PHYSICAL GEOLOGY
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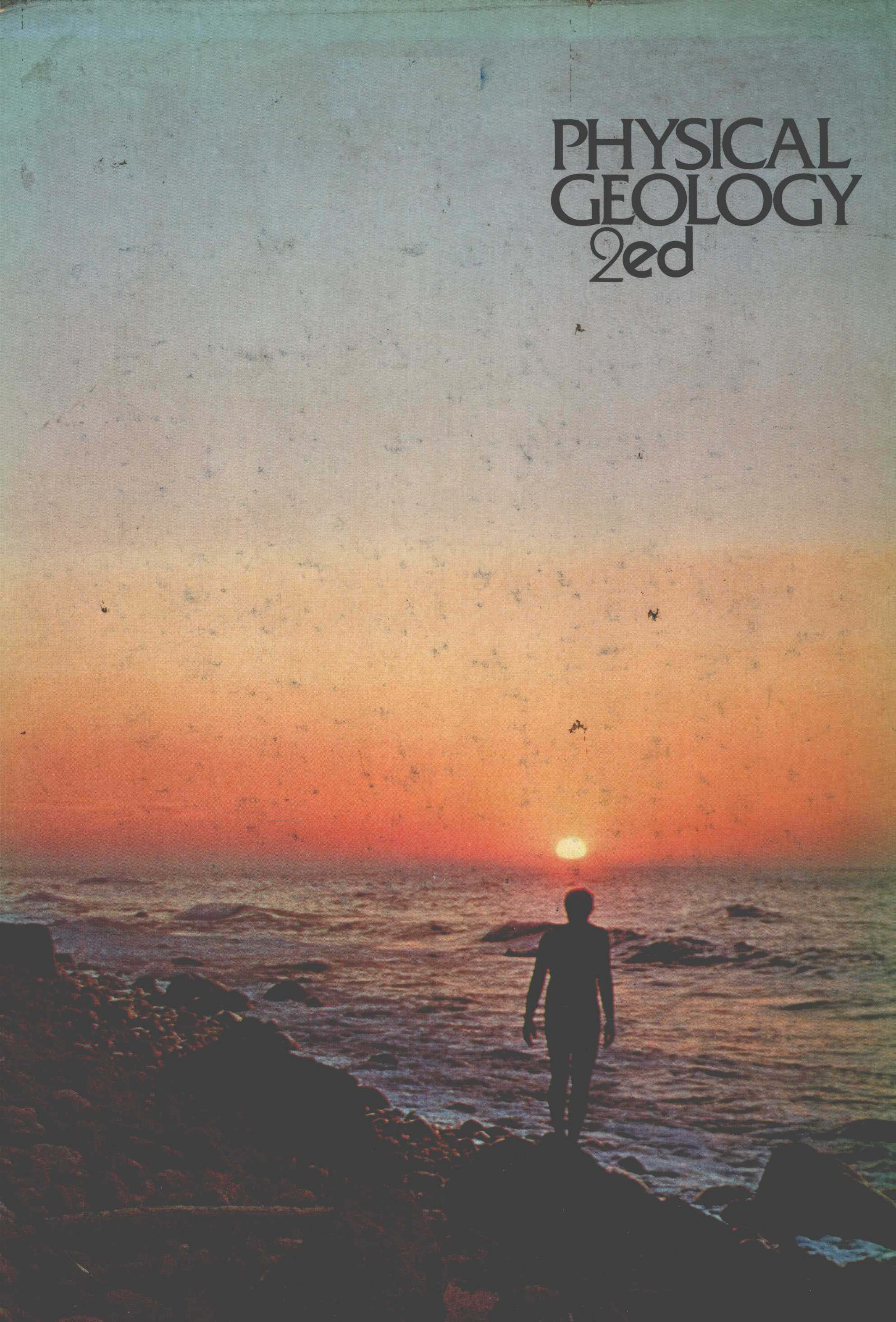

PHYSICAL GEOLOGY

SECOND EDITION

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PREFACE

Our understanding of Earth with its multitude of materials and intertwined processes is a magnificent heritage from our predecessors. This understanding is built on centuries of patient observation, and brilliant insights. But only recently have we come to realize that each of us plays a small part in the changes that ceaselessly alter the face of the Earth. Though our individual contributions are small, the sum is large. We influence the atmosphere, streams, lakes, and oceans, we affect rates of erosion, we rely on Earth for our supplies, we cover its surface with cities; we are, in fact, a vital force in our own environment. Study of the Earth is a living, evolving, and tremendously exciting science. It is one to which each of us can contribute and in our turn bequeath increased understanding to those who will follow us.

Recent revolutionary advances have brought great changes in the depth and breadth of our knowledge of the Earth. At no time during the previous centuries have so many dramatic increases in understanding occurred within such a short period. Earth science is a field in a ferment, a subject laced with challenging excitement; new observations, new insights and new theories heighten the excitement every day.

In the previous edition of this book we pointed out that much of the excitement has arisen from discoveries related to three recent and revolutionary advances. The first involves an increasing awareness, particularly in industrial nations, of the effect of human activities on environments at the surface of the Earth, accompanied by widespread attempts to analyze such effects and to modify them where necessary. These attempts represent not only scientific concern, but public concern on a broad scale. They are, likewise, closely related to the "energy crisis," which has stimulated renewed appraisal of Earth's sources of energy and of the ways in which energy is used. We have finally understood that people are not just one of the minor forces of nature—they are a major force. What the Earth will be like in the future depends very much on how we act.

The second advance concerns the way Earth works, the dynamics of the lithosphere. Exploration of ocean floors and of Earth's crust and mantle has revealed crucial new facts that force the rethinking of Earth's dynamics. For the first time we can offer answers to such questions as the origin of ocean basins, why the continents are where they are, and how mountain ranges form where they do. Many processes are being reexamined; new concepts are replacing older assumptions. A fundamental group of these concepts has coagulated into the dramatic theory of plate tectonics.

The third advance springs from the start of systematic investigations of the Moon, Mars, Venus, Mercury, and other members of the Solar System. Earth and its fellow planets have a common birthright, and though each planet has evolved differently, common threads run through their histories. By unravelling those common threads we have been led to a deeper understanding of the history of Planet Earth. We are reaching a point where we can attempt answers to such questions as why Earth exists at all, why it is like it is, and are there likely to be other, hospitable, Earth-like planets in the Universe?

The present book, a successor to a long line of Yale textbooks of physical geology, has been written in sharp realization of our heritage of knowledge and of the need to integrate with the corpus of classical knowledge the many fruits of the current revolution. We have tried to do so in a cohesive form that is intelligible to students at a beginning level. Many of the chapters are entirely new and in one, where climate is discussed, a completely new topic is introduced; other chapters have been rewritten to whatever extent seemed desirable in light of new information. Inevitably the flavor of the book differs from its predecessors. More attention has been paid to the role of people, to their involvement with and reliance on resources from the Earth; plate tectonics is integrated throughout the book rather than being treated as an isolated topic and the total coverage has been greatly increased over the previous edition; the early history of continents is discussed more fully.

We have continued features of earlier editions that have proved to be well received. Among these are the review summaries at the ends of chapters and the unique scheme of defining technical terms within the body of the text. A term defined in the text appears in boldface italic type, and the defining phrase or clause appears in lightface italics. The page on which the term is defined is indicated by boldface type in the index. The definition thus occurs in context, in the presence of additional information, and perhaps also in one or more clarifying illustrations. Thus, in some instances, the reader can see how a definition is built and even why some definitions are difficult to frame. In addition, a glossary is included for those who may wish it.

We have used metric units throughout the book. For those wishing to convert from metric to English units, we have included an appendix of conversion factors.

For an outline, ideas, and phrases, besides help and guidance in many matters, our sincere thanks go to Margaret C. H. Flint.

As work on this edition of *Physical Geology* drew to a close, Richard Foster Flint died suddenly, tragically, and unexpectedly. With his passing we are all the poorer; he was a giant in his special area of geology, and he was one of those insightful scientists who contributed greatly to our heritage of knowledge and to the current revolution in Earth sciences. Richard Flint taught and trained many of the current leaders in geology. Equally importantly, he believed, and worked tirelessly to impart the belief, that an appreciation of the Earth and the way it works is as important for an educated person as an appreciation of literature or music. Richard Flint's eloquent teaching and concise, profound writing for the beginner enticed generations of students to see, know, and appreciate the fragile complexity of the world around them.

B.J.S.

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"Here are our neighbors."

"Let's invite them to lunch and get away from the crowd." (*Luis Villota/Photo Researchers.*)

PART ONE
BASICS

1 EXPANDING HORIZONS FOR A SHRINKING EARTH

The dominant species
Agriculture and expanding populations
Energy consumption takes over
No more frontiers
Earth, small but intricate

You, who belong to the present generation of students, have inherited the fruits of countless thousands of inquiring minds. You are heirs to a vast legacy of knowledge about the Earth, our environment, our home. You can, if you will study this legacy, understand how the Earth works, how the natural activities that shape it are interwoven in complex ways, and how the environment of which you are a part was created. You can understand also a threat of frightening dimensions—how that environment can be changed, distorted, and even shattered, by the impact of human activity.

Being heirs to a body of knowledge is nothing new. Each generation enjoys that privilege. But, unhappily, yours is not merely another in a long line of generations; it is unique. It is the first to face the terrifying reality that man is now so powerful and so numerous that he rivals all the other forces of nature that change and shape our fragile environment. Therefore, you have a crisis on your hands, one that has come to a head so recently and so quickly that earlier generations, confused by long-accustomed ways of doing and thinking, have failed to join battle with it. But you have something that prior generations lacked; you have a point of view toward man's place in the natural world. You must now use your understanding of the Earth to impel your own generation, and future ones, to accept discipline, to make hard decisions, to sort out and choose a list of priorities by which the quality of life can be maintained and enhanced.

This responsibility, that now devolves on us all, has been enormously intensified by three great scientific discoveries. The first concerns life, and was finally stated by Charles Darwin in his theory of evolution. The second concerns matter and energy, and startled the world when physicists discovered the structure of the atom. The third concerns the Earth, and happened only when a new theory, the theory of plate tectonics, burst forth to transform our understanding of the Earth's dynamic movements.

These three discoveries have flooded the scientific world with new knowledge. Thanks to the scientists who are now analyzing that knowledge, you face the realization that Earth's capacities are finite. Earth's natural resources are limited, and its responsiveness to the demands of industrial mankind are weakening its ability to recover from thoughtless or deliberate exploitation. The demands of an increasing population have become so great that human ability to change and shape environments has come to equal that of natural forces.

At this point it helps us gain perspective if we look back into history and see how the crisis in Earth's development has come about. As we look back, we can see easily that the crisis had to happen some time, simply because of the presence of the species we call man. The only uncertainty was *when* it would happen. Now, just past the middle of the 20th Century A.D., in about the 4.6-billionth year since Planet Earth was formed, and in at least the 3-billionth year since life on the planet began, the crisis has arrived.

It came about in this way. Through billions of years of evolution, Earth's surface has been inhabited by various kinds of living things that gradually became more and more complex. The fossils found in Earth's layers of rock tell us that about 1 billion years ago, small but distinct animals as well as plants were living in the ocean. By 400 million years ago both plants and animals had invaded the lands, and animals with backbones had developed. By 150 million years ago reptiles (including dinosaurs) dominated the lands, although primitive kinds of mammals and birds had already appeared. By 60 million years ago, mammals had displaced reptiles as the dominant land animals. By 3 million years ago (and perhaps much earlier), man had evolved from the mammal stock and had begun to make tools from stone. The fossil human bones and the tools are here to prove it.

The dominant species

By half a million years ago *Homo sapiens,* our own species of man, had evolved and was making tools with increasing skill. His exceptionally large and complex brain enabled him both to make the tools and to use them in ever more sophisticated ways. Throughout his long existence, Stone-Age man was a skillful hunter of wild game. But as he increased in number, game became less abundant; the meat-eating population began to have trouble and, little by little, turned for its food to small mammals, birds, and fish, supplementing that diet with wild seeds and berries.

Agriculture and expanding populations

Still, populations kept on increasing and so, between 12,000 and 9,000 years ago, a worldwide agricultural revolution got under way. Agriculture and the domestication of animals began to supplant hunting as the principal source of food. Agriculture made other things happen. Instead of living in caves as small bands of hunters, people began to build primitive dwellings, gathered into villages, and thus turned to a more settled life. Gradually, cities containing thousands of inhabitants grew up. Forests were cut down and were replaced by fields, for agriculture could provide much more food than hunting ever did. Gradually, streams were diverted, rivers were dammed, and hillslopes were terraced to provide more favorable growing conditions (Fig. 1.1). Such changes began early. Evidence in the country south of Baghdad in Iraq

Figure 1.1
These mountain slopes in the Philippines were terraced 2,000 years ago for growing rice and are still being used today. (*WHO Monkmeyer.*)

shows that in order to irrigate crops, people had begun to interfere with the Tigris and Euphrates Rivers as early as 7,000 years ago (Fig. 1.2).

The effect of this tremendous change was to replace natural groups of living things—wild animals and wild plants—with artificial groups consisting of domesticated plants and domesticated animals. But the change also had a side effect. It removed people one long step from direct participation in a wholly natural economy; it pushed them toward a life in a world of their own creation. Although the turn to agriculture increased the supply of food, the increase barely kept up with the steepening curve of human population.

Energy consumption takes over

Agriculture as the principal basis of human economy had lasted many thousands of years when, on both sides of the Atlantic Ocean, and beginning in the 18th Century, a marked change in the use of energy began to make itself felt. This was the start of the age of intensive use of energy, also called the industrial age because it is an age of high-energy industry.

Stone-Age people had an industry too: they made weapons and

Figure 1.2
Irrigated vegetable fields in the Coachella Valley, southern California. The snaky line, center, is a canal bringing water from the Colorado River. The desert, right, is just as it was before irrigation. (*J. S. Shelton.*)

tools of stone. But the energy needed to make stone tools was only the small amount supplied by human muscle. Other sources of energy remained to be tapped. Six thousand years ago people discovered metal ores and learned to smelt them and to work the metals into implements. The smelting required energy, most of which came from the burning of wood. Still, until the 18th Century, human industry drew its energy mostly from the muscles of men, horses, and cattle, and so production remained small.

The 18th Century brought with it the invention of steam engines and the ability to convert the energy locked up in wood, coal, and other fuels into other forms of energy. Machines could do work formerly done by men and by horses, so that, in theory, all individuals could have machine "servants" and machine "animals" working for them. Coal came into wide use as a fuel because it yields, on an equal-weight basis, far more energy than wood. Then, with the invention of internal-combustion engines, petroleum became a widely used fuel. From our vantage point in the last quarter of the 20th Century, it appears that nuclear energy could eventually become a successor to wood, coal, and petroleum. The use of high-energy fuels enabled a given number of people to exploit more plants, animals, and inorganic materials and to produce much more food and many more products than had been possible in the days of predominant agriculture. But high-energy fuels led also to huge industrial plants, giant cities, commuters and high-rise apartment buildings. Machines and cities are built with cement, metals, and other materials won from the Earth. Every year we seem to need more and more, until today we use Earth's materials in such vast amounts that it is hard to imagine where they all go (Fig. 1.3).

This huge change affected everyone who participated in a high-energy economy. It surrounded people with a whole range of artificial things. In doing so it removed them a further long step from direct participation in a natural economy. And it resulted in major changes in the environments in which energy use was highest. Stone-Age people had made little more change in their

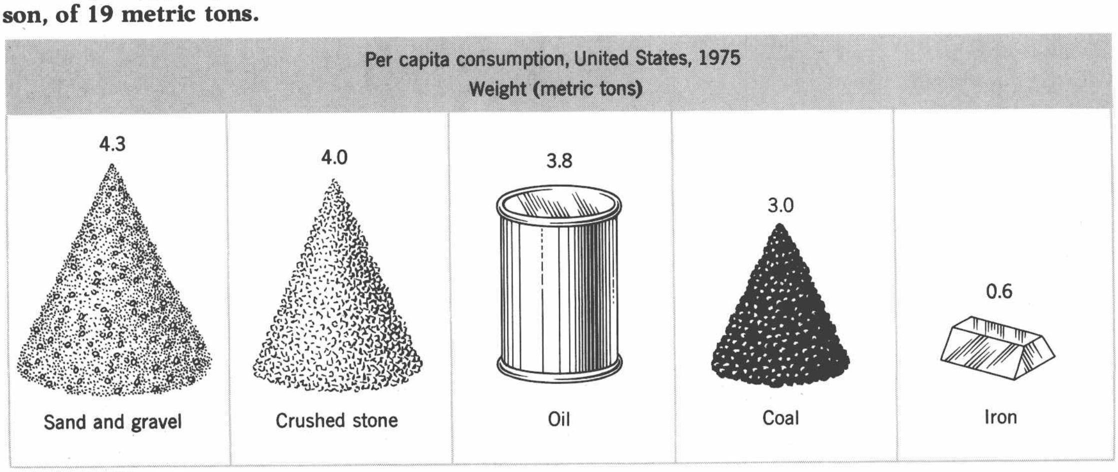

Figure 1.3
The total amount of material mined and dug from the Earth increases each year. During 1975 the United States used nearly 3.4 billion metric tons of such material, mostly cement, sand, gravel, and crushed stone for building, coal and petroleum for fuel, iron and other metals for machines and a myriad other purposes. When we divide the total consumption of *all* minerals by the U.S. population we get an average yearly consumption, per person, of 19 metric tons.

environments than did other species of animals then living; they fitted well into their natural surroundings. But with the turn to agriculture, things began to be different. The most obvious change was the destruction of forests, but in and near cities there was pollution of streams. With the age of intensive energy, the changes became far greater. There were many more people, many more cities, and new, powerful machines. The result was gradual destruction of the plant cover, devastation of whole landscapes, pollution of the air, of streams and lakes, and even of the ocean. Gradually, parts of Earth's lands have approached a state in which they will no longer be habitable. Yet the growth of Earth's human population (Fig. 1.4) continues unchecked. Despite slowdowns in some countries, including the United States, world population as a whole is still doubling every 33 years. Unless a miracle occurs, by the year 2000 the world will be swarming with seven billion human beings. The demand for food is already pushing forward ever more strongly the exploitation of plants and animals, and will tend to increase the existing intensities of pollution. That is to say, this demand will subject the delicately balanced natural economy to additional pressure. To put the case differently still, the human species is becoming less and less well-adapted to its proper place in nature. That this is true is shown by three basic indicators: (1) serious overcrowding, (2) decreases in per-capita consumption of food along with increases in per-capita consumption of energy, and (3) widespread destruction of terrain and pollution of air and water.

With a limited view confined to the natural community around us, we sometimes fail to realize that human activity creates tremendous changes in Earth's natural features. A major example is the group of changes being wrought by strip mining of coal in the Appalachian region of the United States. Destruction of terrain and pollution of water are clearly evident in the huge continuous gashes along hillsides. Broad horizontal shelves floored with

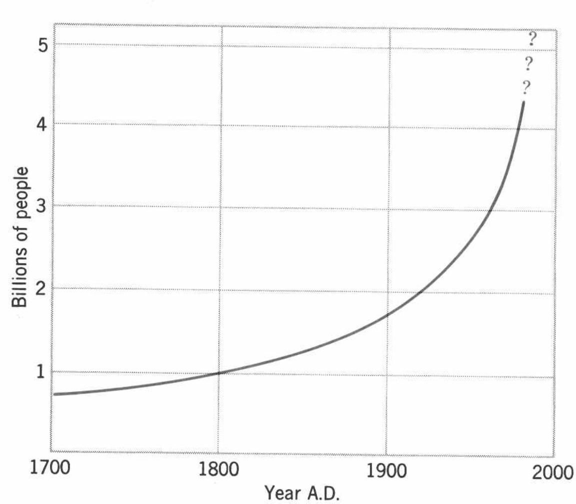

Figure 1.4
From the time when man first appeared on Earth, his numbers have slowly increased. Beginning with the industrial age that commenced in the 18th Century, the world's population has approximately doubled every 33 years.

broken rock waste and backed by sheer rock walls are the most conspicuous feature of many Appalachian landscapes. By 1975 such shelves aggregated more than 30,000km in length, a length that begins to approach the circumference of the Earth. As stripping proceeds, it destroys forests and soil, reduces the amount and quality of the water in the ground, pollutes streams by pouring into them quantities of debris and acid chemicals released from the coal, creates landslides, and causes erosion that leads to the piling-up of debris on valley floors. Slopes once forested become dangerous eyesores; entire stream systems become clogged and lifeless.

The bad effects of human interference with natural systems are evident also in the recent history of the Caspian Sea, the world's largest salt lake, about the size of the state of California. Since about 1930, its water surface has lowered by nearly 2.5 meters, leaving many port facilities literally high and dry. The water has increased in salinity and the commercial catch of fish has decreased by half. Also, because there were fewer fish to eat the mosquito larvae, there were epidemics of malaria.

The principal source of water for the Caspian is the huge Volga River. Because the lake has no outlet, the inflow of water is balanced by evaporation under a warm, dry climate. Since about 1930, contribution of water by the Volga has decreased markedly. The decrease resulted in part from decrease in rainfall and a warming trend in the climate, but also has been influenced to a considerable though unknown extent by withdrawal of water from the Volga for irrigation. A proposed plan to counteract the decline would divert a large Arctic river into the Volga. Although this would increase the flow into the Caspian, it might have other, unforeseen consequences.

We should not give the impression that man's interference with nature is always bad. Terrain can sometimes be rearranged on a very large scale without obvious unfavorable consequences. The conversion of shallow sea floor into usable land is an example (Fig. 1.5). Since about A.D. 1200, the Dutch people have been reclaiming land from the sea by building dikes and draining lakes and marshes. Today the reclamation process has become part of the high-energy economy, and the resulting dikes and other engineering works are huge. The reclaimed land adds up to more than 10 percent of the area of the Netherlands. But that much land—5,000 square kilometers—is less than the estimated area of Dutch terrain that has been lost to the sea, since the year 1200, by waves and currents along other parts of the coast. The engineers are not even holding their own!

Two vital lessons can be learned from the three examples described, and from the many other examples given in this book. The first is that any artificial change in a natural system will probably lead to unforeseen and undesirable side effects. The second is nicely illustrated by the Dutch reclamation example: the more a natural system is changed—the further it is pushed out of