Planet and Population: An Overview

About five billion years ago, out of a swirling mass of gas and dust, evolved a system of varied planets hurtling around a nuclear-powered star—our solar system. One of these planets, and one only, gave rise to complex life-forms. Over time, a tremendous diversity of life-forms and ecological systems developed, while the planet, too, evolved and changed, its interior churning, its landmasses shifting, its surface constantly being reshaped. Within the last several million years, the diversity of life on earth has included humans, increasingly competing for space and survival on the planet's surface. With the control over one's surroundings made possible by the combination of intelligence and manual dexterity, humans have found most of the land on the planet inhabitable; they have learned to use not only plant and animal resources, but minerals, fuels, and other geologic materials; in some respects, humans have even learned to modify natural processes that inconvenience or threaten them. As we have learned how to study our planet in systematic ways, we have developed an ever-increasing understanding of the complex nature of the processes shaping, and the problems posed by, our geological environment. **Environmental geology** explores the many and varied interactions between humans and that geologic environment.

As the human population grows, these interactions expand. It becomes increasingly difficult for us to survive on the resources and land remaining, to avoid those hazards that cannot be controlled, and to refrain from making irreversible and undesirable changes in environmental systems. The urgency of perfecting our understanding, not only of natural processes but

Geology provides the ground we live on, the soil in which our crops are grown, many of the mineral and energy resources on which we depend, and even striking scenery. Over a thousand years ago, the Ancestral Puebloans found shelter and building materials amid the cliffs in what is now Mesa Verde National Park.

also of our impact on the planet, is becoming more and more apparent worldwide, and has motivated increased international cooperation and dialogue on environmental issues. In 1992, more than 170 nations came together in Rio de Janeiro for the United Nations Conference on Environment and Development, to address such issues as global climate change, sustainable development, and environmental protection. The resultant UN Framework Convention on Climate Change marked the start of a series of meetings and agreements on environmental issues that continues to this day; the most recent such agreement, adopted in Paris in 2016, involves commitment to limit carbon emissions and global warming. These and other environmental accords will be explored further in chapters 17 and 19. For now, we can note that even when nations agree on what the problematic issues are (and this is not always the case!), agreement on solutions is commonly more difficult to achieve, and implementation of those solutions frequently both complex and slow. Meanwhile, global population continues to grow.

1.1 Earth in Space and Time

The Early Solar System

In recent decades, scientists have been able to construct an ever-clearer picture of the origins of the solar system and, before that, of the universe itself. Most astronomers now accept some sort of "Big Bang" as the origin of today's universe. Just before it occurred, all matter and energy would have been compressed into an enormously dense, hot volume a few millimeters (much less than an inch) across. Then everything was flung violently apart across an ever-larger volume of space. The time of the Big Bang can be estimated in several ways. Perhaps the most direct is the back-calculation of the universe's expansion to its apparent beginning. Other methods depend on astrophysical models of creation of the elements or the rate of evolution of different types of stars. Most age estimates overlap in the range of 12 to 14 billion years.

Stars formed from the debris of the Big Bang, as locally high concentrations of mass were collected together by gravity, and some became large and dense enough that energy-releasing atomic reactions were set off deep within them. Stars are not permanent objects. They are constantly losing energy and mass as they burn their nuclear fuel. The mass of material that initially formed the star determines how rapidly the star burns; some stars burned out billions of years ago, while others are probably forming now from the original matter of the universe mixed with the debris of older stars.

Our sun and its system of circling planets, including the earth, are believed to have formed from a rotating cloud of gas and dust (small bits of rock and metal), some of the gas debris from older stars (**figure 1.1**). Most of the mass of the cloud coalesced to form the sun, which became a star and began to "shine," or release light energy, when its interior became so dense and hot from the crushing effects of its own gravity that nuclear reactions were triggered inside it. Meanwhile, dust condensed from the gases remaining in the flattened cloud disk rotating around the young sun. The dust clumped into planets, the formation of which was essentially complete over 4½ billion years ago.

The Planets

The compositions of the planets formed depended largely on how near they were to the hot sun. The planets formed nearest to the sun contained mainly metallic iron and a few minerals with very high melting temperatures, with little water or gas. Somewhat farther out, where temperatures were lower, the

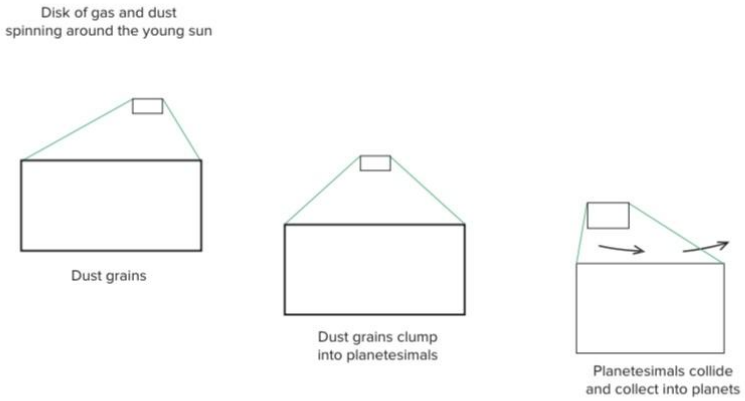


Figure 1.1
Our solar system formed as dust condensed from the gaseous nebula, then clumped together to make planets.

Table 1.1 Some Basic Data on the Planets

Planet	Mean Distance from Sun (millions of km)	Mean Temperature (°C)	Equatorial Diameter, Relative to Earth	Density* (g/cu. cm)	
Mercury	58	167	0.38	5.4	Predominantly rocky/metal planets
Venus	108	464	0.95	5.2	
Earth	150	15	1.00	5.5	
Mars	228	−65	0.53	3.9	
Jupiter	778	−110	11.19	1.3	Gaseous planets
Saturn	1427	−140	9.41	0.7	
Uranus	2870	−195	4.06	1.3	
Neptune	4479	−200	3.88	1.6	

Source: Data from NASA.

*No other planets have been extensively sampled to determine their compositions directly, though we have some data on their surfaces. Their approximate bulk compositions are inferred from the assumed starting composition of the solar nebula and the planets' densities. For example, the higher densities of the inner planets reflect a significant iron content and relatively little gas.

developing planets incorporated much larger amounts of lower-temperature minerals, including some that contain water locked within their crystal structures. (This later made it possible for the earth to have liquid water at its surface.) Still farther from the sun, temperatures were so low that nearly all of the materials in the original gas cloud condensed—even materials like methane and ammonia, which are gases at normal earth surface temperatures and pressures.

The result was a series of planets with a variety of compositions, most quite different from that of Earth. This is confirmed by observations and measurements of the planets. For example, the planetary densities listed in **table 1.1** are consistent with a higher metal and rock content in the four planets closest to the sun and a much larger proportion of ice and gas in the planets farther from the sun (see also **figure 1.2**). These differences should be kept in mind when it is proposed that other planets could be mined for needed minerals. Both the basic chemistry of these other bodies and the kinds of ore-forming or other resource-forming processes that might occur on them would differ considerably from those on Earth, and may not have led to products we would find useful. (This is leaving aside any questions of the economics or technical practicability of such mining activities!) In addition, our principal current energy sources required living organisms to form, and so far, no such life-forms have been found on other planets or moons. Venus—close to Earth in space, similar in size and density—shows marked differences: Its dense, cloudy atmosphere is thick with carbon dioxide, producing planetary surface temperatures hot enough to melt lead through runaway greenhouse-effect heating (see chapter 10). Mars would likewise be inhospitable: It is very cold, and we could not breathe its atmosphere. Though its surface features indicate the presence of liquid water in its past, there is none now, and only small amounts of water ice have been found. There is not so much as a blade of grass for vegetation; the brief flurry of excitement over possible evidence of life on Mars referred only to fossil microorganisms, and more-intensive investigations suggested that the tiny structures in question likely are inorganic, though the search for Martian microbes continues.

Earth, Then and Now

The earth has changed continuously since its formation, undergoing some particularly profound changes in its early history. The early earth was very different from what it is today, lacking the modern oceans and atmosphere and having a much different surface from its present one, probably more closely resembling the barren, cratered surface of the moon. Like other planets, Earth was formed by accretion, as gravity collected together the solid bits that had condensed from the solar nebula. Some water may have been contributed by gravitational capture of icy comets, though recent analyses of modern comets do not suggest that this was a major water source. The planet was heated by the impact of the colliding dust particles and meteorites as they came together to form the earth, and by the energy release from decay of the small amounts of several naturally radioactive elements that the earth contains. These heat sources combined to raise the earth's internal temperature enough that parts of it, perhaps eventually most of it, melted, although it was probably never molten all at once. Dense materials, like metallic iron, would have tended to sink toward the middle of the earth. As cooling progressed, lighter, low-density minerals crystallized and floated out toward the surface. The eventual result was an earth differentiated into several major compositional zones: the central **core,** the surrounding **mantle,** and a thin **crust** at the surface (see **figure 1.3**). The process was complete well before 4 billion years ago.

Although only the crust and a few bits of uppermost mantle that are carried up into the crust by volcanic activity can be sampled and analyzed directly, we nevertheless have a good deal of information on the composition of the earth's interior. First, scientists can estimate from analyses of stars the starting composition of the cloud from which the solar system formed. Geologists can also infer aspects of the earth's bulk composition from analyses of certain meteorites believed to have formed at the same time

Figure 1.2

The planets of the solar system vary markedly in both composition and physical properties. For example, Mercury (A), as shown in this image from a 2008 *Messenger* spacecraft flyby, is rocky, iron-rich, dry, and pockmarked with craters. Mars (B) shares many surface features with Earth (volcanoes, canyons, dunes, slumps, stream channels, and more), but the surface is now dry and barren; (C) a 2008 panorama by the Mars rover *Spirit*. Jupiter (D) is a huge gas ball, with no solid surface at all, and dozens of moons of ice and rock that circle it to mimic the solar system in miniature. Note also the very different sizes of the planets (E). The Jovian planets—named for Jupiter—are gas giants; the terrestrial planets are more rocky, like Earth.

Sources: (A) NASA image courtesy Science Operations Center at Johns Hopkins University Applied Physics Laboratory; (B) NASA; (C) Image courtesy NASA/JPL/Cornell; (D) NSSDC Goddard Space Flight Center; (E) NASA.

A

B

C

D

E

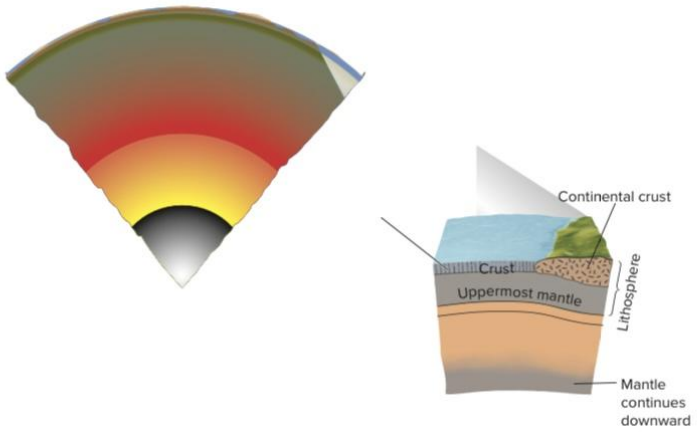


Figure 1.3

A chemically differentiated Earth. The core consists mostly of iron; the outer part is molten. The mantle, the largest zone, is made up primarily of ferromagnesian silicates (see chapter 2) and, at great depths, of oxides of iron, magnesium, and silicon. The crust (not drawn to scale, but exaggerated vertically in order to be visible at this scale) forms a thin skin around the earth. Oceanic crust, which forms the sea floor, has a composition somewhat like that of the mantle, but is richer in silicon. Continental crust is both thicker and less dense. It rises above the oceans and contains more light minerals rich in calcium, sodium, potassium, and aluminum. The "plates" of plate tectonics (the lithosphere) comprise the crust and uppermost mantle. (100 km ≈ 60 miles)

as, and under conditions similar to, the earth. Geophysical data demonstrate that the earth's interior is zoned and also provide information on the densities of the different layers within the earth, which further limits their possible compositions. These and other kinds of data indicate that the earth's core is made up mostly of iron, with some nickel and a few minor elements; the outer core is molten, the inner core solid. The mantle consists mainly of iron, magnesium, silicon, and oxygen combined in varying proportions in several different minerals. The earth's crust is much more varied in composition and very different chemically from the average composition of the earth (see **table 1.2**). As is evident from this table, many of the metals we have come to prize as resources are relatively uncommon elements in the crust. Crust and uppermost mantle together form a somewhat brittle shell around the earth.

The heating and subsequent differentiation of the early earth led to another important result: formation of the atmosphere and oceans. Many minerals that had contained water or gases in their crystals released them during the heating and melting, and as the earth's surface cooled, the water could condense to form the oceans. Without this abundant surface water, which in the solar system is unique to Earth, most life as we know it could not exist. The oceans filled basins, while the continents, buoyant because of their lower-density rocks and minerals, stood above the sea surface. At first, the continents were barren of life.

The earth's early atmosphere was quite different from the modern one, aside from the effects of modern pollution. The first atmosphere had little or no free oxygen in it. It probably consisted dominantly of nitrogen and carbon dioxide (the gas most commonly released from volcanoes, aside from water) with minor amounts of such gases as methane, ammonia, and various sulfur gases. Humans could not have survived in this early atmosphere. Oxygen-breathing life of any kind could not exist before the single-celled blue-green algae appeared in large

Table 1.2 Most Common Chemical Elements in the Earth

WHOLE EARTH		CRUST	
Element	Weight Percent	Element	Weight Percent
Iron	32.4	Oxygen	46.6
Oxygen	29.9	Silicon	27.7
Silicon	15.5	Aluminum	8.1
Magnesium	14.5	Iron	5.0
Sulfur	2.1	Calcium	3.6
Nickel	2.0	Sodium	2.8
Calcium	1.6	Potassium	2.6
Aluminum	1.3	Magnesium	2.1
(All others, total)	.7	(All others, total)	1.5

(Compositions cited are averages of several independent estimates.)

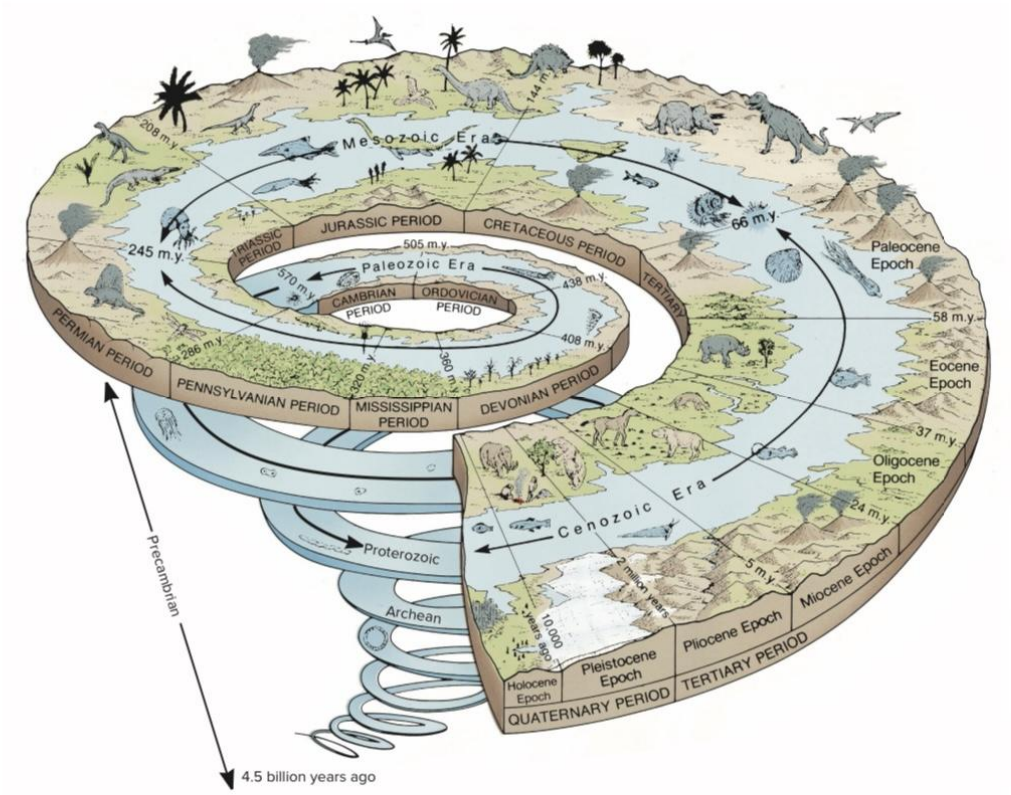


Figure 1.4

The "geologic spiral": Important plant and animal groups appear where they first occurred in significant numbers. If earth's whole history were equated to a 24-hour day, modern thinking humans *(Homo sapiens)* would have arrived on the scene just about six seconds ago. For another way to look at these data, see table A.1 in appendix A.

Source: Modified after U.S. Geological Survey publication Geologic Time.

numbers to modify the atmosphere. Their remains are found in rocks as much as several billion years old. They manufacture food by photosynthesis, using sunlight for energy, consuming carbon dioxide, and releasing oxygen as a by-product. In time, enough oxygen accumulated that the atmosphere could support oxygen-breathing organisms.

Life on Earth

The rock record shows when different plant and animal groups appeared. Some are represented schematically in **figure 1.4**. The earliest creatures left very few remains because they had no hard skeletons, teeth, shells, or other hard parts that could be preserved in rocks. The first multicelled oxygen-breathing creatures probably developed about 1 billion years ago, after oxygen in the atmosphere was well established. By about 550 million years ago, marine animals with shells had become widespread.

The development of organisms with hard parts—shells, bones, teeth, and so on—greatly increased the number of preserved animal remains in the rock record; consequently, biological developments since that time are far better understood. Dry land was still barren of large plants or animals half a billion years ago. In rocks about 500 million years old is the first evidence of animals with backbones—the fish—and soon thereafter, early land plants developed, before 400 million years ago. Insects appeared approximately 300 million years ago. Later, reptiles and amphibians moved onto the continents. The dinosaurs appeared about 200 million years ago and the first mammals at nearly the same time. Warm-blooded

animals took to the air with the development of birds about 150 million years ago, and by 100 million years ago, both birds and mammals were well established.

Such information has current applications. Certain energy sources have been formed from plant or animal remains. Knowing the times at which particular groups of organisms appeared and flourished is helpful in assessing the probable amounts of these energy sources available and in concentrating the search for these fuels on rocks of appropriate ages.

On a timescale of billions of years, human beings have just arrived. The most primitive human-type remains are no more than 4 to 5 million years old, and modern, rational humans *(Homo sapiens)* developed only about half a million years ago. Half a million years may sound like a long time, and it is if compared to a single human lifetime. In a geologic sense, though, it is a very short time. If we equate the whole of earth's history to a 24-hour day, then shelled organisms appeared only about 3 hours ago; fish, about 2 hours and 40 minutes ago; land plants, 2 hours ago; birds, about 45 minutes ago—and *Homo sapiens* has been around for just the last 6 *seconds.* Nevertheless, we humans have had an enormous impact on the earth, at least at its surface, an impact far out of proportion to the length of time we have occupied it. Our impact is likely to continue to increase rapidly as the population does likewise.

1.2 Geology, Past and Present

Two centuries ago, geology was mainly a descriptive science involving careful observation of natural processes and their products. The subject has become both more quantitative and more interdisciplinary through time. Modern geoscientists draw on the principles of chemistry to interpret the compositions of geologic materials, apply the laws of physics to explain these materials' physical properties and behavior, use the biological sciences to develop an understanding of ancient life-forms, and rely on engineering principles to design safe structures in the presence of geologic hazards. The emphasis on the "why," rather than just the "what," has also increased.

The Geologic Perspective

Geologic observations now are combined with laboratory experiments, careful measurements, and calculations to develop theories of how natural processes operate. Geology is especially challenging because of the disparity between the scientist's laboratory and nature's. In the research laboratory, conditions of temperature and pressure, as well as the flow of chemicals into or out of the system under study, can be carefully controlled. One then knows just what has gone into creating the product of the experiment. In nature, the geoscientist is often confronted only with the results of the "experiment" and must deduce the starting materials and processes involved.

Another complicating factor is time. The laboratory scientist must work on a timescale of hours, months, years, or, at most, decades. Natural geologic processes may take a million or a billion years to achieve a particular result, by stages too slow even to be detected in a human lifetime (**table 1.3**). This understanding may be one of the most significant contributions of early geoscientists: the recognition of the vast length of geologic history, sometimes described as "deep time." The qualitative and quantitative tools for sorting out geologic events and putting dates on them are outlined in appendix A. For now, it is useful to bear in mind that the immensity of geologic time can make it difficult to arrive at a full understanding of how geologic processes operated in the past from observations made on a human timescale. It dictates caution, too, as we try to project, from a few years' data on global changes associated with human activities, all of the long-range impacts we may be causing.

Also, the laboratory scientist may conduct a series of experiments on the same materials, but the experiments can be stopped and those materials examined after each stage. Over the vast spans of geologic time, a given mass of earth material may have been transformed a half-dozen times or more, under different conditions each time. The history of the rock that ultimately results may be very difficult to decipher from the end product alone.

Table 1.3 Some Representative Geologic-Process Rates

Process	Occurs Over a Time Span of About This Magnitude
Rising and falling of tides	1 day
"Drift" of a continent by 2–3 centimeters (about 1 inch)	1 year
Accumulation of energy between large earthquakes on a major fault zone	10–100 years
Rebound (rising) by 1 meter of a continent depressed by ice sheets during the Ice Age	100 years
Flow of heat through 1 meter of rock	1000 years
Deposition of 1 centimeter of fine sediment on the deep-sea floor	1000–10,000 years
Ice sheet advance and retreat during an ice age	10,000–100,000 years
Life span of a small volcano	100,000 years
Life span of a large volcanic center	1–10 million years
Creation of an ocean basin such as the Atlantic	100 million years
Duration of a major mountain-building episode	100 million years
History of life on earth	Over 3 billion years

Geology and the Scientific Method

The **scientific method** is a means of discovering basic scientific principles. One begins with a set of observations and/or a body of data, based on measurements of natural phenomena or on experiments. One or more *hypotheses* are formulated to explain the observations or data. A **hypothesis** can take many forms, ranging from a general conceptual framework or model describing the functioning of a natural system, to a very precise mathematical formula relating several kinds of numerical data. What all hypotheses have in common is that they must all be susceptible to testing and, particularly, to *falsification.* The idea is not simply to look for evidence to support a hypothesis, but to examine relevant evidence with the understanding that it may show the hypothesis to be wrong.

In the classical conception of the scientific method, one uses a hypothesis to make a set of predictions. Then one devises and conducts experiments to test each hypothesis, to determine whether experimental results agree with predictions based on the hypothesis. If they do, the hypothesis gains credibility. If not, if the results are unexpected, the hypothesis must be modified to account for the new data as well as the old or, perhaps, discarded altogether. Several cycles of modifying and retesting hypotheses may be required before a hypothesis that is consistent with all the observations and experiments that one can conceive is achieved. A hypothesis that is repeatedly supported by new experiments advances in time to the status of a **theory,** a generally accepted explanation for a set of data or observations.

Much confusion can arise from the fact that in casual conversation, people often use the term *theory* for what might better be called a hypothesis, or even just an educated guess. ("So, what's your theory?" one character in a TV mystery show may ask another, even when they've barely looked at the first evidence.) Thus, people may assume that a scientist describing a theory is simply telling a plausible story to explain some data. A scientific theory, however, is a very well-tested model with a very substantial and convincing body of evidence that supports it. A hypothesis may be advanced by just one individual; a theory has survived the challenge of extensive testing to merit acceptance by many, often most, experts in a field. The Big Bang theory is not just a creative idea. It accounts for the decades-old observation that all the objects we can observe in the universe seem to be moving apart. If it is correct, the universe's origin was very hot; scientists have detected the cosmic microwave background radiation consistent with this. And astrophysicists' calculations predict that the predominant elements that the Big Bang would produce would be hydrogen and helium—which indeed overwhelmingly dominate the observed composition of our universe.

The classical scientific method is not strictly applicable to many geologic phenomena because of the difficulty of experimenting with natural systems, given the time and scale considerations noted earlier. For example, one may be able to conduct experiments on a single rock, but not to construct a whole volcano in the laboratory, nor to replicate a large meteorite impact (like that of **figure 1.5**) to study its effects. In such cases, hypotheses are often tested entirely through further observations or theoretical calculations and modified as necessary until they accommodate all the relevant observations (or are discarded when they cannot be reconciled with new data). This broader conception of the scientific method is well illustrated by the development of the theory of plate tectonics, discussed in chapter 3. "Continental drift" was once seen as a wildly implausible idea, advanced by an eccentric few, but in the latter half of the twentieth century, many kinds of evidence were found to be explained consistently and well by movement of plates—including continents—over earth's surface. Still, the details of plate tectonics continue to be refined by further studies. Even a well-established theory may ultimately be proved incorrect. (Plate tectonics in fact supplanted a very different theory about how mountain ranges form.) In the case of geology, complete rejection of an older theory has most often been caused by the development of new analytical or observational techniques, which make available wholly new kinds of data that were unknown at the time the original theory was formulated.

Figure 1.5

Meteor Crater, Arizona.

Source: U.S. Geological Survey/Photograph by David J. Roddy, USGS Branch of Astrogeology.

The Motivation to Find Answers

In spite of the difficulties inherent in trying to explain geologic phenomena, the search for explanations goes on, spurred not only by the basic quest for knowledge, but also by the practical problems posed by geologic hazards, the need for resources, and concerns about possible global-scale human impacts, such as ozone destruction and global warming.

The hazards may create the most dramatic scenes and headlines, the most abrupt consequences: The 1989 Loma Prieta (California) earthquake caused more than $5 billion in damage; the 1995 Kobe (Japan) earthquake (**figure 1.6**), similar in size to Loma Prieta, caused over 5200 deaths and about $100 billion in property damage; the 2004 Sumatran earthquake claimed nearly 300,000 lives; the 2011 quake offshore from

Figure 1.6

Overturned section of Hanshin Expressway, eastern Kobe, Japan, after 1995 earthquake. This freeway, elevated to save space, was built in the 1960s to then-current seismic design standards.

Source: Photograph by Christopher Rojahn, Applied Technology Council.

Honshu, Japan, killed over 15,000 people and caused an estimated $300 billion in damages. The 18 May 1980 eruption of Mount St. Helens (**figure 1.7**) took even the scientists monitoring the volcano by surprise, and the 1991 eruption of Mount Pinatubo in the Philippines not only devastated local residents but caught the attention of the world through a marked decline in 1992 summer temperatures. Efforts are underway to provide early warnings of such hazards as earthquakes, volcanic eruptions, and landslides so as to save lives, if not property. Likewise, improved understanding of stream dynamics and more prudent land use can together reduce the damages from flooding (**figure 1.8**), which amount in the United States to over $1 billion a year and the loss of dozens of lives annually. Landslides and other slope and ground failures (**figure 1.9**) take a similar toll in property damage, which could be reduced by more attention to slope stability and improved engineering practices. It is not only the more dramatic hazards that are costly: On average, the cost of structural damage from unstable soils each year approximately equals the combined costs of landslides, earthquakes, and flood damages in this country.

Figure 1.7

Ash pours from Mount St. Helens, May 1980.

Source: U.S. Geological Survey/Photograph by Peter Lipman.

Figure 1.8

A major river like the Mississippi floods when a large part of the area that it drains is waterlogged by more rain or snowmelt than can be carried away in the channel. Such floods—like that in summer 1993, shown here drenching Jefferson City, Missouri—can be correspondingly long-lasting. Over millennia, the stream builds a floodplain into which the excess water naturally flows; we build there at our own risk.

Source: Photograph by Mike Wright, courtesy Missouri Department of Transportation.

It is worth noting that as scientists become better able to predict such events as earthquakes and volcanic eruptions, new challenges arise: How certain should they be before a prediction is issued? How best to educate the public—and public officials—about the science behind the predictions and its limitations, so that they can prepare/respond appropriately? What if a prediction is wrong? Such issues will be examined in later chapters.

Our demand for resources of all kinds continues to grow and so do the consequences of resource use. In the United States, average per-capita water use is 1500 gallons per day; in many places, groundwater supplies upon which we have come to rely heavily are being measurably depleted. Worldwide, water-resource disputes between nations are increasing in number.

Figure 1.9

Damage from the 2005 Laguna Beach, California, landslide.

Source: U.S. Geological Survey EROS Data Center Image Gallery/Photograph by Pam Irvine, California Geological Survey.

As we mine more extensively for mineral resources, we face the problem of how to minimize associated damage to the mined lands (**figure 1.10**). The grounding of the *Exxon Valdez* in 1989, dumping 11 million gallons of oil into Prince William Sound, Alaska, and the massive spill from the 2010 explosion of the *Deepwater Horizon* drilling platform in the Gulf of Mexico were reminders of the negative consequences of petroleum exploration, just as the 1991 war in Kuwait, and the later invasion of Iraq, were reminders of U.S. dependence on imported oil.

As we consume more resources, we create more waste. In the United States, total waste generation is estimated at close to 300 million tons per year—or more than a ton per person. Careless waste disposal, in turn, leads to pollution. The Environmental Protection Agency continues to identify toxic-waste disposal sites in urgent need of cleanup; by 2000, over 1500 so-called priority sites had been identified. Cleanup costs per site have risen to over $30 million, and the projected total costs to remediate these sites alone is over $1 trillion. As fossil fuels are burned, carbon dioxide in the atmosphere rises, and modelers of global climate strive to understand what that may do to global temperatures, weather, and agriculture decades in the future.

These are just a few of the kinds of issues that geologists play a key role in addressing.

Figure 1.10

The Grasberg Mine in Irian Jaya, Indonesia, is one of the world's largest gold- and copper-mining operations. The surface pit is nearly 4 km (2½ miles) across; note the sharp contrast with surrounding topography. Slopes oversteepened by mining have produced deadly landslides, and local residents worry about copper and acid contamination in runoff water.

Source: Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center.

Wheels Within Wheels: Earth Cycles and Systems

The earth is a dynamic, constantly changing planet—its crust shifting to build mountains; lava spewing out of its warm interior; ice and water and windblown sand and gravity reshaping its surface, over and over. Some changes proceed in one direction only: For example, the earth has been cooling progressively since its formation, though considerable heat remains in its interior. Many of the processes, however, are cyclic in nature.

Consider, for example, such basic materials as water or rocks. Streams drain into oceans and would soon run dry if not replenished; but water evaporates from oceans, to make the rain and snow that feed the streams to keep them flowing. This describes just a part of the *hydrologic* (water) *cycle,* explored more fully in chapters 6 and 11. Rocks, despite their appearance of permanence in the short term of a human life, participate in the *rock cycle* (chapters 2 and 3). The kinds of evolutionary paths rocks may follow through this cycle are many, but consider this illustration: A volcano's lava (**figure 1.11**) hardens into rock; the rock is weathered into sand and dissolved chemicals; the debris, deposited in an ocean basin, is solidified into a new rock of quite different type; and some of that new rock may be carried into the mantle via plate tectonics, to be melted into a new lava. The time frame over which this process occurs is generally much longer than that over which water cycles through atmosphere and

Chemicals, too, cycle through the environment. The carbon dioxide that we exhale into the atmosphere is taken up by plants through photosynthesis, and when we eat those plants for food energy, we release CO_2 again. The same exhaled CO_2 may also dissolve in rainwater to make carbonic acid that dissolves continental rock; the weathering products may wash into the ocean, where dissolved carbonate then contributes to the formation of carbonate shells and carbonate rocks in the ocean basins; those rocks may later be exposed and weathered by rain, releasing CO_2 back into the atmosphere or dissolved carbonate into streams that carry it back to the ocean. The cycling of chemicals and materials in the environment may be complex, as we will see in later chapters.

Furthermore, these processes and cycles are often interrelated, and seemingly local actions can have distant consequences. We dam a river to create a reservoir as a source of irrigation water and hydroelectric power, inadvertently trapping stream-borne sediment at the same time; downstream, patterns of erosion and deposition in the stream channel change, and at the coast, where the stream pours into the ocean, coastal erosion of beaches increases because a part of their sediment supply, from the stream, has been cut off. The volcano that erupts the lava to make the volcanic rock also releases water vapor into the atmosphere, and sulfur-rich gases and dust that influence the amount of sunlight reaching earth's surface to heat it, which, in turn, can alter the extent of evaporation and resultant rainfall, which will affect the intensity of landscape erosion and weathering of rocks by water. . . . So although we divide the great variety and complexity of geologic processes and

Figure 1.11

Bit by bit, lava flows like this one on Kilauea have built the Hawaiian Islands.

©Carla Montgomery.

oceans, but the principle is similar. The Appalachian or Rocky Mountains as we see them today are not as they formed, tens or hundreds of millions of years ago; they are much eroded from their original height by water and ice, and, in turn, contain rocks formed in water-filled basins and deserts from material eroded from more-ancient mountains before them (**figure 1.12**).

A B

Figure 1.12

Rocks tell a story of constant change. (A) The folds of the Ouachita Mountains of Oklahoma formed deep in the crust when Africa and North America converged hundreds of millions of years ago; now they are eroding and crosscut by rivers. (B) The sandstones of Zion National Park preserve ancient windswept dunes, made of sand eroded from older rocks, deeply buried and solidified into new rock, then uplifted to erode again.

Sources: (A) NASA image created by Jesse Allen & Robert Simmon, using data provided courtesy of NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team; (B) ©Carla Montgomery.

phenomena into more manageable, chapter-sized units for purposes of discussion, it is important to keep such interrelationships in mind. And superimposed on, influenced by, and subject to all these natural processes are humans and human activities.

1.3 Nature and Rate of Population Growth

Animal populations, as well as primitive human populations, are generally quite limited both in the areas that they can occupy and in the extent to which they can grow. They must live near food and water sources. The climate must be one to which they can adapt. Predators, accidents, and disease take a toll. If the population grows too large, disease and competition for food are particularly likely to cut it back to sustainable levels.

The human population grew relatively slowly for hundreds of thousands of years. Not until the middle of the nineteenth century did the world population reach 1 billion. However, by then, a number of factors had combined to accelerate the rate of population increase. The second, third, and fourth billion were reached far more quickly; the world population is now over 7 billion and is expected to rise to nearly 10 billion by 2050 (**table 1.4**).

Humans are no longer constrained to live only where conditions are ideal. We can build habitable quarters even in extreme climates, using heaters or air conditioners to bring the temperature to a level we can tolerate. In addition, people need not live where food can be grown or harvested or where there is abundant fresh water: The food and water can be transported, instead, to where the people choose to live.

Growth Rates: Causes and Consequences

Population growth occurs when new individuals are added to the population faster than existing individuals are removed from it. On a global scale, the population increases when its birthrate exceeds its death rate. In assessing an individual nation's or region's rate of population change, immigration and emigration must also be taken into account. Improvements in nutrition and health care typically increase life expectancies, decrease mortality rates, and thus increase the rate of population growth. Increased use of birth-control or family-planning methods reduces birthrates and, therefore, also reduces the rate of population growth; in fact, a population can begin to decrease if birthrates are severely restricted.

The sharply rising rate of population growth over the past few centuries can be viewed another way. It took until about A.D. 1830 for the world's population to reach 1 billion. The population climbed to 2 billion in the next 130 years, and to 3 billion in just 30 more years, as ever more people contributed to the population growth and individuals lived longer. The last billion people have been added to the world's population in just a dozen years.

There are wide differences in growth rates among regions (**table 1.4**; **figure 1.13**). The reasons for this are many. Religious or social values may cause larger or smaller families to be regarded as desirable in particular regions or cultures. High levels of economic development are commonly associated with reduced rates of population growth; conversely, low levels of development are often associated with rapid population growth. The impact of improved education, which may accompany economic development, can vary: It may lead to better nutrition and prenatal and child care, and thus to increased growth rates, but it may also lead to increased or more effective practice of family-planning methods, thereby reducing growth rates.

A few governments of nations with large and rapidly growing populations have considered encouraging or mandating family planning. India and the People's Republic of China have taken active measures, with varying results: China's population growth rate is just 0.2% per year; its population is expected to peak at just over 1.4 billion, then to decline by 2050. But India's remains a relatively high 1.0% per year; its population will shortly surpass that of China and is projected to be over 1.7 billion by 2050.

Table 1.4 World and Regional Population Growth and Projections (in millions)

Year	World	North America	Latin America and Caribbean	Africa	Europe	Asia	Oceania
1950	2520	172	167	221	547	1402	13
Mid-2016	7417	360	637	1203	740	4437	40
2050 (projected)	9868	445	775	2527	728	5327	66
Growth rate (%/year)	1.0	0.77	0.83	2.4	0	0.78	1.7
Doubling time (years)	70	91	84	29	*	90	41

*Not applicable; population expected to decline by 2050.

Source: Data for 1950 from *United Nations World Population Estimates and Projections;* all other data from *2016 World Population Data Sheet,* Population Reference Bureau, 2016. Population projections to 2050 involve longer-term estimates of future growth rates, which in most areas are expected to decrease from the present levels reported here.

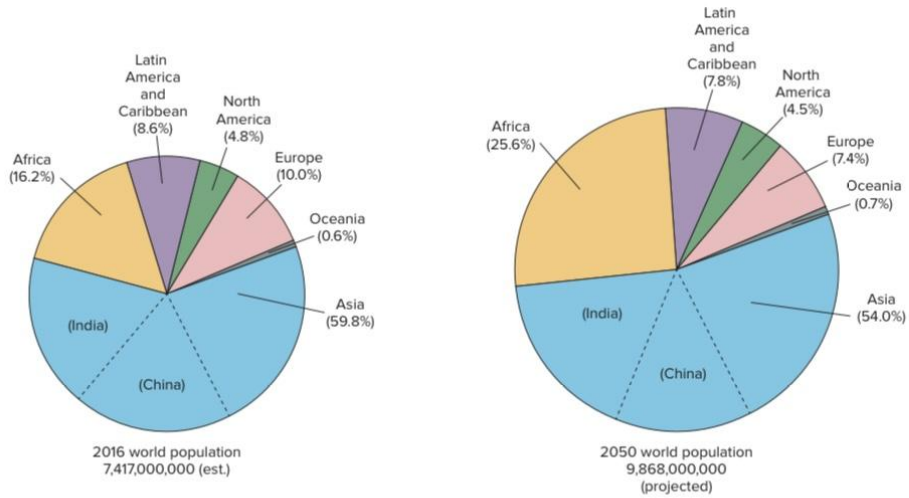


Figure 1.13

Population distribution by region in mid-2016 with projections to the year 2050. Size of circle reflects relative total population. The most dramatic changes in proportion are the relative growth of the population of Africa and decline of population in Europe. Data from table 1.4.

A relatively new factor that strongly affects population growth in some less-developed nations is AIDS. In more-developed countries, typically less than one-half of 1% of the population aged 15 to 49 is afflicted; the prevalence in some African nations is over 20%. In Swaziland, where AIDS/HIV prevalence in this age group is about 23% for men and 34% for women, life expectancy is down to 49 years (world average life expectancy is 72 years). How population in such countries will change over time depends greatly on how effectively the AIDS epidemic is controlled.

Even when the population growth rate is constant, the number of *individuals* added per unit of time increases over time. This is called **exponential growth,** a concept to which we will return when discussing resources in Section IV. The effect of exponential growth is similar to interest compounding. If one invests $100 at 10% per year and withdraws the interest each year, one earns $10/year, and after 10 years, one has collected $100 in interest. If one invests $100 at 10% per year, compounded annually, then, after one year, $10 interest is credited, for a new balance of $110. But if the interest is not withdrawn, then at the end of the second year, the interest is $11 (10% of $110), and the new balance is $121. By the end of the tenth year (assuming no withdrawals), the interest for the year is $23.58, but the interest *rate* has not increased. And the balance is $259.37 so, subtracting the original investment of $100, this means total interest of $159.37 rather than $100. Similarly with a population of 1 million growing at 5% per year: In the first year, 50,000 persons are added; in the tenth year, the population grows by 77,566 persons. The result is that a graph of population versus time steepens over time, even at a constant growth rate. If the growth rate itself also increases, the curve rises still more sharply.

For many mineral and fuel resources, consumption has been growing very rapidly, even more rapidly than the population. The effects of exponential increases in resource demand are like the effects of exponential population growth (**figure 1.14**). If demand increases by 2% per year, it will double not in 50 years, but in 35. A demand increase of 5% per year leads to a doubling in demand in 14 years and a tenfold increase in demand in 47 years! In other words, a prediction of how soon mineral or fuel supplies will be used up is very sensitive to the assumed rate of change in demand. Even if population is no longer growing exponentially, consumption of many resources is.

Growth Rate and Doubling Time

Another way to look at the rapidity of world population growth is to consider the expected **doubling time,** the length of time required for a population to double in size. Doubling time (D) in years may be estimated from growth rate (G), expressed in

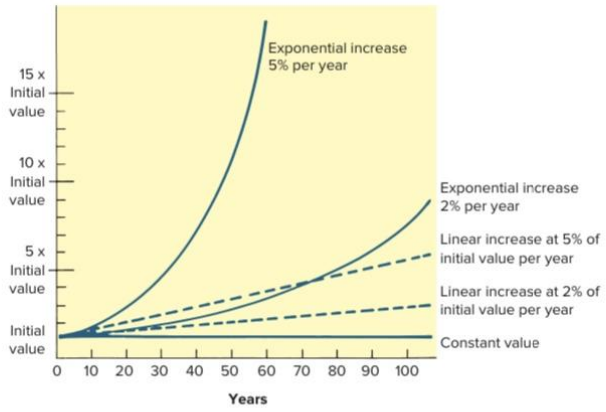


Figure 1.14

Graphical comparison of the effects of linear and exponential growth, whether on consumption of minerals, fuels, water, and other consumable commodities, or population. With linear growth, one adds a fixed percentage of the *initial* value each year (dashed lines). With exponential growth, the same percentage increase is computed each year, but year by year the value on which that percentage is calculated increases, so the annual increment keeps getting larger.

percent per year, using the simple relationship $D = 70/G$, which is derived from the equation for exponential growth (see "Exploring Further" question 2 at the chapter's end). The higher the growth rate, the shorter the doubling time of the population (see again **table 1.4**). By far the most rapidly growing segment of the population today is that of Africa. Its population, estimated at 1.20 billion in 2016, is growing at about 2.4% per year. The largest segment of the population, that of Asia, is increasing at 0.8% per year, and since the over 4 billion people there represent well over half of the world's total population, this leads to a relatively high global average growth rate. Europe's population has begun to decline slightly, but Europe contains only about 10% of the world's population.

The average worldwide population growth rate is about 1.0% per year, which corresponds to a doubling time of about 70 years. At that, the present population growth rate actually represents a substantial decline from nearly 2% per year in the mid-1960s, and that decline is expected to continue. However, a decreasing *growth rate* is not at all the same as a decreasing population. Depending upon projected fertility rates, estimates of world population in the year 2050 can vary by several billion. Using a medium fertility rate, the Population Reference Bureau projects a 2050 world population of almost 9.9 billion. **Figure 1.13** illustrates how those people will be distributed by region, considering differential growth rates from place to place.

Even breaking the world down into regions of continental scale masks a number of dramatic individual-country cases. Discussion of these, and of their political, economic, and cultural implications, is well beyond the scope of this chapter, but consider the following: While the population of Europe is nearly stable, in many parts of northern and eastern Europe, sharp declines are occurring. By 2050, the populations of Russia, Ukraine, and Bulgaria are expected to drop by 6, 21, and 18 percent, respectively. Conversely, parts of the Middle East are experiencing explosive population growth, with projected increases by 2050 of 68% in Israel, 58% in Saudi Arabia, 83% in the Palestinian Territory, and 101% in Iraq. The demographics differ widely between countries, too. Globally, 26% of the population is under 15, and only 8% above age 65. But in Japan, only 13% of the population is below age 15, with 27% age 65 or older; in Afghanistan, 44% of people are under 15 and only 2% age 65 or over. Thus, different nations face different challenges. Where rapid population growth meets scarcity of resources, problems arise.

1.4 Impacts of the Human Population

The problems posed by a rapidly growing world population have historically been discussed most often in the context of food: that is, how to produce sufficient food and distribute it effectively to prevent the starvation of millions in overcrowded countries or in countries with minimal agricultural development. This is a particularly visible and immediate problem, but it is also only one facet of the population challenge.

Farmland and Food Supply

Whether or not the earth can support 7 billion people, or 10 billion, or more, is uncertain. In part, it depends on the quality of life, the level of technological development, and other standards that societies wish to maintain. Yet even when considering the most basic factors, such as food, it is unclear just how many people the earth can sustain. Projections about the adequacy of food production, for example, require far more information than just the number of people to be fed and the amount of available land. The total arable land (land suitable for cultivation) in the world has been estimated at 3.5 billion acres, or about half an acre per person of the present population. The major limitation on this figure is availability of water, either as

rainfall or through irrigation. Further considerations relating to the nature of the soil include the soil's fertility, water-holding capacity, and general suitability for farming. Soil character varies tremendously, and its productivity is similarly variable. Moreover, farmland can deteriorate through loss of nutrients and by wholesale erosion of topsoil, and this degradation must be considered when making production predictions.

There is also the question of what crops can or should be grown. Today, this is often a matter of preference or personal taste, particularly in farmland-rich (and energy- and water-rich) nations. The world's people are not now always being fed in the most resource-efficient ways. To produce one ton of corn requires about 250,000 gallons of water; a ton of wheat, 375,000 gallons; a ton of rice, 1,000,000 gallons; a ton of beef, 7,500,000 gallons. Some new high-yield crop varieties may require irrigation, whereas native varieties did not. The total irrigated acreage in the world has more than doubled in three decades. However, water resources are dwindling in many places; the water costs of food production must increasingly be taken into account.

Genetic engineering is now making important contributions to food production, as varieties are selectively developed for high yield, disease resistance, and other desirable qualities. These advances have led some to declare that fears of global food shortages are no longer warranted, even if the population grows by several billion more. However, at least two concerns remain: One, poor nations already struggling to feed their people may be least able to afford the higher-priced designer seed or specially developed animal strains to benefit from these advances. Second, as many small farms using many, genetically diverse strains of food crops are replaced by vast areas planted with a single, new variety, there is the potential for devastating losses if a new pest or disease to which that one strain is vulnerable enters the picture.

Food production as practiced in the United States is also a very energy-intensive business. The farming is heavily mechanized, and much of the resulting food is extensively processed, stored, and prepared in various ways requiring considerable energy. The products are elaborately packaged and often transported long distances to the consumer. Exporting the same production methods to poor, heavily populated countries short on energy and the capital to buy fuel, as well as food, may be neither possible nor practical. Even if possible, it would substantially increase the world's energy demands.

Population and Nonfood Resources

Food is at least a renewable resource. Within a human life span, many crops can be planted and harvested from the same land and many generations of food animals raised. By contrast, the supplies of many of the resources considered in later chapters—minerals, fuels, even land itself—are finite. There is only so much oil to burn, rich ore to exploit, and suitable land on which to live and grow food. When these resources are exhausted, alternatives will have to be found or people will have to do without.

The earth's supply of many such materials is severely limited, especially considering the rates at which these resources are presently being used. Many could be effectively exhausted within decades, yet most people in the world are consuming very little in the way of minerals or energy. Current consumption is strongly concentrated in a few highly industrialized societies. Per-capita consumption of most mineral and energy resources is higher in the United States than in any other nation. For the world population to maintain a standard of living comparable to that of the United States, mineral production would have to increase about fourfold, on the average. There are neither the recognized resources nor the production capability to maintain that level of consumption for long, and the problem becomes more acute as the population grows.

Some scholars believe that we are already on the verge of exceeding the earth's **carrying capacity,** its ability to sustain its population at a basic, healthy, moderately comfortable standard of living. Estimates of sustainable world population made over the last few decades range from under 7 billion—and remember, we are already past that—to over 100 billion persons. The wide range is attributable to considerable variations in model assumptions, including standard of living and achievable productivity of farmland. Certainly, given global resource availability and technology, even the present world population could not enjoy the kind of high-consumption lifestyle to which the average resident of the United States has become accustomed.

It is true that, up to a point, the increased demand for minerals, fuels, and other materials associated with an increase in population tends to raise prices and promote exploration for these materials. The short-term result can be an apparent increase in the resources' availability, as more exploration leads to discoveries of more oil fields, ore bodies, and so on. However, the quantity of each of these resources is finite. The larger and more rapidly growing the world population, and the faster its level of development and standard of living rise, the more rapidly limited resources are consumed, and the sooner those resources will be exhausted.

Land is clearly a basic resource. Seven, 10, or 100 billion people must be *put* somewhere. Already, the global average population density is about 55 persons per square kilometer of land surface (140 persons per square mile), and that is counting *all* the land surface, including jungles, deserts, and mountain ranges, leaving out only the Antarctic continent. The ratio of people to readily inhabitable land is plainly much higher. Land is also needed for agriculture, manufacturing, energy production, transportation, and a variety of other uses. Large numbers of people consuming vast quantities of materials generate vast quantities of wastes. Some of these wastes can be recovered and recycled, but others cannot. It is essential to find places to put the latter, and ways to isolate the harmful materials from contact with the growing population. This effort claims still more land and, often, resources. All of this is why land-use planning—making the most of every bit of land available—is becoming increasingly important. At present, it is too often true that the ever-growing population settles in areas that are demonstrably unsafe or in which the possible problems are imperfectly known (**figures 1.15** and **1.16**).

Figure 1.15

The landslide hazard to these structures sitting at the foot of steep slopes in Rio de Janeiro is obvious, but space for building here is limited.

Uneven Distribution of People and Resources

Even if global carrying capacity were ample in principle, that of an individual region may not be. None of the resources—livable land, arable land, energy, minerals, or water—is uniformly distributed over the earth. Neither is the population (see **figure 1.17**). In 2016, the population density in persons per square kilometer of arable land was 213 in the United States, 79 in Canada, 52 in Australia, and a staggering 983,000 in Singapore. Such data clearly have implications for a nation's ability to feed itself, whatever the availability of farmland globally may be.

Many of the most densely populated countries are resource-poor. In some cases, a few countries control the major share of one resource. Oil is a well-known example, but there are many others. Thus, economic and political complications enter into the question of resource adequacy. Just because one nation controls enough of some commodity to supply all the world's needs does not necessarily mean that the country will choose to share its resource wealth or to distribute it at modest cost to other nations. Some resources, like land, are simply not transportable and therefore cannot readily be shared. Some of the complexities of global resource distribution will be highlighted in subsequent chapters.

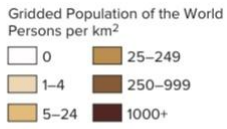
Figure 1.16

Even where safer land is abundant, people may choose to settle in hazardous—but scenic—places, such as barrier islands. Miami Beach, Florida.

Disruption of Natural Systems

Natural systems tend toward a balance or equilibrium among opposing factors or forces. When one factor changes, compensating changes occur in response. If the disruption of the system is relatively small and temporary, the system may, in time, return to its original condition, and evidence of the disturbance will disappear. For example, a coastal storm may wash away beach vegetation and destroy colonies of marine organisms living in a tidal flat, but when the storm has passed, new organisms will start to move back into the area, and new grasses will take root in the dunes. The violent eruption of a volcano like Mount Pinatubo may spew ash and gases high into the atmosphere, partially blocking sunlight and causing the earth to cool, but within a few years, the ash will have settled back to the ground, and normal temperatures will be restored. Dead leaves falling into a lake provide food for the microorganisms that within weeks or months will break the leaves down and eliminate them.

This is not to say that permanent changes never occur in natural systems. The size of a river channel reflects the maximum amount of water it normally carries. If long-term climatic or other conditions change so that the volume of water regularly reaching the stream increases, the larger quantity of water will,



A

B

Figure 1.17

(A) Global population density, 2000; the darker the shading, the higher the population density. Comparison with the distribution of lights at night in 2002 (B) shows that overall population density on the one hand, and urbanization/development on the other, are often, but not always, closely correlated.

Sources: (A) Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT), Gridded Population of the World (GPW), Version 3. Palisades, NY: CIESIN, Columbia University. Available at: http://sedac.ciesin.columbia.edu/gpw. (B) C. Mayhew & R. Simmon (NASA/GSFC), NOAA/NGDC, DMSP.

in time, carve out a correspondingly larger channel to accommodate it. The soil carried downhill by a landslide certainly does not begin moving back upslope after the landslide is over; the face of the land is irreversibly changed. Even so, a hillside forest uprooted and destroyed by the slide may, within decades, be replaced by new growth in the soil newly deposited at the bottom of the hill.

Human activities can cause or accelerate permanent changes in natural systems. The impact of humans on the global environment is broadly proportional to the size of the population, as well as to the level of technological development achieved. This can be illustrated especially easily in the context of pollution. The smoke from one campfire pollutes only the air in the immediate vicinity; by the time that smoke is dispersed through the atmosphere, its global impact is negligible. The collective smoke from a century and a half of increasingly industrialized society, on the other hand, has caused measurable increases in several atmospheric pollutants worldwide, and these pollutants continue to pour into the air from many sources. It was once assumed that the seemingly vast oceans would be an inexhaustible "sink" for any extra CO_2 that we might generate by burning fossil fuels, but decades of steadily climbing atmospheric CO_2 levels have proven that in this sense, at least, the oceans are not as large as we thought. Likewise, seven people carelessly dumping wastes into the ocean would not appreciably pollute that huge volume of water. The prospect of 7 *billion* people doing the same thing, however, is quite another matter. And every hour, now, world population increases by nearly *8500 people*.

Case Study 1

Earth's Moon

Scientists have long strived to explain the origin of Earth's large and prominent satellite. Through much of the twentieth century, several different models competed for acceptance; within the last few decades a new theory of lunar origin has been developed. While a complete discussion of the merits and shortcomings of these is beyond the scope of this book, they provide good examples of how objective evidence can provide support for, or indicate weaknesses in, hypotheses and theories.

Any acceptable theory of lunar origin has to explain a number of facts. The moon orbits the Earth in an unusual orientation (**figure 1**), neither circling around Earth's equator nor staying in the plane in which the planets' orbits around the sun lie (the ecliptic plane). Its density is much lower than that of Earth, meaning that it contains a much lower proportion of iron. Otherwise, it is broadly similar in composition to the earth's mantle. However, analysis of samples from the *Apollo* missions revealed that relative to Earth, the moon is depleted not only in most gases, but also in volatile (easily vaporized) metals such as lead and rubidium, indicating a hot history for lunar material.

The older "sister-planet" model proposed that the Earth and moon accreted close together during solar system formation, and that is how the moon comes to be orbiting Earth. But in that case, why is the moon not orbiting in the ecliptic plane, and why the significant chemical differences between the two bodies?

The "fission hypothesis" postulated that the moon was spun off from a rapidly rotating early earth after earth's core had been differentiated, so the moon formed mainly from earth's mantle. That would account for the moon's lower density and relatively lower iron content. But analyses of the lunar samples revealed the many additional chemical differences between the moon and earth's mantle. Furthermore, calculations show that a moon formed this way should be orbiting in the equatorial plane, and that far more angular momentum would be required to make it happen than is present in the earth-moon system.

A third suggestion was that the moon formed elsewhere in the solar system and then passed close enough to Earth to be "captured" into orbit by gravity. A major flaw in this idea involves the dynamics necessary for capture. The moon is a relatively large satellite for a body the size of Earth. For Earth's gravity to snare it, the rate at which the moon came by would have to be very, very slow. But Earth is hurtling around the sun at about 107,000 km/hr (66,700 mph), so the probability of the moon happening by at just the right distance and velocity for capture to occur is extremely low. Nor does capture account for a hot lunar origin.

So how to explain the moon? The generally accepted theory for the past two decades (sometimes informally described as the "Big Whack") involves collision between the Earth and a body about the size of Mars, whose orbit in the early solar system put it on course to

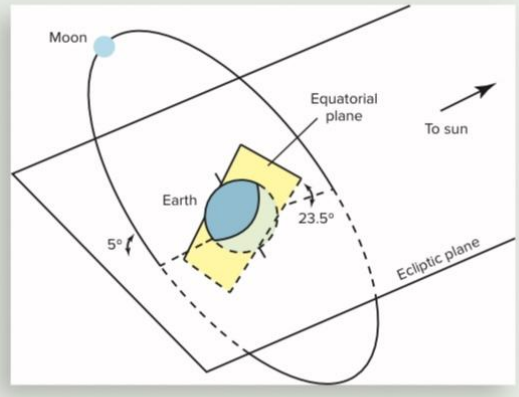


Figure 1
The moon's unusual orbit.

Summary

The solar system formed over 4½ billion years ago. The earth is unique among the planets in its chemical composition, abundant surface water, and oxygen-rich atmosphere. The earth passed through a major period of internal differentiation early in its history, which led to the formation of the atmosphere and the oceans. Earth's surface features have continued to change throughout the last 4^{+} billion years, through a series of processes that are often cyclical in nature, and commonly interrelated. The oldest rocks in which remains of simple organisms are recognized are more than 3 billion years old. The

intercept Earth. The tremendous energy of the collision would have destroyed the impactor and caused extensive heating and melting on Earth, ejecting quantities of vaporized minerals into space around Earth. If this impact occurred after core differentiation, that material would have come mainly from the mantles of Earth and the impactor. The orbiting material would have condensed and settled into a rotating disk of dust that later accreted to form the moon.

This theory, exotic as it sounds, does a better job of accounting for all the necessary facts. It provides for a (very) hot origin for the material that became the moon, explaining the loss of volatiles. With mantle material primarily involved, a resulting lunar composition similar to that of earth's mantle is reasonable, and contributions from the impactor would introduce some differences as well. An off-center hit by the impactor could easily produce a dust disk (and eventual lunar orbit) oriented at an angle to both the ecliptic plane and earth's equatorial plane. We know that the moon was extensively cratered early in its history, and accretion of debris from the collision could account for this. And computer models designed to test the mechanical feasibility of this theory have shown that indeed, it is physically plausible. So the "Big Whack" is likely to remain the prevailing theory of lunar origin—until and unless new evidence is found that does not fit.

Though humans have not been back to the moon for four decades, new information about it can still be generated. Since *Apollo*, computers have become much more powerful, and chemical-analysis techniques more sensitive and sophisticated. Reprocessing of *Apollo*-era seismic data has indicated that the moon has an iron-rich core like the Earth's, though proportionately much smaller. Reanalysis of lunar samples has provided more-detailed information on the moon's composition, including evidence for water in the lunar mantle. Such data will provide further tests of the "Big Whack" theory.

New chemical and mathematical analyses are also being applied to questions such as how much of the moon was derived from earth material and how much from the impactor, or whether, indeed, there were multiple impactors over an extended period of time.

Interest in returning humans to the moon, to study and even to live, has recently been growing. However, the environment is a daunting one (**figure 2**). The moon has essentially no atmosphere, to breathe or to trap heat to moderate surface temperatures, so in sunlight the surface soars to about 120°C (250°F) and during the lunar night plunges to about –175°C (–280°F). There is no vegetation or other life. In 2009, an ingenious experiment demonstrated that some water ice is buried in the lunar soil. A spent rocket was deliberately crashed into a shaded area within a crater; an accompanying spacecraft analyzed the resultant debris and identified ice and water vapor in it. However, how much ice is there, and how widespread, is unknown. To bring water to the moon for human use would cost an estimated $7000–$70,000 *per gallon.* Many other raw materials would certainly have to be shipped there. Furthermore (as the *Apollo* astronauts discovered), the moon presents another special challenge: a surface blanket of abrasive rock dust, the result of pounding by many meteorites over its history—dust that can abrade and foul equipment and, if breathed, injure lungs. So at least for now, any lunar colony is likely to be very small, and necessarily contained in a carefully controlled environment.

Figure 2

The lunar surface is not an environment in which humans could live outside protective structures, with high energy and resource costs. Geologist/astronaut Harrison Schmitt, lunar module commander of the Apollo 17 mission.

Source: NASA.

earliest plants were responsible for the development of free oxygen in the atmosphere, which, in turn, made it possible for oxygen-breathing animals to survive. Human-type remains are unknown in rocks over 4 to 5 million years of age. In a geologic sense, therefore, human beings are quite a new addition to the earth's cast of characters, but they have had a very large impact. Geology, in turn, can have an equally large impact on us.

The world population, now over 7 billion, might well be close to 10 billion by the year 2050. Even our present population cannot entirely be supported at the level customary in the more developed countries, given the limitations of land and resources. Extraterrestrial resources cannot realistically be expected to contribute substantially to a solution of this problem.