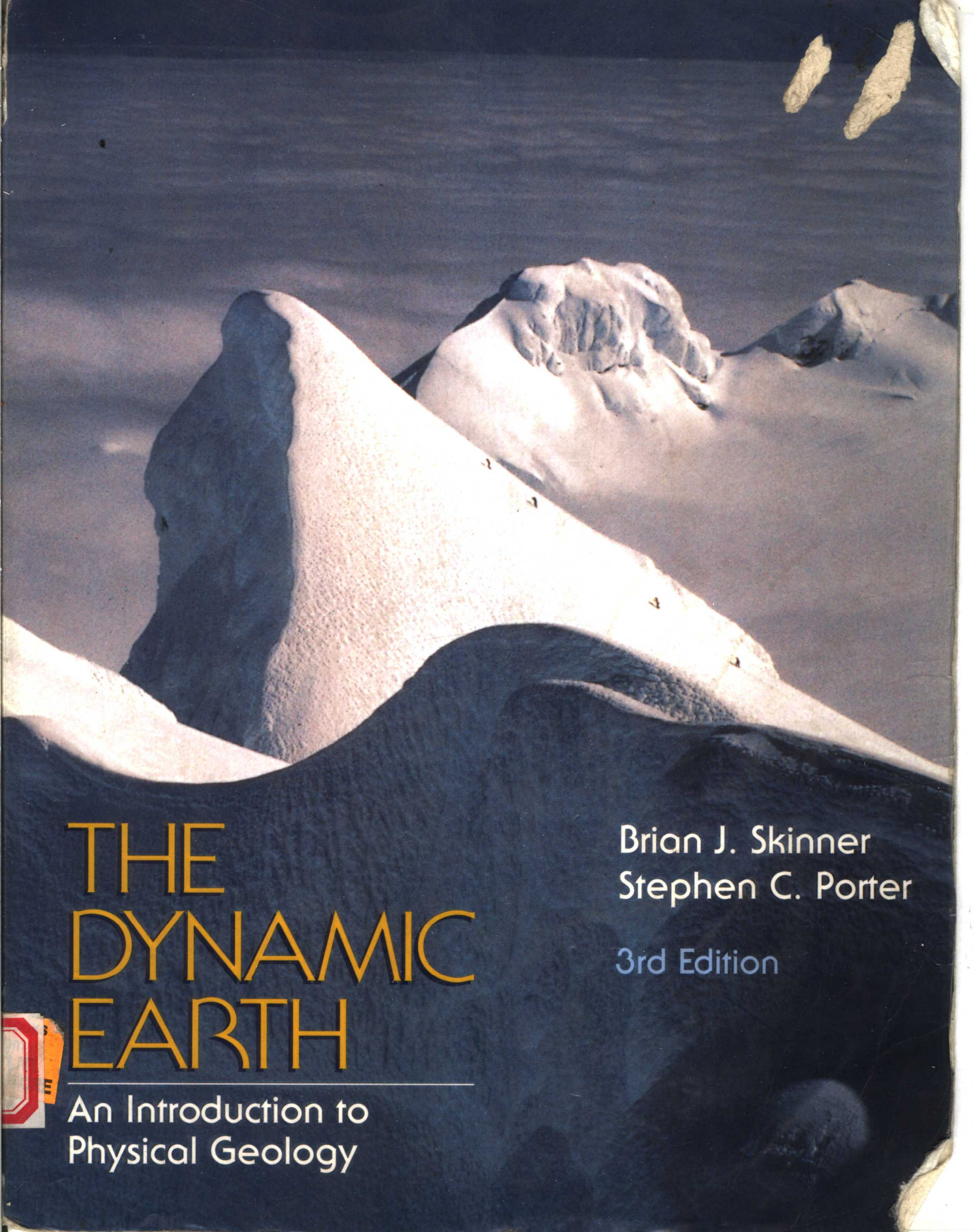

THE DYNAMIC EARTH

An Introduction to Physical Geology

Brian J. Skinner
Stephen C. Porter

3rd Edition

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An Introduction to Physical Geology

Third Edition

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PREFACE

We live on an extraordinary planet, the only one that supports life, that has abundant oxygen in its atmosphere, that rains water from its clouds. What we humans are and why our environment has the form it does are the result of innumerable interactions among the Earth's solid rocks and soil beneath our feet, the water and ice on land and in the oceans, and living matter.

The science that studies the Earth and all its interactions is geology, and those involved in the studies are geologists. It is a unique and fascinating science because its laboratory is the world in which we live. Geologists find it very difficult to carry out controlled experiments in their "geological laboratory"—the scales of space and time needed for such experiments are simply too large. Even if the space and time problems could be handled, there is always the chance that the experiments would cause the environment we live in to change in some unfortunate way. Geologists must study the Earth as it exists. From their assembled observations they draw conclusions about the processes that are shaping the Earth today and events that have shaped the Earth over the past 4.6 billion years. Increasingly, geologists are called upon to use their understanding of the Earth to suggest what changes might be expected in the future, and how our collective human activities may be causing some of the changes.

A SCIENCE IN FERMENT

Revolutionary advances in the breadth and depth of our knowledge of the Earth and the other planets of the solar system have occurred during the past 45 years. Never before have so many dramatic discoveries been made in such a short time, and the revolutionary discoveries continue unabated. For example, samples of ice drilled from glaciers in Greenland, Antarctica, China, and elsewhere have been found to carry samples of air trapped since the ice formed from falling snow thousands to tens of thousands of years ago. To everyone's surprise, this research has revealed that large and rapid changes in the composition of the atmosphere have occurred; humans played no role in them. So far there is no adequate explanation for these changes.

Another example of a recent, intriguing discovery concerns a vast submarine lava field in the western Pacific Ocean. Ocean-going geologists mapped and then drilled into the lava field. The size of the field and the discovery that the lavas were erupted with great rapidity 120 million years ago, just when the Earth's climate became very warm, has led geologists to suggest that gigantic volcanic "burps" released enough carbon dioxide into the atmosphere every now and then to completely change the climate. The most remarkable part of the hypothesis is that the volcanic "burps" seem to be controlled by the Earth's molten core, implying that the core must play a role in determining the climate. The observations behind these extraordinary concepts are discussed in Chapter 19.

Geology, then, is a science in ferment, a science laced with challenging excitement. New discoveries, new insights, and new theories heighten the excitement almost every day. It is not a science that has grown distant from everyday life—it is the science of the world around us, a science in which everyone can participate.

KNOWING THE EARTH

The science of geology is like all other sciences in that it is based on observations. We have tried to write this book so that readers can sense the fun of making their own observations and then the challenge of drawing conclusions; the reader does not need a geologic background to read the text and apply the principles it introduces.

We believe that everyone, when given a chance to do so, quickly becomes intrigued to learn how the Earth works. We hope that the reader of this book will become actively involved in the science of geology. *The Dynamic Earth* was written to provide that chance. It is a book for everyone.

Organization

The book is divided into three parts. To emphasize the global coverage, each part opens with a map on which the photos used in that part are located. Part I covers the Earth's overall features and its materials. Part II covers all of the processes that shape the Earth's surface, including newly added material on the oceans, and Part III concerns the evolving Earth, mineral resources, and planetology. Each chapter in the book was written to stand alone. Teachers who prefer to teach a subject in an order that differs from the text can easily do so.

Themes

We stress four major themes throughout the book. The first is plate tectonics—the slow, lateral motions of fragments of the Earth's outermost 100 km (called plates) at rates of up to 20 cm per year. The shapes and locations of continents and oceans, the locations of mountains and volcanoes, and the violence of earthquakes are all determined by plate tectonics. We have used plate tectonics as a framework within which to integrate most geological processes. Plate tectonics is the link between the Earth's internal and external activities, and as a result the topic appears in most chapters.

The second theme concerns the influence that the human race is having on the Earth's external processes. These influences, which are often given such names as environmental change, are emphasized throughout the book because it is essential that we all understand what is happening to the human race and to the planet on which we live. We humans are now so numerous (about 5.5 billion and increasing by approximately three people a second) that our daily activities are having measurable effects on such things as rainfall, climate, and rates of erosion. To understand how the Earth works today, therefore, we must appreciate the part played by humans in geological processes.

This second theme is so important to us that we devote our final chapter (Chapter 19, "Our Changing Planet,") to a topic that has received too little attention in physical geology textbooks, namely how human activity is changing the Earth's climate. We emphasize again that the Earth is a complex, interactive, and dynamic system in which a change in one part is likely to change other parts, often in unanticipated ways. As we burn fuels to run society, we pollute the atmosphere and alter its chemical composition. In doing so, we unwittingly have contributed to changes in the Earth that may have serious effects on all of us in the years ahead. Geology provides a record of billions of years of natural environmental change on our planet. It therefore has an extremely important role to play in our attempt to understand how both natural and human-induced changes may affect our planet and its inhabitants. In Chapter 19 we introduce the ozone hole, the greenhouse effect, and other global environmental changes in which each of us plays a role.

The third and fourth themes also concern the human race. The third is the mitigation of natural disasters. In one way or another all of us are at risk. We can't stop volcanic eruptions, earthquakes, hurricanes, or floods, but by knowing how the Earth works we can warn populations of pending danger and reduce the threat by taking appropriate actions. The fourth theme is the human use of natural resources. Each of us uses, on average, about 10 tons of mineral resources each year. (In North America the figure is closer to 20 tons per person.) Finding where to dig those resources is one of the greatest challenges faced by geologists. Understanding the consequences of using mineral resources at the rate we do is another great challenge for geologists. We have, therefore, integrated the topic of natural resources throughout the book, while Chapter 17, a short chapter devoted to mineral and energy resources, covers those economic and technical issues of resources that do not fit readily into other chapters.

The Third Edition

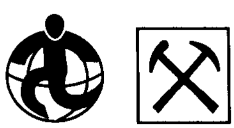
In preparing this third edition, we have retained the overall topic structure and themes that served us well in the past two editions. We have, however, added some topics in response to suggestions from users of this text, and we have recast some features in order to emphasize important environmental themes. In the Introduction, for example, we illustrate the interactions among the Earth's systems through brief introductions to topics such as human-induced changes to the atmosphere and the consequences of using natural resources at ever-increasing rates. These and other environmental issues are addressed in greater detail in Chapter 19. We have expanded and changed the focus of Chapter 13, now titled "The Oceans and Their Margins," so that it now deals with the deep water and the role that the oceans play in determining the Earth's climate. We believe that one cannot truly understand the functioning of the Earth if one does not understand the key role played by the oceans. Finally, of course, we have updated the text throughout, adding discussions of the recent Northridge earthquake and the great floods of 1993 and the most recent data wherever available, for example, on such topics as the ozone hole, global warming, soil orders, and the dating of magnetic reversals.

Several features of the first and second editions of *The Dynamic Earth* that drew favorable comments from users and reviewers have been retained and expanded; two features have been added.

Chapter essays

Each chapter opens with a short essay as before, but most of these essays are new and all of them now have a consistent, overarching theme: our environment or the effect the environment has on us. Chapter 9, for example, opens with an essay on the great flood of 1993, and Chapter 14 opens with an essay on how geology controlled the terrain and the terrain in turn affected one of the great battles of World War I.

Each chapter also contains an in-text essay dealing with special applications or research areas, as before, but now these essays are devoted either to the environment or to resources. The Introduction, for example, deals with an environmental topic, the disappearance of the Aral Sea; Chapter 3 discusses volcanoes and geothermal energy resources; and Chapter 9 discusses mineral deposits formed by weathering. Their focus is indicated by icons: a green icon for the environment, and crossed pickaxes (a traditional symbol for mining) for resources. These icons are also used with occasional text headings to highlight the environmental or resources application of those topics.



"A Closer Look" sections

We have also highlighted much of the quantitative material in the text by giving it the title of "A Closer Look." In Chapter 6, for example, the "A Closer Look" section deals with radioactive dating calculations. This material remains in text for maximum flexibility. Instructors who wish to cover quantitative material can do so within the flow of the discussion; those who do not can omit the "A Closer Look" sections without loss of continuity.

"Good Stewardship" essays

We have added a new feature to the end of each part, a "Good Stewardship" essay by guest essayists. These essays deal with environmental issues related to the overall topic of each part and the positive role that geologists can play in resolving these issues. Too often, students get the idea that our environmental problems are overwhelming, intractable, and pathways to disaster. The perception is incorrect; solutions do exist, and the essayists provide examples. Part One ends with an essay by Barbara Murck of the University of Toronto about the ways that geologists can help alert populations to imminent dangers, such as earthquakes and volcanic eruptions. Part Two ends with an essay by Sally Abella of the University of Washington concerning the clean-up of the once highly polluted Lake Washington. Finally, Part Three ends with an essay by Konrad Krauskopf of Stanford University concerning the safe disposal of radioactive wastes.

The artwork

The art program has been revised and simplified based, to a large extent, on feedback from adopters. Many new line drawings were added, and about 33% of the pieces were redrawn. Photographic research has been intensive. The first and second editions were commended by users for the fine photos; this third edition has 40% new photographs and the same broad geographic coverage of the earlier editions. We have enlarged as many photos and line drawings as possible to clarify details and to give students an appreciation of the small details as well as the large.

Student review material

Pedagogical material such as chapter summaries, questions for review, and short lists of important words and phrases have been retained, with the number of technical terms kept to a minimum. A glossary of important terms is found at the end of the book; it includes both terms identified as key terms in the chapters and many other terms for student reference. Finally, the appendices at the end of the book contain useful information for students on units and their conversions, the properties of chemical elements and their isotopes, and the properties of common minerals.

SUPPLEMENTS

A full range of supplements to accompany the third edition of *The Dynamic Earth* is available to assist both the instructor and student.

The *Study Guide*, prepared by Roger Morton of the University of Alberta, provides a brief, inexpensive set of chapter summaries, key terms, and practice test questions to help students prepare for exams.

Making Earth: An Interactive Guide to the Planet, by Michael and Susan Kimberley of North Carolina State University, can be used in addition to, or in place of, a traditional study guide. By integrating multiple choice questions into every paragraph, it allows students to actively participate in the creation of the planet and the study of physical geology. The topic order reflects that of *The Dynamic Earth*, 3/e. This supplement also provides answers to the questions that appear at the end of each chapter in *The Dynamic Earth*, 3/e.

Geoscience Laboratory (Friendship Publications copyright ©1993), by Tom Freeman of the University of Missouri–Columbia, contains 19 labs covering the major topics in physical geology. It also integrates geological principles and relevant questions. To order copies, contact Tom Freeman, Friendship Publications, 9 Geological Sciences Building, University of Missouri, Columbia, MO 65211, (314) 882-6673.

Environmental Science Activities, by Dorothy B. Rosenthal, provides 46 interdisciplinary student activities that require a hands-on approach and inspire critical thinking. Through the use of readily available materials, this supplement allows students to investigate, analyze, and appreciate the world around them through a class or on their own.

The *Instructor's Manual and Test Bank* was also prepared by Roger Morton of the University of Alberta. It includes a test bank, chapter overviews and outlines, lecture suggestions and demonstrations, film and video sections, and references to outside reading.

Overhead Transparency Acetates include approximately 100 full-color textbook illustrations, resized and edited for maximum effectiveness in large lecture halls. These images are also available as 35-mm slides.

The *Slide Package* includes the 100 images provided as transparency acetates in 35-mm slide form and a set of *Supplementary Slides* consisting of nearly 200 images from the authors' personal collections.

The *Computerized Test Bank* is a full-featured, easy-to-use, test-generating program that enables instructors to choose test questions from the printed test bank, print the completed tests for use in the classroom, and save the tests for later use or modification.

A *Videotape package* of six one-hour lectures by Brian Skinner on physical geology from Yale University's Great Teachers series is available in a two-videotape set.

The *Geology CD-ROM* is a compilation of the illustration and photo programs from *Dynamic Earth*, Third Edition, and *The Blue Planet*, First Edition, both by Brian J. Skinner and Stephen C. Porter. Available for IBM and compatible computers, the CD-ROM includes an image manager, "Picture Prowler."

ACKNOWLEDGMENTS

The second edition of The Dynamic Earth came to fruition under the guidance of Barry Harmon, then the Earth Sciences editor at John Wiley & Sons, and the publisher, Kaye Pace. The third edition has been guided by Earth Sciences editor Chris Rogers. With his encouragement we updated and changed 33% of the line art, replaced 40% of the photos, and added or changed about 30% of the text. Our tasks were made infinitely more enjoyable and considerably easier through the skilled attention and careful guidance of senior developmental editor Barbara Heaney.

The professional skills and competence of the staff at John Wiley & Sons and of the freelance experts they found to work with us are outstanding: Sandra Russell, Katharine Rubin, and Pam Kennedy oversaw production; Stella Kupferberg, Alexandra Truitt, and Michelle Orlans sought exactly the photos we needed; Anna Melhorn and Ishaya Monokoff managed the illustration program; Kevin Murphy designed the text; Joan Kalkut, Brent Peich, and Eric Stano obtained the text's supplements; Catherine Faduska developed the marketing program; and Beth Brooks and Matthew van Hattem provided editorial assistance. They and everyone else at Wiley were always cordial and always helpful, no matter how badly our travel schedules upset book schedules. John Woolsey was a pleasure to work with as he tried to change our crude sketches into finished drawings. Alice Thiede skillfully drew the new maps for us. Above all, the patient, insightful, and very helpful editing of Irene Nunes must be mentioned. Through Irene's eyes, as we worked on the second edition, we managed to understand why readers have sometimes had trouble with our words. Both this text and our own writing skills were greatly improved, and we are much indebted for her guidance. We benefited from Irene's work on the third edition through her careful checking of our changes and additions to ensure a smooth flow for students.

We thank Barbara Murck of the University of Toronto, Sally Abella of the University of Washington, and Konrad Krauskopf of Stanford University for contributing the "Good Stewardship" essays that conclude each part of the text. We also thank our colleagues who contributed essays that were adapted for some of our new chapter-opening essays: William Fyfe of the University of Western Ontario (Introduction), Barbara Murck of the University of Toronto (Chapters 1, 5, and 16), Jill Schneiderman of Vassar College (Chapter 2), and James C. G. Walker of the University of Michigan (Chapter 18). M. L. Crawford of Bryn Mawr graciously contributed a fine essay on careers in geology; this essay follows the table of contents.

We are also indebted to the many people who provided elegant colored photographs that appear in the book. Most of the photographers are geologists, and their discerning eyes can be sensed through the beautiful photos they took. Their names are listed in the Photo Credits in the back of the book, but being so placed is no reflection on their importance. Several people deserve additional thanks for their help in suggesting new sources for photos and for helping with illustrations and data; these include Brian Atwater, Eric Cheney, Darrell Cowan, and Richard Fiske.

We especially thank the thoughtful and dedicated teachers who commented on the previous texts or reviewed the present text. These fine people not only helped us keep a reasonable balance to the book, they also helped us keep the volume as up-to-date as possible without downplaying the great geological discoveries of the past. They are:

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A CLOSING THOUGHT

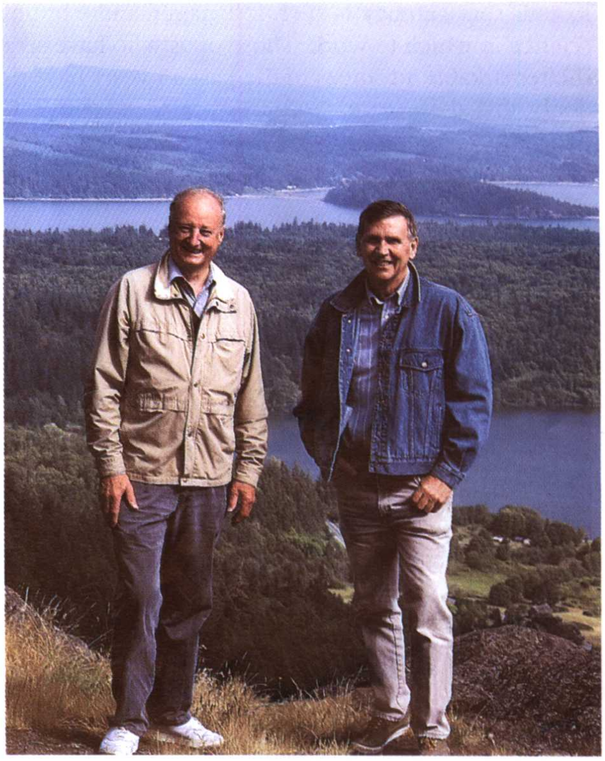
After digesting a beginning geology textbook, the reader may well come away with a feeling that we geologists have all the answers, that the major principles are known, and the significant challenges have been resolved. We hope this will not happen with this book. We have tried to show that we do not have all the answers. In fact, it is because we have so many important and challenging questions remaining before us that geology is such a dynamic and exciting science in which to work. Those of us who have seen the remarkable advances of the past 45 years have no doubt that the next 45 will produce even more startling discoveries about our dynamic Earth.

Brian J. Skinner
Stephen C. Porter

ABOUT THE AUTHORS

The authors of this book have been privileged to work as geologists all of their professional lives. They have attempted in this book to share the excitement and wonder gained from the study of the intricacies of our planet Earth. In writing this book they have drawn extensively on their own experience, as well as the experience of numerous fellow geologists whose collective geological knowledge spans the field of physical geology. Brian Skinner's research has focused on the physical properties of minerals and on the genesis of base metal deposits. He has worked in Australia, Africa, and North America, and with students in Asia and Europe. Stephen Porter's professional career has been largely concerned with studies of glaciation in many of the world's major mountain systems and with the history of the climatic changes that their deposits record. He also has studied the evolution of midocean and continental volcanoes, the products of their prehistoric eruptions, and how volcanic eruptions may have influenced the Earth's climate. With foreign colleagues he has studied the hazards of large rockfalls in the Alps and the thick, extensive deposits of windblown dust in central China that provide one of the longest continuous records we have of climatic change during the last several million years.

Between them, the authors have carried out geologic field work on all of the continents. This global perspective is reflected in the book by examples and illustrations from around the world, for it is important to emphasize that geology is a global science, a science that recognizes no political boundaries. Only by studying the Earth in its entirety can we hope to understand how our amazing planet works.



Brian J. Skinner and Stephen C. Porter, with the San Juan Islands in the background.

CAREERS IN GEOLOGY

by M. L. Crawford

Many geologists choose their careers because of an interest in natural processes and the outdoors. Because of the focus on field work, often in remote or rugged areas, geology has an image of being especially suited to physically rugged individuals. An examination of the many successful geologists shows, however, that almost everyone enjoys field work but the key skills are an inquiring mind and a curiosity about the way the Earth and planets work.

Geological Hazards

Many large population centers are sited in areas of geological instability such as California, Japan, or Indonesia. These areas may be subject to such geologically related hazards as volcanic eruptions, earthquakes, and their associated effects: landslides, land subsidence, and collapse. Population centers built beside rivers are subject to floods; shoreline cities are ever at risk from shoreline-driven waves. Determining the nature and mitigation of such geologically related hazards is a significant area of geological investigation and employment. Volcanologists and seismologists work to identify areas subject to these hazards and assist in planning to adapt the human population to the risks the hazards pose. They are often exposed to a good deal of risk themselves; the famous volcanologist couple, Maurice and Katia Krafft, died as the result of the eruption of Unzen volcano, Japan, 1992. Geologists also work to understand and hence help mitigate the problems of environmentally sensitive areas, such as coastlines and glacial environments, subject to rapid geological change. Many areas of expertise are called on for work with active geological processes, including volcanology, glaciology, structural geology, and geomorphology.

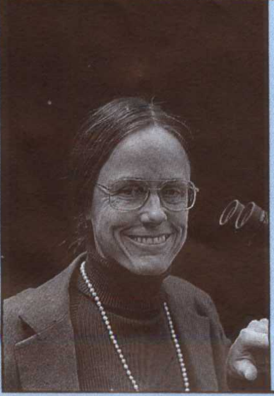
Jobs in these fields are commonly available in federal, state, and local planning agencies as well as in private companies that work with and for those agencies. In these areas, as well as in water and soil related studies, there are opportunities for individuals to establish their own consulting firms. An indication of the health of these parts of the geoscience profession is the number of small consulting firms that has arisen in recent years.

Education and Research

Many geologists choose to be educators and/or to work in a variety of research endeavors. The authors of this book and the writer of this article are all educators who also conduct research. In addition to teachers at all levels, educational fields include scientists working in museums, those working in various media fields such as television and print, and in some areas of government activity. Educators and geologists engage in research to understand and communicate broad questions of how the Earth works, its relation to the rest of the solar system, and how it has changed over time. Geologists develop a unique historical perspective on how earth processes have operated in the past as well as in the present and this perspective provides a necessary framework for informed decisions about possible future changes.

Earth Resources

The largest area of study and employment for geologists has always been in areas related to resources. Geologists who work in these areas can be grouped into disciplines that focus on nonrenewable materials extracted from the Earth and those that manage renewable resources.



M. L. Crawford I chose a geology course to satisfy the science requirement at Bryn Mawr College because it was a field about which I knew very little. I soon learned that this was a science with many open-ended questions and included a search for minerals and fossils on fun trips with friends and colleagues all excited about finding out what on earth was there. These experiences got me into the field. I was in college at a time when geology was dominated by men, although there were some niches for women doing lab work in areas that I thought sounded very dull. I continued to study areas that I found interesting and chose to go to graduate school and embark on a career in college teaching because that was the area for which my interest in minerals and metamorphic rocks seemed best suited. Teaching has given me a chance to share with others the fun and challenge of solving questions about how the Earth has behaved and how it thus is probably still evolving. It has also given me the chance to get others started in careers as diverse as science writer, director of the U.S. Bureau of Mines, State Geologist of Utah, consulting environmental geologist, higher school teacher, bibliographic reference, and many others, including college professors like myself.

The former category includes coal, oil, and gas used for energy production; metals; construction materials; chemicals; and fertilizers used for producing the foods we require. The number of geologists working to locate, extract, and conserve specific resources has fluctuated over time as societal needs and the availability of a particular resource have changed. Resource production very much depends on the development of technology necessary to provide a demand for a particular material and then to locate and extract the material in question, as well as economic circumstances that make it possible to afford the costs involved in extraction and production. Geologists play the key role in finding deposits of metals and other industrial materials, as well as the fuel resources needed to power industry and to house and transport an increasingly urban society. Broad geological expertise is necessary in resource exploration as it requires an understanding of the geological framework of an area as well as the ability to obtain detailed information about the origin of the substance to be extracted that can be used to predict where it might occur. Locating favorable sites for exploration also relies on a grasp of the Earth's chemical framework and on remote sensing of rock properties; the latter uses physical techniques developed and employed by geophysicists to measure density, magnetic, and electrical properties of the rocks.

Because materials extracted from the Earth occur in a wide variety of settings, individuals from most of the geological specialties participate in the resource industries. Most of the jobs in discovery and development are in industry, although research and regulation in these areas is also conducted in state and federal agencies. Geologists also participate as advisors for those wishing to invest in the resource industry.

We have come to realize that soil and surface and underground water, commonly taken for granted because the supply has been apparently unlimited, need attention because they too are valuable resources. Although these resources can be considered renewable or sustainable on a human time scale, they can be consumed and altered in a variety of ways that are of concern as population growth puts pressure on their availability. Increasing numbers of geologists and other earth scientists are turning to the problems involved in understanding and managing these resources.

Soil and water, the two basic geological ingredients of the environment, currently provide the largest increase in job opportunities for earth scientists. Jobs in these fields are often included under the general heading of environmental science as well as soil science and hydrogeology. Commonly geologists and engineers work together to solve problems related to water flow and water extraction from underground reservoirs. Soil resources are a concern of sedimentary geologists and soil scientists, many of whom had jobs related to agriculture as well as to geology. Geochemists work to solve problems of water and soil pollution. Jobs in these areas are available from environmental consulting firms; in local, state, and federal government agencies; and with an increasing number of large and smaller industries whose activities include providing a water supply for their operations and disposal of waste products.

Other Specialties and Salaries

Other geologists and earth scientists tend to group themselves into specialties that reflect the techniques they use, such as rock or water chemistry, rock mechanical properties, or remote sensing devices. Other groupings are built around the focus of study, such as the study of fossil life, the planets, the oceans, or changing planets. The areas of geological employment commonly cross the boundaries between disciplines and involve geologists with training in a variety of fields. According to the American Geological Institute's Geoscientific and Hiring Survey—1991, about 85,000 geoscientists work in the United States. AGI reports that in the early 1990s the range of average starting salaries for graduates with bachelor's degrees was $21,000 to $36,000; for those with master's degrees, from $24,000 to $38,500; and from $30,000 to $44,000 for Ph.D.'s.

Geologists share the challenge of solving problems based on observation of data obtained from the Earth and earth materials, the need to use techniques from other fields of science and of mathematics to solve earth problems, and a curiosity about earth history and evolution. As with all sciences, the variety of skills that geologists bring to their profession range from theoretical model building to extensive hands-on involvement with the rocks and other materials that are the database of the discipline. Although job opportunities in specific industries or disciplines have varied over time as the needs of society have evolved, people with a well-grounded understanding of how the Earth system works will always be in demand as humanity continues to explore ways to successfully inhabit the Earth.

BRIEF CONTENTS

CONTENTS