory work associated with a typical course in physical geology. It includes exercises on rocks, minerals, topographic maps, stereo aerial photographs, landsat images and geologic maps.

3. Slide Set. A set of 200 slides to complement both lecture and laboratory presentations has been carefully selected as an aid to adopting instructors.

4. Instructor's Guide. This guide was prepared to help the instructor utilize the text and related supplement material more efficiently. It contains suggestions for lecture preparation, discussion material and a test bank of over 1000 questions keyed to the text. This thoroughly class-tested test bank is also available on personal computer for IBM.

The real test of any textbook is how well it helps the student to learn. I welcome feedback from students and instructors who have used this book. Please address your comments, criticisms, and suggestions to:

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Two artists who contributed to previous editions of this book deserve special recognition. William L. Chesser executed the drawings for the first edition; many of his fine illustrations reappear here. And Robert Pack prepared new figures for the third edition, many of which reappear here as well. In addition, Dale Claflin has revised some of the artwork and prepared new illustrations especially for this edition. The combined talents and imaginative work of these three artists form a major contribution to this book,

My secretary, Sherrie Hartley, has my sincere thanks and appreciation for her typing and all her help on this project.

Madalyn Stone, the Development Editor at Macmillan, has contributed greatly to this edition by her constructive criticism and keen insight. Her work went far beyond the call of duty, and I am very grateful.

W. K. H.

TO THE STUDENT

Our Approach to Writing. One of the most difficult problems you face in beginning a course in a new subject is to identify fundamental facts and concepts and separate them from supportive material. This problem is often expressed by the question, *What do I need to learn?* We have attempted to overcome this problem by presenting the material in each chapter in a manner that will help you recognize immediately the essential concepts. In each chapter, the major subdivisions are introduced under the subheading *Statement.*

The *Statement* at the beginning of each topic presents major concepts, principles, or theories. It is not intended to be a summary or abstract of the section, but it expresses the facts and concepts of the subject in one all-embracing view. These may be difficult for you to comprehend fully the first time you read the *Statement,* but you will gain further insight from the paragraphs under the subheading *Discussion.*

The *Discussion* presents a more complete discussion of the major concepts and principles presented in the *Statement.* Terms are defined, illustrations are presented, and evidence supporting the statement of principles is given. If it is pertinent to an understanding of a concept, a brief history of how it developed is included. This material is designed to help you grasp the ideas presented in the *Statement.*

To expand on this system we have added, where appropriate, a third major element under the heading, *Examples.* In this way supportive examples are separated from the details of the discussion.

With this organization you can easily recognize the major facts and concepts that are separated from the supportive discussion and examples. The great value of this system is that you can focus on the main concepts in the *Statement* and clearly understand it by the elaboration presented in the *Discussion.* In this way you can effectively utilize your study time. In a review for a test, for example, you need only make sure that you understand the *Statement.* Thus the critical material for review is reduced by about 70 percent.

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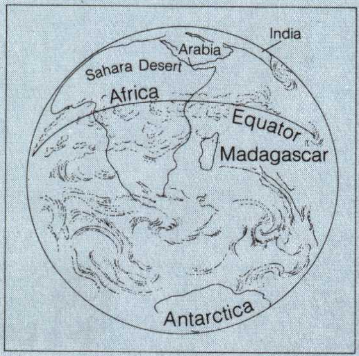
THE PLANET EARTH



Until recently, we obtained most of our knowledge of the Earth by looking horizontally from viewpoints at or near its surface. This perspective was nearsighted and limited, and in an attempt to overcome it, local observations on the surface were plotted on maps and charts, which served as models of the real world. Rivers, mountains, shorelines, and weather patterns were surveyed and studied from hundreds of observation points, but observers were never able to see the Earth in a regional, panoramic view, or to see how it functions as a planet in space. Now, for the first time in all of time we can see the Earth as it really is, suspended in the black of empty space.

In this new view of the planet Earth there is more action than one might imagine. The swirling patterns of clouds that dominate the scene underline the importance of water in the Earth's system. Huge quantities of water are in constant motion, in the sea, the air, and on land. Several complete cyclonic storms, spiraling over hundreds of square kilometers, can be seen pumping vast amounts of water from the ocean to the atmosphere. Much of this water is precipitated on the continents and erodes the land as it flows back to the sea.

Large parts of Africa and Antarctica are visible, and the major climatic zones of our planet are clearly delineated. Much of the vast tropical forest of central Africa is seen beneath the discontinuous cloud cover. Of particular interest in this view is the rift system of the Red Sea, a large fracture in the African continent, separating the Arabian Peninsula from the rest of Africa. Also, large portions of the South Polar ice cap, a glacier more than 3000 m thick that covers the continent of Antarctica, are clearly visible.

We have not only seen the Earth from space, we have seen the ocean floor, mapped its topography and structure, and gained insight as to its origin and history. From this new ability to see the Earth as it truly is, we have discovered the forces that make and shape the Earth, and how the Earth functions as a dynamic system. We now recognize that volcanism, earthquakes, mountain building, and continental drift are all manifestations of the Earth's internal heat. In our time, the right tools, sophisticated technology, and decisive evidence have all come together to allow us to understand how the Earth works. In this chapter we will briefly describe the major geologic features of the planet Earth—features that make it unique in the solar system.

MAJOR CONCEPTS

1. The surface features of the Earth provide an important record of its dynamics.
2. The surface fluids of the Earth (air and water) are in constant motion, and the movement of these fluids continually modifies the landscape.
3. Continents and ocean basins are the principal surface features of the Earth.
4. The continents consist of three major components: (a) shields, (b) stable platforms, and (c) belts of folded mountains. All of these components show the mobility of the crust.
5. The ocean floor contains several major structural and topographic divisions: (a) the oceanic ridge, (b) the abyssal floor, (c) seamounts, (d) trenches, and (e) continental margins.
6. The Earth is a differentiated planet, with its materials segregated and concentrated according to density. The major units are (a) a central core, (b) a thick mantle, and (c) a crust.
7. The lithosphere is the strong, rigid outer layer of the Earth and includes the crust and the uppermost mantle. It is broken into a series of large fragments, or plates.
8. The asthenosphere is a soft layer in the upper mantle beneath the lithosphere. It is near the melting point and capable of plastic deformation.

INTRODUCTION

Geology, the science of the Earth, is an incredibly fascinating subject. It concerns the Earth and all that is in it: its origin, history, and the dynamics of how it changes. Geologists study such diverse phenomena as volcanoes and glaciers, rivers and beaches, earthquakes, and even the history of life. It is a study about what happened in the past and what is happening at present; a study which increases our understanding of nature and our place in it.

But geology does much more than satisfy intellectual curiosity. As cities expand and suburbs spread across the countryside, geology is being called upon to help guide engineers in planning buildings, highways, dams, harbors, and canals, and to recognize how natural hazards such as landslides, earthquakes, floods, and beach erosion can be avoided or dealt with effectively. The discovery of natural resources is perhaps the strongest driving force in our attempt to understand the Earth. All Earth materials including water, soils, minerals, fossil fuels, and building materials, are "geologic" and are discovered, developed, and managed with the aid of the geologic science. But perhaps, in the long run, comprehending nature more fully is as important as the discovery of oil fields and finding mineral deposits.

Natural curiosity in all of us is aroused whenever we look about and contemplate our natural environment. What makes hills and mountains? When were they formed? How long will they last? Why does climate change? Why are there earthquakes and volcanoes? Speculations on these and similar questions stretch back at least as far as the ancient Greeks, long before modern scientific study.

Early Geology

The Earth is large, and throughout most of human history, little was known about how it functions as a dynamic planet. Natural phenomena were explained by myths, legends, and the supernatural. Although Eratosthenes measured the circumference of the Earth 200 years before Christ, it must be remembered that Columbus's crew worried about sailing over the edge of the Earth, and natural disasters such as floods, earthquakes, and volcanic eruptions represented the wrath of angry gods. Even four centuries later little was known about the Earth's composition and history. Most people in the Christian world just 200 years ago believed that the Earth, and everything in it, was created as it now stands approximately 6000 years before Christ (some still do today).

Not until James Hutton published his book, *A Theory of the Earth,* in 1795, did people begin to think seriously about the immensity of geologic time and an Earth that constantly changes. Hutton's work inspired others. Fossils were recognized as remains of ancient life and a means of determining the relative age of the rocks in which they were found. By the mid-1800s, field studies in Europe and America provided a broad base of factual information upon which a geologic theory could be based. Rock bodies were mapped and studied not only as part of the structure of the crust but also as records of sequences of events in the Earth's history.

With the discovery of radioactivity in the early years of this century, a means of measuring the age of rocks was developed and a geologic time scale in specific numbers of years ensued. We now understand something about the immensity of geologic time—time sufficient for:

1. Mountain ranges to be eroded down to sea level.
2. The sediment deposited in the sea by river systems to become layers of solid rock.
3. The rock to be uplifted into mountain ranges and then eroded again.
4. Continents to drift thousands of miles apart.
5. Living organisms to evolve and diversify.

Major problems remained, however. We could conceive of the immensity of time but had trouble explaining the mechanism of change. How mountains formed remained obscure. Were they due to a contracting Earth? What caused volcanic eruptions in such diverse places around the world while elsewhere they were completely absent? Why are there continents and ocean basins? The oceans—which account for more than 70% of the Earth's surface—were virtually unexplored before the 1950s, and with such large areas of the planet unknown, any theory about the Earth was bound to be inaccurate and incomplete.

Then, in the years following World War II, new methods of mapping the ocean floor were developed and ushered in a mass of new data and the stage was set for a new paradigm. It came in 1967 in the revolutionary theory of plate tectonics, a theory elegant in its simplicity and yet far-reaching in its ramifications. This revolution has left nothing untouched; few of our present views of the Earth remain as they were 20 years ago. Undoubtedly, more revision is yet to come. This is an unprecedented era of exploring the Earth. We have seen the Earth from space and mapped the topography and structure of the ocean floor. We have started to unlock the mysteries of the world's climate and in doing so come closer to solving the riddle of the great ice age. This gives us a glimpse of the future. We have traveled to other worlds to find secrets they alone hold about the origin of the Earth and the events that transpired during its birth and early history.

Our Earth is but a small and insignificant sphere in space, yet from our perspective it is a vast and complex system that has evolved over billions of years. To learn about the Earth and the forces that change it is the intellectual journey upon which you are about to embark—a journey that we hope you will never forget.

Let us begin by reviewing some of the more important characteristics of our planet: what we have learned about its surface features, the composition of its crust, and the structure of its interior.

INTERPRETING THE SURFACE FEATURES OF A PLANET

What can the surface features tell us about planetary dynamics?

Statement

The surface features of a planet usually preserve some imprint of the processes by which they were formed. In some cases, the record is clear and easily understood. Sand dunes of the Sahara desert obviously formed from wind action; the beaches of the Atlantic coast are the result of wave action; the islands of Hawaii are clearly a record of volcanic eruptions. The origin of other landforms, however, can be more obscure, but generally they tell something about the dynamics of the planet and its history. The fascinating thing about the surface of a planet is that it can be explained by natural, physical, chemical, and geologic processes. As Einstein once said, "The eternal mystery of the world is its comprehensibility."

Discussion

The Moon

In an attempt to appreciate the significance of landforms, let us first consider the Moon and what its cratered surface tells about its history and internal dynamics (Figure 1.1). We know from telescopic views, as well as from space photographs, that the Moon's surface is practically saturated with craters, and thus we conclude that the major geologic process on the Moon has been the impact of meteorites. The Moon does not have water or an atmosphere, so there are no stream valleys or windblown sand. The surface of the Moon has been modified only by the impact of meteorites coming from space and by the internal energy that once deformed its crust and produced volcanic features. From rock samples brought back by the Apollo missions and from close-up satellite photographs, we know that the smooth, dark areas called maria (Latin, "seas") are covered by the vast floods of lava. As shown in Figure 1.1, lava flows filled large, circular basins and adjacent lowlands and spread out over parts of the rugged, densely cratered terrain. Clearly, the densely cratered terrain was formed before the lava flows occurred—an obvious, but fundamental, temporal relationship between two major events in lunar history.

Two additional facts are apparent from Figure 1.1. First, the maria, or lava plains, have relatively few craters. The rate of meteorite impact must have decreased greatly after the lava was extruded. Second, the outlines of all craters, young and old, remain circular and undeformed. We therefore conclude that the crust of the Moon has not undergone enough compression to produce major buckling and folding.

From these observations of the Moon's surface features, we can recognize the following sequence of events in lunar history:

1. A period of intense meteorite bombardment, when the densely cratered terrain was formed.