CHAPTER 1

▶ **CATASTROPHE IN HAITI** Residents of Port-au-Prince struggle for food following the devastating earthquake on January 12, 2010. Emergency relief was delayed because of the near-total destruction of infrastructure in the city. *(Jewel Samad/AFP/Getty Images)*

Introduction to Natural Hazards

Learning Objectives

Natural processes, such as volcanic eruptions, earthquakes, landslides, tsunami, floods, and hurricanes, threaten human life and property throughout the world. As the world's population continues to grow, disasters and catastrophes will become more common. Your goals in reading this chapter should be to

- Recognize that natural disasters and catastrophes are high-energy events caused by natural Earth processes
- Understand that natural hazards have social, economic, and political dimensions that are just as important as the hazards themselves
- Understand the differences among hazard, risk, disaster, and catastrophe
- Understand the concept that the magnitude of a hazardous event is inversely related to its frequency
- Understand the basics of risk assessment
- Recognize that many natural hazards are linked to one another
- Recognize that population growth, concentration of infrastructure and wealth in hazardous areas, and poor land-use decisions are increasing our vulnerability to natural disasters
- Be aware that the frequency and severity of some destructive natural events may be affected by climate change
- Understand that hazardous natural processes can also provide benefits

The 2010 Haiti Earthquake: Lessons Learned

One of the fundamental realities in the study of natural hazards is that people and governments are poorly prepared for rare natural disasters; they commonly behave as if these disasters will never happen. This unfortunate reality is well illustrated by five recent catastrophes: the tsunami in the Indian Ocean in December 2004, Hurricane Katrina on the U.S. Gulf Coast in August 2005, the earthquake in northern Pakistan in October 2005, the Wenchuan earthquake in southwest China in May 2008, and the Haiti earthquake in January 2010. Each of these events provides hard lessons that can help us reduce the toll of future disasters. Here, we illustrate these lessons using the Haiti earthquake as an example.

The massive earthquake struck southern Haiti without warning in the late afternoon (local time) of January 12, 2010. The *epicentre* was near the town of Léogâne, about 25 km west of Port-au-Prince, Haiti's capital. After several tens of seconds of strong shaking, close to 230 000 people had lost their lives, an estimated 300 000 were injured, and more than a million had been rendered homeless.[1] Equally devastating was the loss of Haiti's infrastructure, including most of the significant buildings and other engineered structures in Port-au-Prince.

The earthquake had a *magnitude* of 7.0 and was much smaller than many recent catastrophic earthquakes, such as those in Sumatra in 2004, China in 2008, and Chile in 2010. Yet it was one of worst natural disasters in history, with a loss of life comparable to the quake that levelled the city of Tangshan, China, in 1976, killing more than 250 000 people.

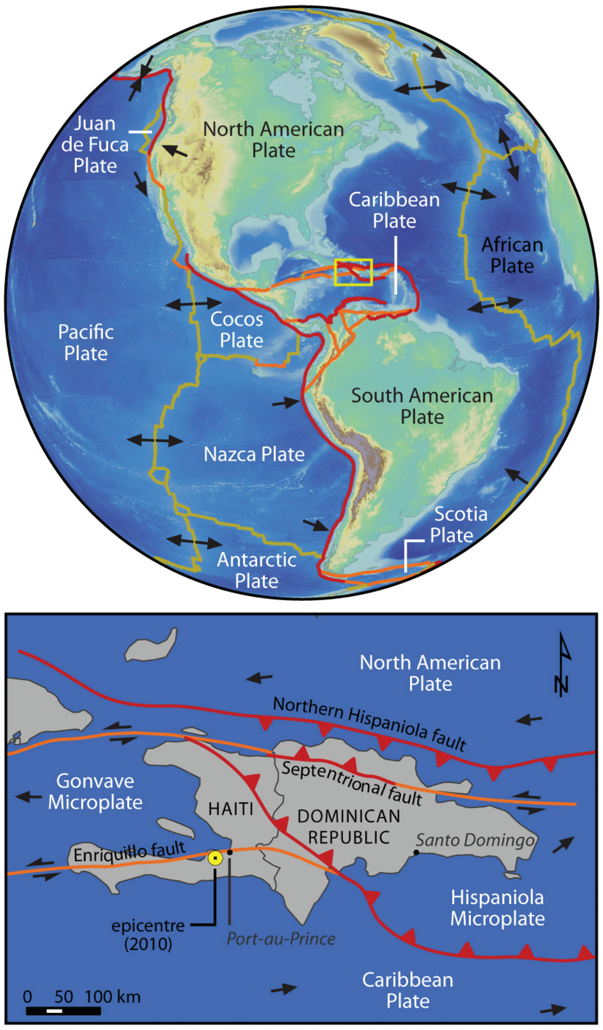


FIGURE 1.1 BACKDROP FOR A CATASTROPHE Earth's lithosphere comprises slowly moving lithospheric plates. Earthquakes are common at and near plate boundaries, including spreading ridges (yellow) where new crust is created, subduction zones (red) where one plate moves beneath another, and transform faults (orange) where two plates move laterally past one another. Haiti and the Dominican Republic are located near the northern edge of the Caribbean plate and experience frequent earthquakes on transform faults (arrows show direction of plate movement). *(Created by Nick Roberts/Simon Fraser University)*

Why did this catastrophe occur where it did? Haiti comprises the western half of the island of Hispaniola, which is situated near the north margin of the relatively small and largely oceanic Caribbean *lithospheric plate* (Figure 1.1). To the east, the Caribbean plate is *subducting*, or moving beneath, the North America plate. There the plate boundary is delineated by 17 active volcanoes that anchor the islands of the Lesser Antilles, including Montserrat, Martinique, Guadeloupe, and Saint Vincent. On the west, the Caribbean and North America plates are separated by a transform fault, along which, each year, the 20–30 mm of differential lateral motions of the two plates are accommodated. Deformation along this plate boundary is distributed: Some motion is accommodated by a series of west-trending *faults* within the interior of the plate and up to 200 km south of the plate boundary. The earthquake of January 12, 2010, occurred on the Enriquillo fault, which extends westward across the southern part of Haiti to Jamaica.[2]

The built environments in Port-au-Prince, Jacmel, Jérémie, Les Cayes, and other urban areas in southern Haiti suffered grievous damage. The destruction and loss of life were exacerbated by poor building materials and construction practices stemming from a lack of official building codes and insufficient attention to planning.[3] Buildings of all types failed—poured concrete, mortared and dry-stacked concrete blocks and stone, and scavenged wood and metal (Figures 1.2 and 1.3). Slums cover the slopes surrounding Port-au-Prince, which have expanded with little control in recent years due to migration of rural Haitians into the capital city. Most buildings on slopes lack proper foundations or containment structures and, consequently, many slid down hillsides during the quake (Figure 1.2). Several tens of thousands of commercial buildings collapsed or were severely damaged, including Haiti's prized Cathédrale de Port-au-Prince, the National Assembly building, Palace of Justice (Supreme Court building), the headquarters of the United Nations Stabilization Mission, and several ministerial buildings. The Prison Civile de Port-au-Prince was also destroyed, allowing about 4000 inmates to escape.The second floor of the Presidential Palace completely collapsed, leaving the third floor resting on the first.

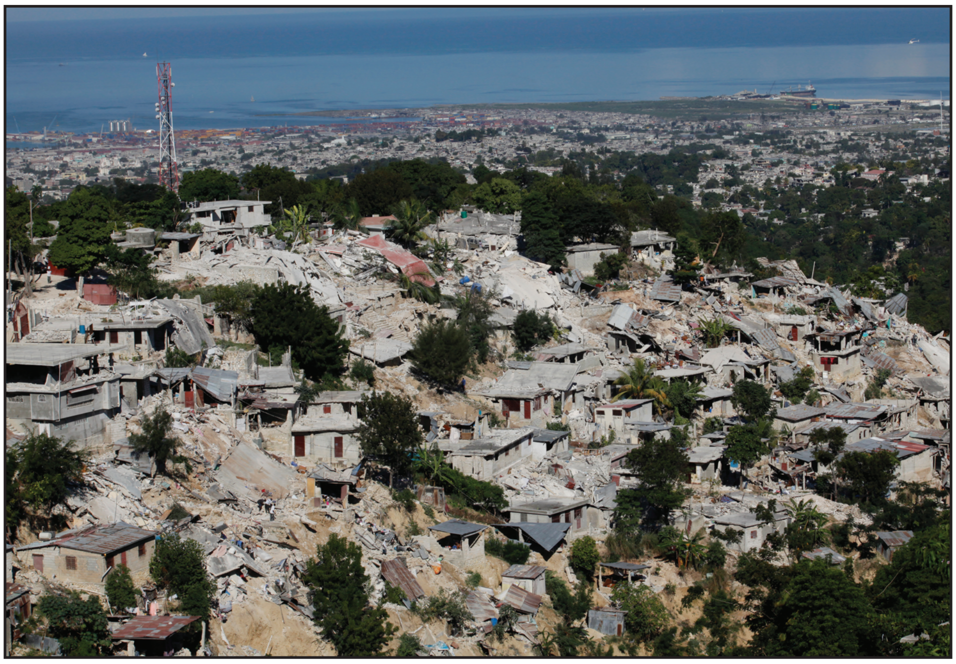


FIGURE 1.2 COLLAPSED BUILDINGS IN PORT-AU-PRINCE Unreinforced and poorly reinforced masonry and concrete slab buildings in Canapé Vert, a shanty town in the hills around Port-au-Prince, collapsed during the January 12, 2010, earthquake. *(Reuters/Eduardo Munoz/Landov)*

The seaport ceased to function due to damage caused by *liquefaction* of loose, water-saturated sediment. Docks and piers slid into the sea, and cargo cranes fell from their footings. Damage was so extensive that vessels providing international relief were forced to dock along adjacent shores. Many roads were covered with rubble from collapsed buildings or were rendered impassable due to ground fissuring caused by liquefaction.

Although it had horrific consequences, the Haiti earthquake is not unprecedented. In an average year, about 17 earthquakes with magnitudes equal to or larger than the Haiti quake occur. Several things made this earthquake different from most historic quakes of similar magnitude. First, it occurred in a heavily populated area—the population of Port-au-Prince before the earthquake was nearly 3 million. Second, buildings in the affected area were not constructed to withstand strong seismic shaking. Access to resources is limited in Haiti, and most of those scant resources are allocated to immediate needs—food and basic shelter—rather than less pressing concerns such as disaster mitigation. Resource availability to all but a small number of Haitians is particularly low: The average annual per-capita income in Haiti is $1400. This situation has been made worse by Haiti's governing bodies, which have long made few resources available for governance issues, including the establishment and enforcement of building standards.

Figure 1.3 Hospital destroyed The nearly completed SODEC hospital in downtown Port-au-Prince collapsed during the devastating earthquake in Haiti on January 12, 2010. *Courtesy of (Sergio Mora-Castro)*

FIGURE 1.4 **KILLER CYCLONE** The aftermath of the 1991 cyclone that devastated Bangladesh and killed approximately 145 000 people. *(Pablo Bartholomew/Getty Images, Inc.-Liaison)*

The Haiti earthquake carries a strong message for people living in earthquake zones, including much of the west coast of North America. Port-au-Prince experienced earthquakes even larger than the 2010 quake in 1751 and 1770.[1] However, a disaster that took place hundreds of years ago is a forgotten one. Due to lack of experience, people and governments were complacent and could not conceive of such an event happening; they were thus completely unprepared, as reflected in the poor construction practices prevalent in Haiti. Scientists have argued that an earthquake as large as the 2010 Haiti event could strike Vancouver, Seattle, or Portland, although no one knows precisely when. We are much better prepared than Haiti was before January 12, 2010, but how will we cope when it's our turn?

What are the lessons of the Haiti earthquake? We must design buildings to meet the highest seismic standards—doing so clearly saves lives. We also must continue to provide adequate research funding to scientists who are seeking to better understand where earthquakes occur, how large they are likely to be, and when they are likely to happen. New technologies, including satellite-based sensors, offer opportunities to "measure the pulse" of Earth and perhaps someday provide clues that will allow us to more accurately forecast or even predict quakes. Communication is also important. We must review and upgrade communication infrastructure and chain-of-command protocols in earthquake-prone areas to ensure that emergency officials receive timely information and respond quickly after an earthquake. And people living close to faults must know what to do in the event of an earthquake. A public education program should teach people about earthquakes and provide instructions on how to prepare, how to act when the shaking starts, and what to do after it stops. One of the most important lessons of the Haiti catastrophe is that wealthy countries must help poorer regions prepare for earthquakes and other natural disasters. Canada and the United States must do more than just respond when disaster strikes, which has been the standard approach to dealing with disasters in developing countries. A better and fairer strategy is a long-term proactive one aimed at helping poor countries develop and prepare for disasters before they occur.

1.1 Why Studying Natural Hazards Is Important

During the past few decades, earthquakes, floods, and hurricanes have killed several million people; the average annual loss of life has been around 150 000, with more than 300 000 deaths in 2005 alone. Financial loss from natural disasters now exceeds $50 billion per year, on average, and can be as high as $200 billion, as happened in 2005 (this figure represents direct property damage and does not include such expenses as loss of employment, mental anguish, and reduced productivity).

Four catastrophes—a cyclone accompanied by flooding in Bangladesh in 1970, earthquakes in China in 1976 and Haiti in 2010, and a tsunami in the Indian Ocean in 2004—each claimed more than 230 000 lives. A cyclone that struck Bangladesh in 1991 killed 145 000 people (Figure 1.4). In 1995, an earthquake in Kobe, Japan, claimed more than 5000 lives, destroyed many thousands of buildings, and caused more than $100 billion in property damage. An earthquake in Islamabad, Pakistan, in 2005 killed 86 000 people and damaged much of the city's infrastructure (Figure 1.5). Hurricane Katrina in 2005 was the most destructive natural catastrophe in United States history and the deadliest hurricane since

FIGURE 1.5 DEVASTATING EARTHQUAKE People search for victims in the rubble of a 10-storey building that collapsed during a large earthquake in Islamabad, Pakistan, in 2005. Close to 86 000 people died and 3 million more were left homeless. *(© Warrick Page/ Corbis. All Rights Reserved)*

Hurricane Okeechobee in 1928.[4] Other notable disasters in the past 15 years include catastrophic flooding in Venezuela, Bangladesh, and central Europe; deadly earthquakes in India, Iran, Turkey, and Chile; a Category 5 hurricane in Central America; record-setting wildfires in British Columbia, Arizona, California, Colorado, and Utah; the worst tornadoes in Oklahoma's history; and a crippling ice storm in Ontario, Quebec, New Brunswick, and New England. During this period, Earth also experienced many of the warmest years of the past 100—and probably even of the past millenium.

These events are the result of enormous forces at work both inside and on the surface of our planet. In this book, we explain these forces and their impacts on people and property. We also discuss how we can better prepare for natural disasters, thus minimizing their impacts when they do occur.

Natural hazards affect the lives of millions of people around the world. All areas of Canada and the United States are at risk from at least one hazardous process.[5,6] Parts of western North America are prone to earthquakes and landslides and experience rare volcanic eruptions; the Pacific coast is vulnerable to tsunami; the Atlantic and Gulf of Mexico Coasts are threatened by hurricanes; forested areas of the continent are prone to wildfires; the mid-continent, from Texas to Ontario, is at risk from tornadoes and blizzards; and drought and flooding can occur almost anywhere. No area is considered hazard-free.

Hazardous Natural Processes and Energy Sources

In our discussion of natural hazards, we will use the word *process* to mean the ways in which events, such as volcanic eruptions, earthquakes, landslides, and floods, affect Earth's surface. All of these processes are driven by energy, and this energy is derived from three sources.

The first source of energy is Earth's internal heat, which produces slow convection in the mantle. The hazardous processes associated with this source of energy are earthquakes and volcanic eruptions. As we will see, these occurrences are explained by the theory of plate tectonics, one of the basic unifying theories of science. Most earthquakes and active volcanoes occur at boundaries between tectonic plates, which are large blocks of Earth's crust.

The second source of energy is the sun. Energy from the sun warms Earth's atmosphere and surface, producing winds and evaporating water. Circulation of the atmosphere and oceans and water evaporation determine Earth's climate and drive the hydrologic cycle. These forces are in turn directly related to hazardous processes such as violent storms, floods, and coastal erosion.

The third source of energy is the gravitational attraction of Earth. Gravity is the force that attracts one body to another—in this case, the attraction of surface materials toward the centre of Earth. Because of gravitational attraction, rocks, soils, and snow on mountainsides and the water that falls as precipitation move downslope. Earth's gravitational field also attracts objects from space that may enter the atmosphere and explode or strike the surface of the planet.

The amount of energy released by natural processes differs greatly. The average tornado expends about 1000 times as much energy as a lightning bolt, whereas Earth receives nearly a trillion times as much solar energy as a lightning bolt each day. However, it is important to keep in mind that a lightning bolt focuses its energy at a point—a tree, for example—whereas solar energy is spread over the entire globe.

Events such as earthquakes, tsunami, volcanic eruptions, floods, and fires are natural processes that have been occurring on Earth's surface for billions of years. They become hazardous only when they threaten human beings. We use the terms **hazard**, **risk**, **disaster**, and **catastrophe** to describe our interaction with these natural processes.

Of course, not all hazards are "natural." Many hazards are caused by people; examples include pandemics, warfare, and technological disasters such as regional power failures. The early 2009 outbreak in humans of a new strain of influenza that is endemic in pigs (H1N1 or "swine flu") is an example of a recent non-"natural" hazard. The virus rapidly spread around the world and was labelled a pandemic by the World Health Organization in June 2008. An example of a technological disaster—which, fortunately, we have not experienced—would be a war in which nuclear weapons are used by the warring countries or by a terrorist organization. Such an event was impossible prior to the production of nuclear bombs in the early 1940s but is now a major concern given the acquisition of nuclear technology by politically unstable countries.

Over the past century, the distinction between natural and human-induced hazards has become blurred, and technological disasters are increasing as the world's population grows and state economies become more connected and interdependent. Social and technological hazards are important and interesting in their own right, but are beyond the scope of this book. Our focus is on hazardous solid Earth and atmospheric processes.

Hazard, Risk, Disaster, and Catastrophe

This book considers hazards within the human context—it focuses on the science of natural hazards, but also explores the social, economic, and political issues that these hazards pose. The text recognizes that the human response to threats posed by natural hazards is just as important as hazard science itself. A *hazard* is any natural process that threatens human life or property. *Risk* is the probability that a particular destructive event will occur multiplied by the event's likely impact on people and property. Risk thus integrates hazard and social and economic vulnerability. The terms *disaster*, or natural disaster, and *catastrophe* refer to events that cause serious injury, loss of life, and property damage over a limited time and within a specific geographic area. Although the distinction between disaster and catastrophe is somewhat vague, the latter is more massive and affects a larger number of people and more infrastructure. Disasters may be regional or even national in scope, whereas catastrophes commonly have consequences far beyond the area that is directly affected and require huge expenditures of time and money for recovery. Examples of catastrophes are the Indian Ocean tsunami of December 2004, Hurricane Katrina in August 2005, and the Haiti earthquake in January 2010.

The United Nations designated the 1990s as the International Decade for Natural Hazards Reduction. The objectives of the UN program were to minimize loss of life and property damage from natural disasters, but these objectives were not met; rather, losses from disasters increased dramatically in the 1990s (Figure 1.6 on the next page). Achieving the UN objectives will require education and increased spending to mitigate specific hazards and contain diseases that accompany disasters and catastrophes. The term **mitigation** is used by scientists, planners, and policy-makers when describing efforts to prepare for disasters and to minimize their harmful effects. After a flood, for example, water supplies may be contaminated by bacteria, causing disease to spread. To mitigate the effects of contamination, a relief agency or government may deploy portable water treatment plants, disinfect water wells, or distribute bottled water.

Death and Damage Caused by Natural Hazards

Natural hazards that cause the greatest loss of life in North America are not the same as those that cause the most property damage. Tornadoes and windstorms cause the largest number of deaths each year, although lightning, floods, and hurricanes also take a heavy toll (Table 1.1). Loss of life from

TABLE 1.1 Effects of Selected Hazards in Canada and the United States

Hazard	Deaths per Year	Catastrophe Potential
Flood	100	High
Earthquake	>50	High
Landslide	30	Low
Snow avalanche	20	Low
Volcano	<1	High
Coastal erosion	0	Low
Expansive soils	0	Very low
Hurricane	60	High
Tornado and windstorm	220	Medium
Lightning	125	Very low
Drought	0	Medium
Heat	>600	Medium
Freezing and frozen rain	>800	Medium

Estimates based on recent or predicted loss over a 150-year period. Actual losses differ considerably from year to year and could be much greater in a given year.

Source: Modified from White, G. F., and J. E. Haas. 1975. Assessment of Research on Natural Hazards. *Cambridge, MA: MIT Press.*

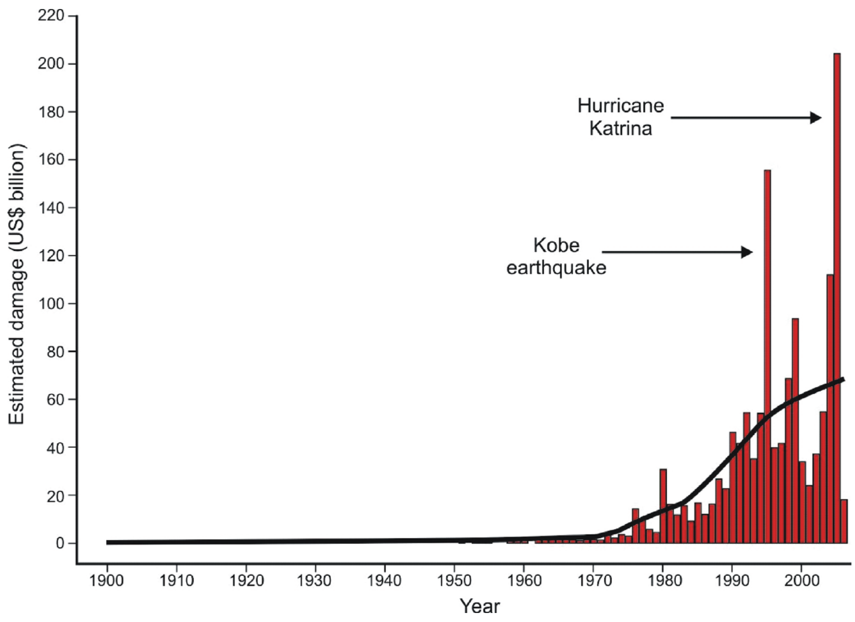


FIGURE 1.6 THE RISING COST OF NATURAL DISASTERS Estimated damage (in billions of US dollars) caused by natural disasters between 1900 and 2007. *EM-DAT, the OFDA/CRED International Disaster Database, www.emdat.be, Université Catholique de Louvain, Brussels, Belgium)*

earthquakes in North America is surprisingly low, largely because of high building construction standards. But a single large earthquake can cause tremendous property damage. For example, the Northridge earthquake in Los Angeles in 1994 caused US$20 billion to US$30 billion in property damage, but killed only 60 people. The next great earthquake in a densely populated part of California or in Seattle or Vancouver could cause more than US$100 billion in damage.[7]

Natural disasters cost Canada billions of dollars annually. Because populations are increasing in high-risk areas of North America, we can expect losses to increase significantly in the future. Floods, landslides, expansive soils that shrink and swell, and frost each cause in excess of US$1.5 billion in damage each year in the United States alone.

It is important to note that the relations between loss of life and property damage discussed above apply only to the fully developed world, mainly North America, Europe, Australia, Japan, and New Zealand. Natural disasters in most developing countries claim far more lives than comparable events in developed ones. For example, the tsunami in the Indian Ocean in December 2004 killed nearly 230 000 people. In comparison, the tsunami in the North Pacific in 1964, although equal in size, killed 119 people. A notable characteristic of North American disasters, however, is their very large toll on the economy. Category 4 and 5 hurricanes typically cause billions of dollars in damage in southern U.S. states; the direct damage from Hurricane Katrina, the worst storm in U.S. history, was more than US$80 billion, and indirect damage, including lost economic activity and employment, was several times that amount.[4]

Natural hazards differ in their potential to cause a catastrophe, mainly because of differences in the size of the area each affects (Table 1.1). Three processes—climate change, eruptions of super volcanoes, and large meteorite impacts—can have global repercussions. Large tsunami, earthquakes, major volcanic eruptions, hurricanes, monsoon floods, and floods on large rivers have regional effects and may result in catastrophes. Landslides, snow avalanches, floods on small streams, most wildfires, and tornadoes generally affect small areas and thus are rarely catastrophic. Coastal erosion, lightning, and expansive soils do not create catastrophes but can still cause much damage.[8]

Risks associated with natural hazards change with time because of changes in population and land use. Hazardous land, such as steep hillsides and floodplains, may be developed as cities grow. Such expansion is a serious problem in many large, rapidly growing cities in developing nations. Urbanization alters drainage, increases the steepness of some slopes, and removes vegetation. Agriculture, forestry, and mining also remove natural vegetation and can increase erosion and sedimentation. Overall, damage from most hazardous natural processes in Canada is increasing, but the number of deaths is decreasing because of better planning, forecasting, warning, and engineering.

1.2 Magnitude and Frequency of Hazardous Events

The *impact* of a hazardous event is partly a function of its magnitude, or the amount of energy released, and partly a function of its frequency. The *magnitude–frequency concept* asserts that an inverse exponential relationship exists between the magnitude of an event and its frequency (Figure 1.7). Large floods or earthquakes, for example, are infrequent, whereas small floods or earthquakes are common. The magnitude-frequency relation for many natural phenomena can be approximated by an exponential equation of the type $M = Fe^{-x}$ where M is the magnitude of the event, F is the frequency, e is the base of the natural logarithm, and x is a constant.

The magnitude-frequency concept also includes the idea that Earth's surface is shaped mainly by events of moderate magnitude and frequency, rather than by events of low magni-

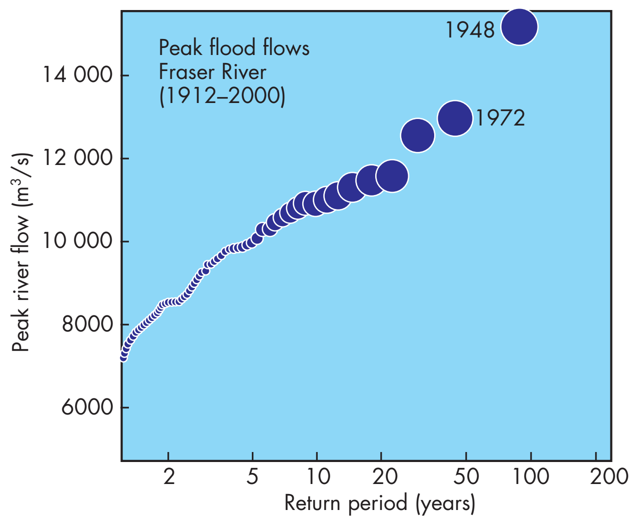


FIGURE 1.7 MAGNITUDE–FREQUENCY RELATION The size and frequency of many physical processes are inversely related. The concept is illustrated here with this plot of average return periods for Fraser River floods of different sizes. Note that the horizontal scale (return period) is logarithmic, not linear. *(Brian Menounos; from Clague, J., and B. Turner. 2006.* Vancouver, City on the Edge: Living with a Geological Landscape. *Vancouver, BC: Tricouni Press)*

tude and high frequency or by events of extremely high magnitude but very low frequency. For example, most of the sediment carried by rivers in Canada is transported by flows of moderate magnitude and frequency. However, there are many exceptions. In arid regions, for example, much of the sediment in normally dry channels may be transported by rare high-magnitude flows produced by intense but infrequent rainstorms.

Impact is also influenced by many other factors, including climate, geology, vegetation, population, and land use. Land use can directly affect the magnitude and frequency of events. People have long tried to reduce the threat of floods, for example, by building levees along rivers. However, levees constrict the width of rivers, and the reduced width lessens the amount of water that can be transported during flood conditions. In effect, our efforts to reduce floods may actually be causing larger, more frequent floods.

Four of the worst natural disasters in recent years were exacerbated by poor land-use practices—Hurricane Mitch in 1998, a flood on the Yangtze River in China, also in 1998, the tsunami in the Indian Ocean in 2004, and Hurricane Katrina in 2005. Hurricane Mitch devastated parts of Central America and claimed approximately 11 000 lives, and the Yangtze River flood killed nearly 4000 people. Land-use changes made the damage from these events particularly severe. For example, Honduras lost nearly one-half its forests in the past century, and wildfires before Hurricane Mitch burned an area of 11 000 km^2. As a result of deforestation and the fire, hillside soils washed away and with them went farms, homes, roads, and bridges. The story is much the same in the case of China. About 85 percent of the forest in the Yangtze River basin has been removed through timber harvesting and conversion of land to agriculture. As a result of these changes, flooding on the Yangtze River is probably much more common and severe than it was previously.[9] The huge loss of life from the 2004 tsunami is due in part to the increase in population along the shores of the Indian Ocean and in part to a growth in tourism in South Asia, especially in Thailand. Thousands of tourists were among the casualties (see Chapter 3). Hurricane Katrina severely damaged the coasts of Mississippi and Louisiana in 2005. Wetlands that might have buffered the hurricane's storm surge had been damaged or removed as a result of human development of the river and coastline (see Chapter 9).

These and other recent catastrophes may be warning signs of things to come. Human activities are likely increasing the severity of some natural disasters. China has heeded this lesson and banned timber harvesting in the upper Yangtze River basin, limited use of the Yangtze floodplain, and allocated several billion dollars for reforestation. If we want to minimize damage from natural disasters, we need to rehabilitate the land and strive for a more harmonious relationship with the processes that shape Earth's surface. An ancillary benefit of this approach is that future generations will have access to the resources that our planet offers.[9] Population growth in developing countries and reckless squandering of resources in the developed world, however, will make it difficult for humanity to achieve this goal.

1.3 Role of Time in Understanding Hazards

Natural disasters are recurrent events, and thus study of past events provides needed information for risk reduction. Whether we are studying floods, landslides, volcanic eruptions, or earthquakes, knowledge of historic events and the recent geologic history of an area is vital to understanding the hazard and evaluating its risk. For example, we can evaluate the risk of flooding along a particular river by identifying floods that have occurred in the recent past. Useful information can be obtained by studying aerial photographs and maps as far back as the record allows. We can extend the historic record by searching for evidence of past floods in stream deposits. Commonly, these deposits contain organic material, such as wood or shells, that can be dated by the *carbon-14 method* to provide a chronology of ancient flood events. This chronology can then be combined with the historic record of high flows to provide an overall perspective of the frequency and size of floods. Similarly, if we are studying landslides in a particular area, we must investigate both historic and prehistoric events to properly forecast the likelihood of future landslides. Geologists have the tools and training to "read the landscape" for evidence of past events and, by linking prehistoric and historic records, they extend our perspective of recurring natural events far back in time.

But how far back in time do we need to gaze in order to understand natural hazards? The answer is far enough to see the complete spectrum of events that can affect a region. In the case of floods and earthquakes, a geologist would like to reconstruct events over a period of hundreds or even thousands of years. In contrast, for rarer events such as meteorite impacts, the answer is millions or tens of millions of years. Although most of the hazardous processes considered in this book have existed since the birth of our planet, they are relevant only within the context of today.

To fully understand natural hazards, you must have some knowledge of the processes that function on Earth. In the next few sections, we discuss these basic processes and their cycles. We then introduce five concepts that are fundamental to understanding natural processes as hazards.

1.4 Geologic Cycle

Geology, topography, and climate govern the type, location, and intensity of natural processes. For example, earthquakes and volcanoes do not occur at random across Earth's surface; rather, most of them mark the boundaries of lithospheric plates. Hurricanes and cyclones form only over warm oceans and have different impacts depending on the topography, and therefore geology, of the areas they strike.

Throughout much of the 4.6 billion years of Earth's history, the materials on or near the surface of the planet have been created and modified by numerous physical, chemical, and biological processes. These processes have produced the mineral resources, fuels, land, water, and atmosphere that we require for our survival. Collectively, these processes constitute the **geologic cycle**, which itself comprises the following:

- the tectonic cycle
- the rock cycle
- the hydrologic cycle
- biogeochemical cycles

The Tectonic Cycle

The term *tectonic* refers to the large-scale geologic processes that deform Earth's crust and produce ocean basins, continents, and mountains. Tectonic processes are driven by forces deep within Earth. The **tectonic cycle** involves the creation, movement, and destruction of *tectonic plates*—the large blocks that form the outer shell of Earth. A single cycle can last more than 200 million years.

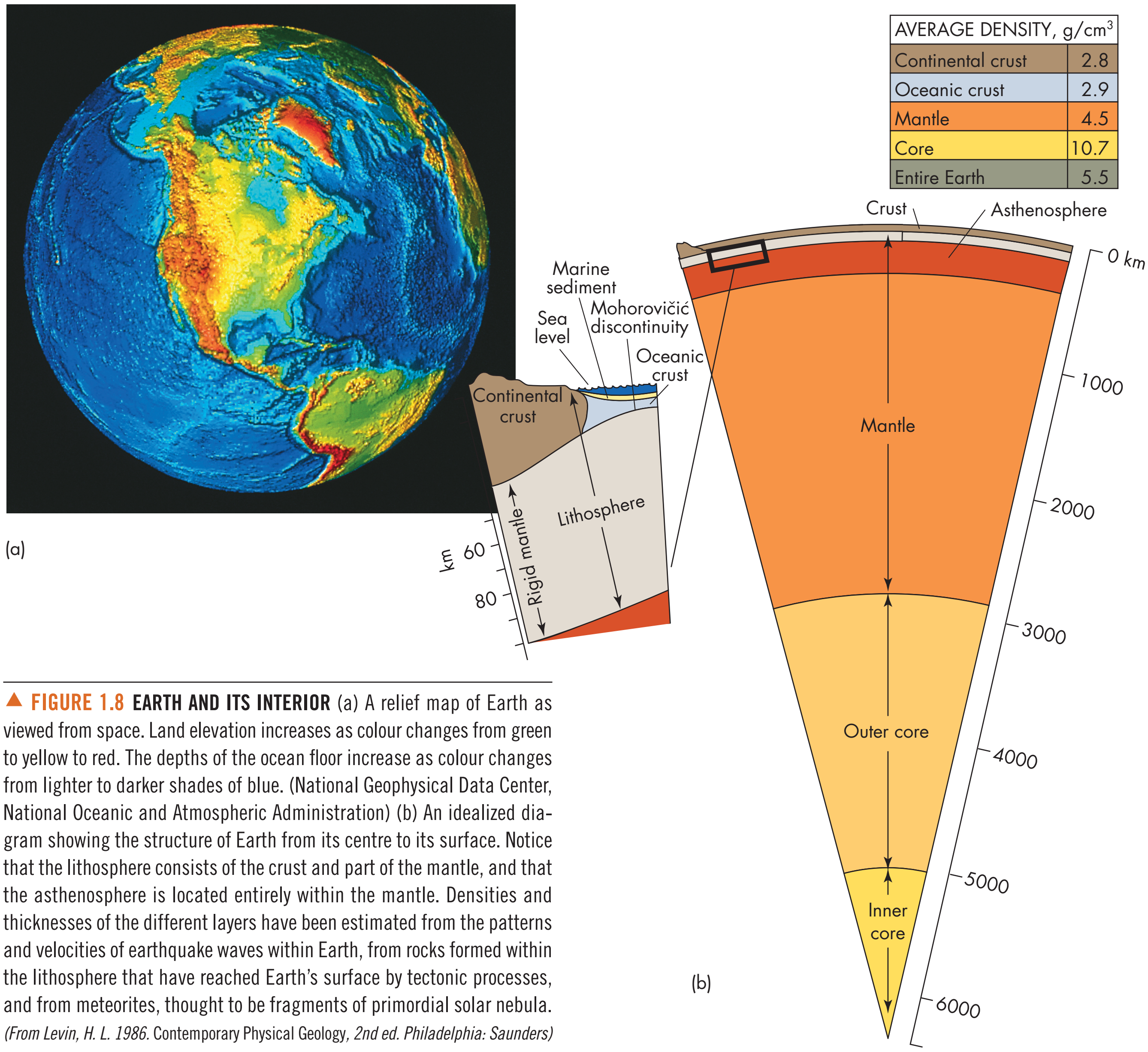
Earth's Lithosphere and Crust Earth comprises several internal layers that differ in composition and physical properties (Figure 1.8). The outermost or surface layer, called the lithosphere, is stronger and more rigid than deeper material. Below the lithosphere lies the asthenosphere, a hot layer of relatively low-strength rock that extends to an average depth of about 250 km. Through detailed study of ocean basins and continents, geophysicists have established that the average thickness of the lithosphere is about 100 km; it ranges from a few kilometres thick beneath the crests of mid-ocean ridges to 400 km thick beneath continents.

The upper part of the lithosphere is the *crust*. Crustal rocks are less dense than the rocks below. There are two types of crust: oceanic and continental. Oceanic crust is denser (Figure 1.8). It is also thinner—the ocean floor has an average crustal thickness of about 7 km, whereas continental crust is about 30 km thick on average and up to 70 km thick beneath mountainous regions.

Types of Plate Boundaries Unlike the asthenosphere, which is thought to be more or less continuous, the lithosphere is broken into large fragments called lithospheric or tectonic plates that move relative to one another (Figure 1.9).[10] Processes associated with the origin, movement, and destruction of these plates are collectively termed *plate tectonics*. Plates are formed and destroyed at their margins or boundaries. Plate boundaries may be *divergent*, *convergent*, or *transform* (Figure 1.10).[10] These boundaries are not narrow cracks, but rather broad zones of intense deformation tens to hundreds of kilometres wide that extend through the crust. It is at these boundaries that most earthquakes and active volcanoes occur.

Divergent boundaries occur where two plates move away from one another and new lithosphere is created. Places where this separation occurs are large, underwater mountain ridges known as *mid-ocean ridges* (Figures 1.10 and 1.11). By a process known as *seafloor spreading*, the lithosphere breaks or *rifts* apart along a series of cracks more or less parallel to the ridge crest.[11] Many of the cracks in the underwater rift zone are injected with molten rock, or *magma*, from below (Figure 1.11). New lithosphere forms as the magma solidifies and is slowly rafted, in a conveyor-belt fashion, away from the ridge crest. The tectonic plates on each side of the ridge move apart at a rate of tens of millimetres to a few hundred millimetres each year (Figure 1.9). At Juan de Fuca Ridge, the spreading ridge off Canada's west coast, new oceanic lithosphere is being produced at a rate of about 45 mm per year, equal to 45 km every million years.[12]

You might wonder how we know that new oceanic lithosphere is forming at mid-ocean ridges and spreading away from them. Seafloor spreading was first hypothesized in 1961, when geophysicists Ronald Mason and Arthur Raff published a magnetic map of the northeast Pacific Ocean off Vancouver Island and Washington State (Figure 1.12).[13] They towed instruments across the surface of the ocean to detect the magnetism of the rocks on the ocean floor below. The survey showed that the seafloor volcanic rocks are permanently magnetized in symmetrical, parallel stripes of normal and reversed polarity extending away from Juan de Fuca Ridge. The map published by Mason and Raff in 1961 clearly



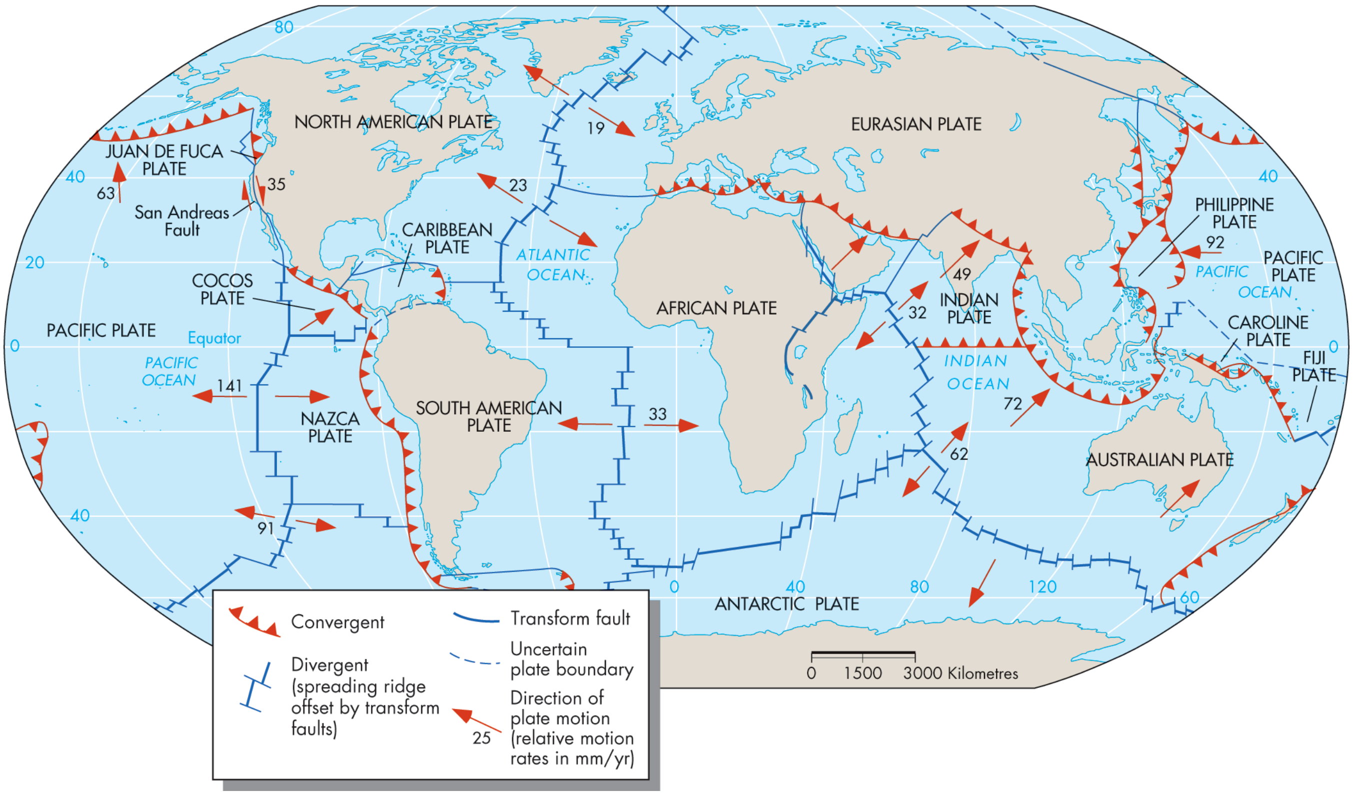
▲ **FIGURE 1.8 EARTH AND ITS INTERIOR** (a) A relief map of Earth as viewed from space. Land elevation increases as colour changes from green to yellow to red. The depths of the ocean floor increase as colour changes from lighter to darker shades of blue. (National Geophysical Data Center, National Oceanic and Atmospheric Administration) (b) An idealized diagram showing the structure of Earth from its centre to its surface. Notice that the lithosphere consists of the crust and part of the mantle, and that the asthenosphere is located entirely within the mantle. Densities and thicknesses of the different layers have been estimated from the patterns and velocities of earthquake waves within Earth, from rocks formed within the lithosphere that have reached Earth's surface by tectonic processes, and from meteorites, thought to be fragments of primordial solar nebula. *(From Levin, H. L. 1986.* Contemporary Physical Geology, *2nd ed. Philadelphia: Saunders)*

showed the parallel magnetic striping and quickly led scientists to accept the hypothesis of seafloor spreading.

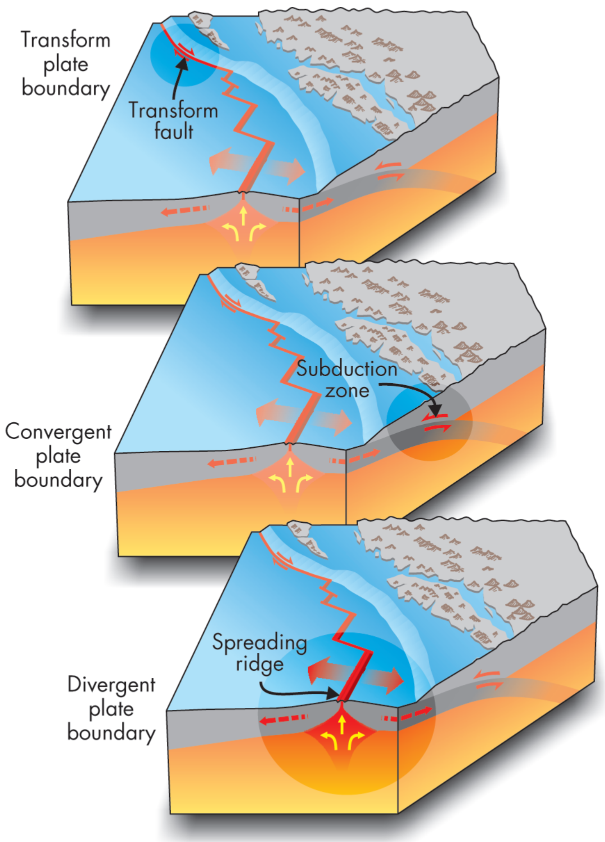
Convergent boundaries occur where two plates collide head-on (Figure 1.10). Commonly, a higher density oceanic plate is drawn down beneath a lower density continental plate. This process is called *subduction*, and convergent boundaries of this type are called *subduction zones* (Figure 1.13). The oceanic plate heats as it moves beneath the continental plate. At depths of 100 to 120 km, it reaches temperatures in excess of 700°C and releases water, carbon dioxide, and other gases that rise into the lower part of the continental crust. The superheated gases cause lower crustal rocks to melt, and the magma moves slowly up through the crust along fractures. Some of the magma reaches the surface, where it erupts and builds volcanoes. A chain of active volcanoes that have formed from repeated eruptions marks the inboard margin of the *Cascadia subduction zone,* which extends along the west coast of North America from northern California to central Vancouver Island (Figure 1.9 and 1.13). Well-known volcanoes in this chain include Mount Baker, Mount Rainier, Mount St. Helens, Mount Hood, and Mount Lassen. The Andes of South America, the Aleutian volcanoes in southwest Alaska, and the volcanoes of Indonesia, Japan, and the Caribbean are other important chains of active volcanoes produced by subduction.

Subduction adds material to continents. Crustal fragments rafted on the mantle (for example, islands that are too light to move under a continent) are accreted to the continent, as are thick sediments and sedimentary rocks covering the subducting plate.

If the two colliding plates are both continental, they have roughly the same density and it is difficult for one to sink beneath the other. In such a situation, the plates meet along a continental collision boundary delineated by high, faulted,



▲ **FIGURE 1.9 EARTH'S TECTONIC PLATES** A map showing the major tectonic plates, plate boundaries, and directions of plate movement. *(Modified from Christopherson, R. W. 1994.* Geosystems, *2nd ed. New York: Macmillan; Press, F., R. Siever, J. Grotzinger, and T. H. Jordan. 2003.* Understanding Earth, *4th ed. New York: W.H. Freeman)*



◀ **FIGURE 1.10 PLATE TECTONICS** Schematic diagram showing plate tectonics processes. Boundaries between tectonic plates are of three types: transform plate boundaries, along which adjacent plates move horizontally past one another; convergent plate boundaries, where one plate moves under another; and divergent plate boundaries, where two plates spread apart at a ridge and new oceanic crust is created. *(From Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006.* At Risk: Earthquakes and Tsunamis on the West Coast. *Vancouver, BC: Tricouni Press, p. 25)*

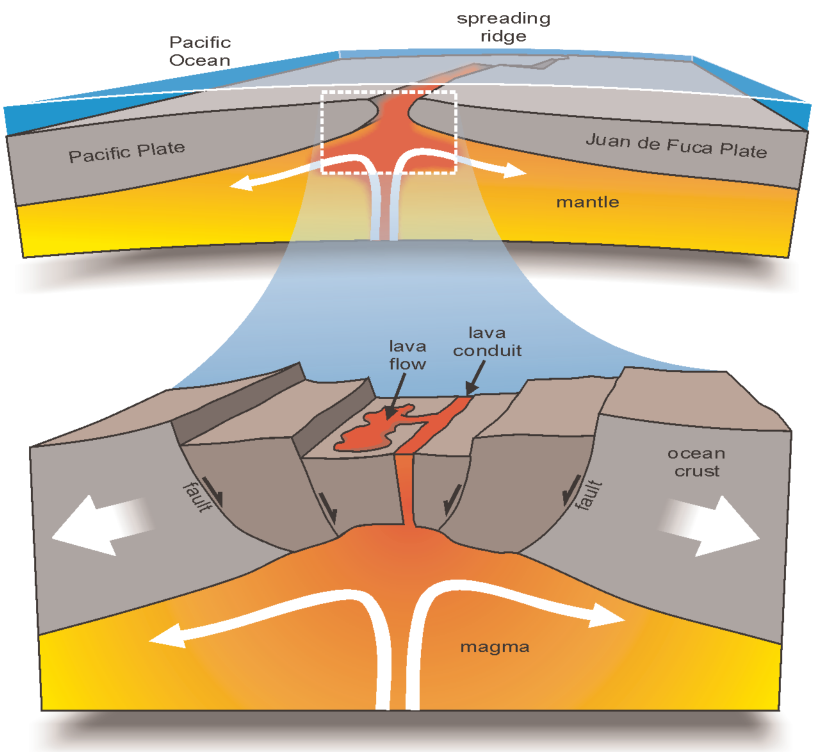


FIGURE 1.11 MID-OCEAN RIDGE In the northeast Pacific Ocean, new oceanic lithosphere is created by upwelling magma along fractures beneath Juan de Fuca Ridge. The newly formed crust moves away from the ridge, forming the trailing edges of the Pacific and Juan de Fuca plates. *(From Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006.* At Risk: Earthquakes and Tsunamis on the West Coast. *Vancouver, BC: Tricouni Press, p. 22)*

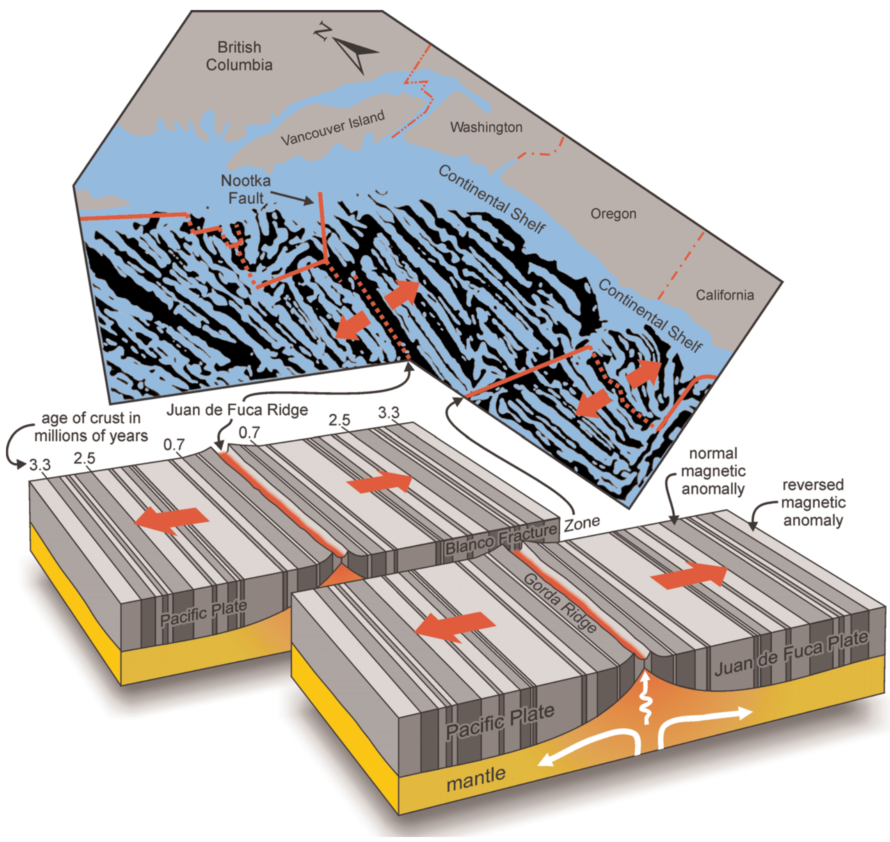
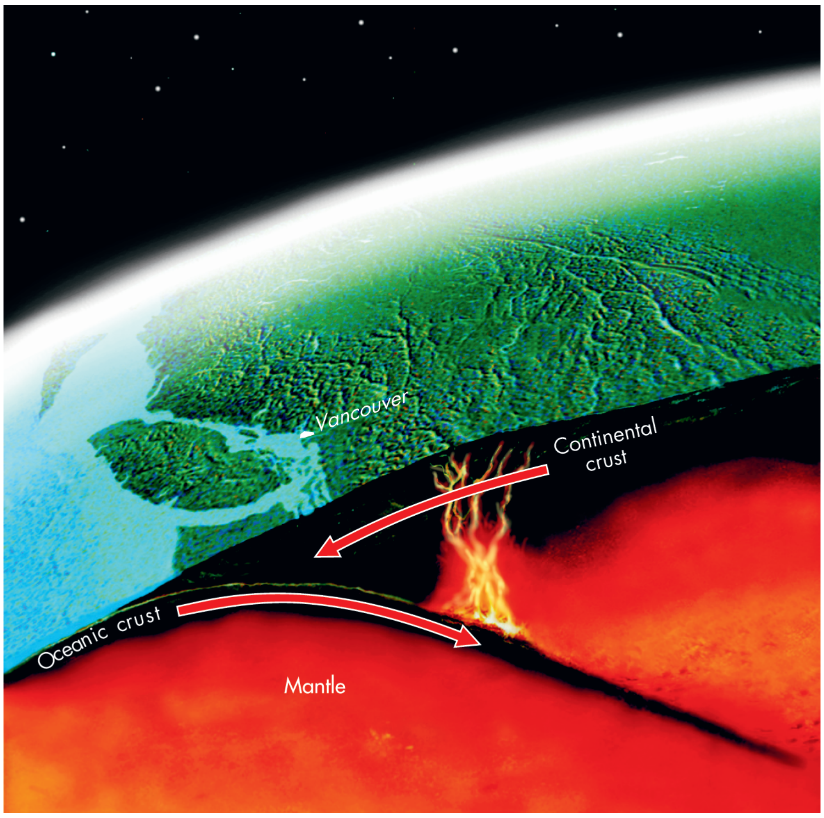
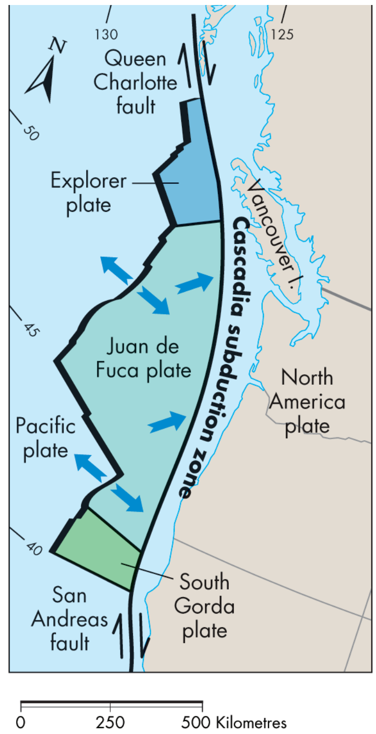


FIGURE 1.12 MAGNETIC STRIPING ON THE FLOOR OF THE NORTHEAST PACIFIC OCEAN Mason and Raff's map of magnetism on the floor of the northeast Pacific (top), published in 1961, is the "Rosetta Stone" of seafloor spreading and plate tectonics. The black stripes record intervals of normal magnetic polarity, like today, and the intervening blue stripes represent intervals when Earth's magnetic field was reversed. The bottom illustration shows the formation of magnetic stripes by the conveyor-like movement of new lithosphere away from the Juan de Fuca spreading ridge. The large red arrows indicate directions of plate movement away from the spreading ridge. The small red arrows are directions of motion along faults that connect segments of the ridge. *(From Clague, J., C. Yorath, R. Franklin, and B. Turner. 2006. At Risk: Earthquakes and Tsunamis on the WestCoast. Vancouver, BC: Tricouni Press, p. 30)*

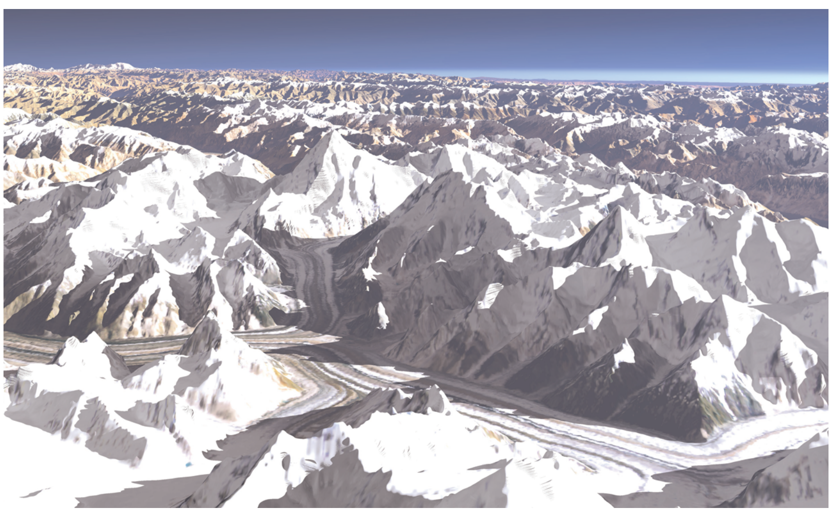
and crumpled mountains, such as the Himalayas in central Asia (Figure 1.14).

Mapping of the seafloor has demonstrated that mid-ocean ridges are not continuous features, but rather consist of a series of spreading ridges offset from one another. The offsets are the third type of plate boundary, where two tectonic plates slide horizontally past one another. This type of boundary is referred to as a *transform boundary*, and the fault along which the movement occurs is known as a *trans-*





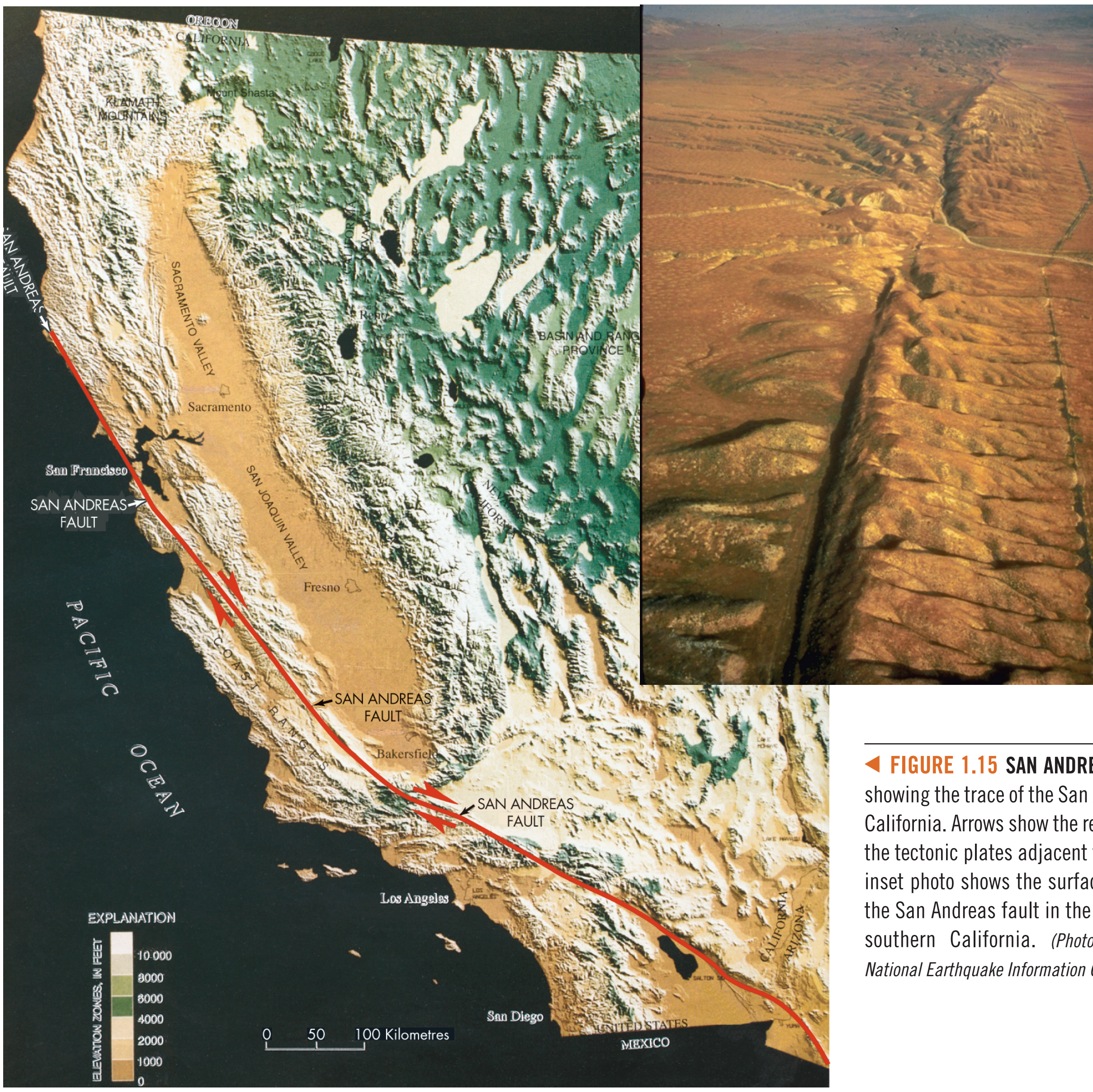
▲ **FIGURE 1.13 SUBDUCTION ZONE OFF CANADA'S WEST COAST** An artist's rendition (a) and map (b) of subduction of the oceanic Juan de Fuca plate beneath the continental North America plate off the southwest coast of British Columbia. *(B. Groulx and T. Poulton/Geoscape Calgary/Poulton, T.; Neumar, T., Osborn, G., Edwards, D., Wozniak, P., Geological Survey of Canada, Miscellaneous Report 72, 2002, poster; http://geoscape.nrcan.gc.ca/calgary/pdf/geoscape_calgary_view_e.pdf © Department of Natural Resources Canada. All rights reserved)*



◀ **FIGURE 1.14 HIMALAYAS** The Himalayan mountain chains mark the collision zone between the Eurasian plate to the north and the Indian plate to the south. The highest mountains on Earth, including Everest, are in the Himalayas. *(Christoph Hormann/Science Photo Library)*

form fault. Most transform faults are located beneath oceans, but some occur on continents. A well-known continental transform fault is the San Andreas fault in California, where the Pacific plate on the west is sliding horizontally past the North America plate on the east (Figure 1.15). Other notable continental transform faults are the Anatolian fault in Turkey, the Alpine fault in New Zealand, and the Queen Charlotte fault off Canada's west coast.

Hot Spots Some volcanoes occur within lithospheric plates at locations known as *hot spots*. The molten rock reaching the surface at hot spots is associated with upwelling of material deep within the mantle, the layer between the core and crust that makes up most of the interior of Earth. Some long-lived hot spots may be fed by molten rock that originates at the boundary between the core and the mantle. The molten material is sufficiently hot and buoyant that it



◀ **FIGURE 1.15 SAN ANDREAS FAULT** Map showing the trace of the San Andreas fault in California. Arrows show the relative motion of the tectonic plates adjacent to the fault. The inset photo shows the surface expression of the San Andreas fault in the Carrizo Plain of southern California. *(Photo: R. E. Wallace/ National Earthquake Information Center)*

moves up through the mantle and the overlying lithosphere.[14,15] An example of a continental hot spot is the volcanic region that includes Yellowstone National Park. Hot spots also occur beneath the Atlantic, Pacific, and Indian ocean floors.

If a hot spot is anchored in the mantle, it will remain relatively fixed as a lithospheric plate moves over it. This motion will produce a line of volcanoes like those that form the Hawaiian–Emperor Seamount chain in the Pacific Ocean (Figure 1.16). Volcanic rocks along the chain increase in age toward the northwest—they are forming today on the Big Island of Hawaii, but are more than 78 million years old near the northern end of the chain. The Emperor *seamounts*, which delineate the oldest part of chain, are former islands that subsided after volcanoes moved off the hot spot and stopped erupting.

The Tectonic Cycle and Natural Hazards The importance of the tectonic cycle to natural hazards cannot be overstated. All of Earth's inhabitants are affected by plate tectonics. As plates slowly move, so do the continents and ocean basins. Most earthquakes and volcanoes that threaten people are near or at plate boundaries; most tsunami are generated by subduction-zone earthquakes; and landslides are concentrated in mountains produced by plate collisions. Tectonic processes operating at plate boundaries determine the types and characteristics of rocks and soils on which we depend for construction and agriculture. And plate motions over millions of years modify patterns of ocean currents and, in this way, affect climate.

The Rock Cycle

Rocks are aggregates of one or more *minerals*. A mineral is a naturally occurring, crystalline substance with a specific elemental composition and a narrow range of physical properties. The term **rock cycle** refers to worldwide recycling of

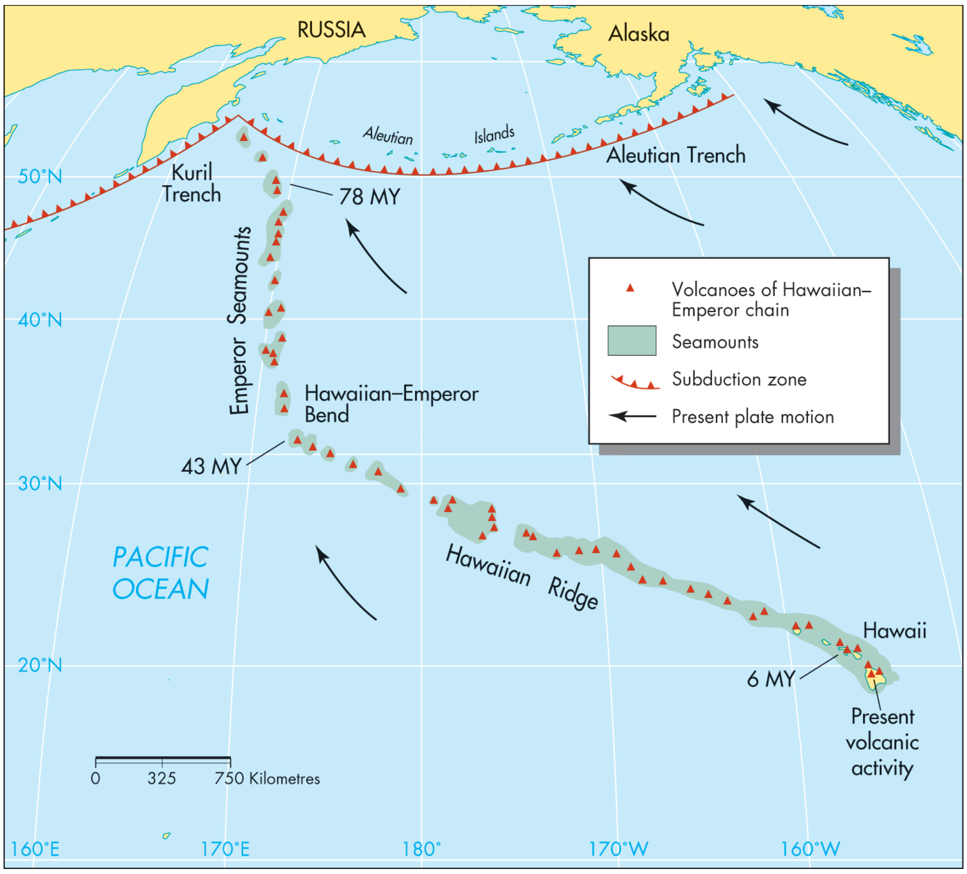


FIGURE 1.16 HAWAII HOT SPOT Map showing the Hawaiian–Emperor chain of volcanic islands and seamounts. Volcanic activity is presently restricted to the Big Island of Hawaii at the southeast end of the chain. *(Modified from Clague, D. A., G. B. Dalrymple, and R. Moberly. 1975. "Petrography and K-Ar ages of dredged volcanic rocks from the western Hawaiian Ridge and southern Emperor Seamount chain." Geological Society of America Bulletin 86:991–998)*

three major groups of rocks, driven by Earth's internal heat and by energy from the sun. The rock cycle is linked to the other cycles, because it depends on the tectonic cycle for heat and energy, the biogeochemical cycle for materials, and the hydrologic cycle for water. Water plays a central role in weathering, erosion, transportation, deposition, and lithification of sediment.

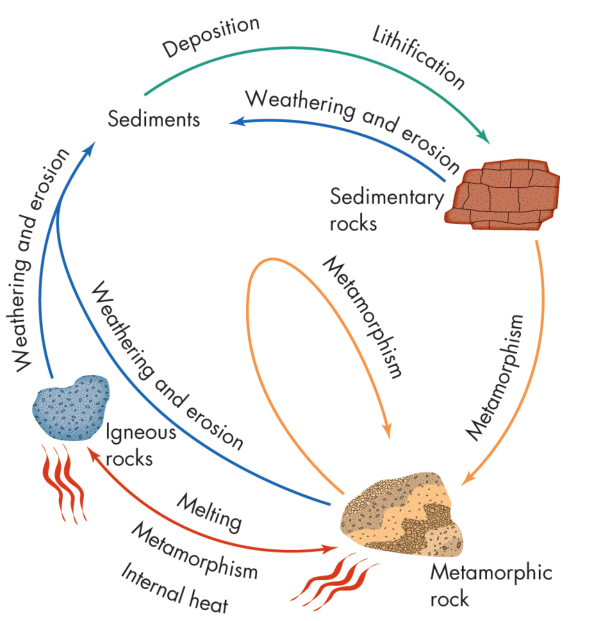


FIGURE 1.17 THE ROCK CYCLE An idealized cycle showing the three families of rocks and important processes that form them.

Although rocks differ greatly in their composition and properties, they can be categorized into three general groups, or families, according to how they formed (Figure 1.17). *Crystallization* of molten rock produces *igneous rocks* beneath and on Earth's surface. Rocks at or near the surface break down chemically and physically by *weathering* to form particles known as *sediment*. These particles range in size from clay to very large boulders and blocks. Sediment formed by weathering is transported by wind, water, ice, and gravity to depositional sites such as lakes and oceans. When the wind or flowing water slackens, the ice melts, or the material moving under the influence of gravity reaches a flat surface, the sediment is *deposited*. During burial, the sediment is converted to *sedimentary rock* by a process called *lithification*—conversion to solid rock. Lithification takes place by compaction and cementation of sediment during burial. With deep burial, sedimentary rock may be *metamorphosed* by heat, pressure, and chemically active fluids into *metamorphic rock*. Metamorphic rocks may be buried to depths where pressure and temperature conditions cause them to melt, beginning the entire rock cycle again.

Like any of Earth's cycles, there are many exceptions to the idealized sequence outlined above. For example, metamorphic rock may change into a different metamorphic rock without undergoing weathering or erosion (Figure 1.17), or sedimentary and metamorphic rocks may be uplifted and

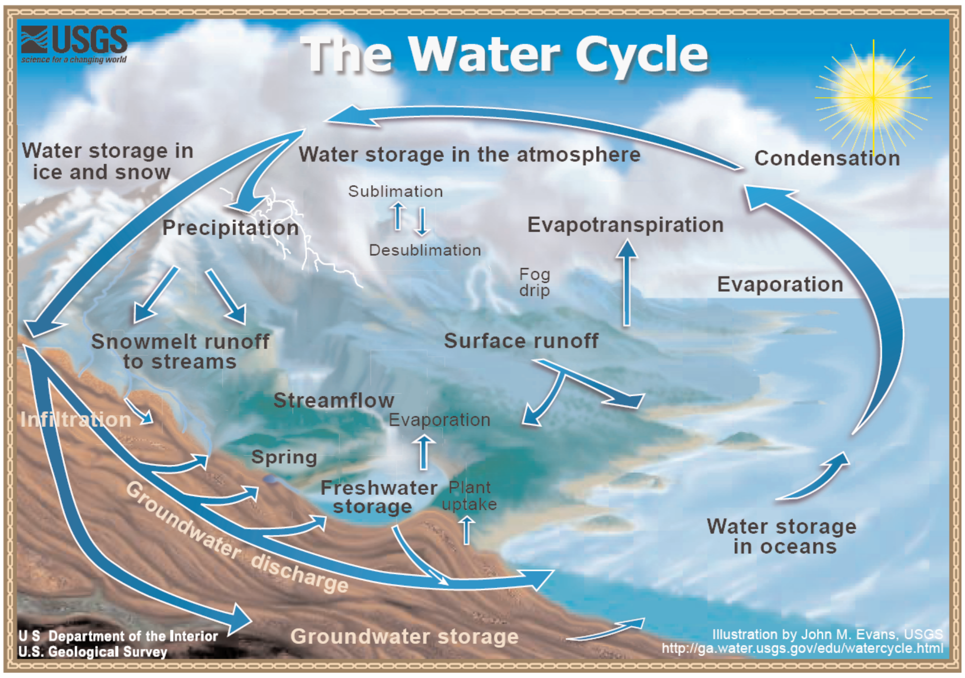


FIGURE 1.18 HYDROLOGIC CYCLE Idealized diagram showing important processes and transfers that define the hydrologic cycle. *(Illustration by John M. Evans, USGS, http://ga.water.usgs.gov/edu/watercycle.html)*

weathered before they continue on to the next stage in the cycle. Finally, some sediments have a biological or chemical origin, and there are types of metamorphism that do not involve deep burial.

The Hydrologic Cycle

The cycling of water from the oceans to the atmosphere, to continents and islands, and back again to the oceans is called the **hydrologic cycle** (Figure 1.18). This cycle is driven by solar energy and operates by way of evaporation, precipitation, surface runoff, and subsurface flow. Along the way, water is stored in different compartments, including oceans, atmosphere, rivers and streams, groundwater, lakes, and glaciers (Table 1.2). The **residence time**, or estimated average amount of time that a drop of water spends in any one compartment, ranges from days in the atmosphere to hundreds of thousands of years in ice sheets.

As you can see from Table 1.2, only a tiny amount of the total water on Earth is active at the surface at any time. Although the combined percentage of water in the atmosphere, rivers, lakes, and shallow subsurface sediments and rocks is only about 0.3 percent of the total, this water is tremendously important for life on Earth and for the rock and biogeochemical cycles. Surface and near-surface water helps move chemical elements in solution, sculpts the landscape, weathers rocks, and transports and deposits sediments. It is also the source of the fresh water that makes life on land possible.

Biogeochemical Cycles

A **biogeochemical cycle** is the transfer or cycling of an element or elements through the atmosphere (the layer of gases surrounding Earth), lithosphere (Earth's outer rocky layer), hydrosphere (oceans, lakes, glaciers, rivers, and groundwater),

TABLE 1.2 The World's Water Supply

Location	Surface Area (km^2)	Water Volume (km^3)	Percentage of Total Water	Estimated Average Residence Time
Oceans	361 000,000	1 230 000 000	97.2	Thousands of years
Atmosphere	510 000,000	12 700	0.001	9 days
Rivers and streams	—	1200	0.0001	2 weeks
Groundwater; shallow	130 000,000	4 000 000	0.31	Hundreds to many thousands of years to depth of 0.8 km
Lakes (freshwater)	855 000	123,000	0.009	Tens of years
Ice caps and glaciers	28 200 000	28 600 000	2.15	Hundreds of years to hundreds of thousands of years

Source: Data from U.S. Geological Survey.

and biosphere (organisms). It follows from this definition that biogeochemical cycles are intimately related to the tectonic, rock, and hydrologic cycles. The tectonic cycle provides water and gases from volcanic activity, as well as heat and energy, all of which are required to transfer dissolved solids in gases, aerosols, and solutions. The rock and hydrologic cycles transfer and store chemical elements in water, soil, and rock.

Elements and chemical compounds are transferred via a series of storage compartments or reservoirs, which include air, soil, groundwater, and vegetation. For example, carbon is exhaled by animals, enters the atmosphere, and is taken up by plants through *photosynthesis*. The amounts of important elements like carbon, nitrogen, and phosphorus in each compartment, and their rates of transfer between compartments, are known only approximately.

1.5 Fundamental Concepts for Understanding Natural Processes as Hazards

The concepts described below are important to understanding natural hazards. They are the foundation for our exploration of specific hazards in subsequent chapters of the text.

1. ***Hazards can be understood through scientific investigation and analysis.***
   Natural hazards, such as earthquakes, volcanic eruptions, landslides, and floods, are natural processes that can be identified and studied using the **scientific method**. Most disasters can be forecast from the past history of similar events, patterns in their occurrence, and types of precursor events.

2. ***An understanding of hazardous processes is vital to evaluating risk.***
   Hazardous processes are amenable to *risk analysis*, which considers both the probability that a damaging event will occur and the consequences of that event.

3. ***Hazards are commonly linked to each other and to the environment in which they occur.***
   Hazardous processes are linked in many ways. For example, earthquakes can produce landslides and tsunami, and hurricanes often cause flooding and coastal erosion. Hazards also are associated with particular environments on Earth.

4. ***Population growth and socio-economic changes are increasing risk from natural hazards.***
   The human and economic costs of natural disasters are increasing because of population growth, property development in hazardous areas, and poor land-use practices. Events that caused limited disasters in the twentieth century are causing catastrophes in the twenty-first century.

5. ***Damage and loss of life from natural disasters can be reduced.***
   Minimizing the adverse effects of hazardous events requires an integrated approach that includes scientific understanding, land-use planning and regulation, engineering, and proactive disaster preparedness.

CONCEPT 1

Hazards can be understood through scientific investigation and analysis.

Science and Natural Hazards

Science is founded on investigations and experiments, the results of which are subject to verification. The scientific method involves a series of steps, the first of which is to formulate a question. With respect to a hazardous event, a geologist might ask: Why did a landslide that destroyed several homes occur? To answer, the geologist will spend time examining the failed slope. She may notice that a great deal of water is flowing from the toe of the landslide. If she also knows that a water pipe is buried in the slope, she may refine the question to: Did the water in the slope cause the landslide? This question is the basis for a hypothesis that may be stated as follows: The landslide occurred because a buried water pipe broke, causing a large amount of water to enter the slope and reduce the strength of the slope materials.

An **hypothesis** is a possible answer to a question and is an idea that can be tested. In our example, we can test the hypothesis that a broken water line caused a landslide by excavating the slope to determine the source of the water. In science we test hypotheses in an attempt to disprove them. If we found that there was no leaking water pipe in the slope on which the landslide occurred, we would reject the hypothesis and develop and test another hypothesis. Use of the scientific method has improved our understanding of many natural processes, including flooding, volcanic eruptions, earthquakes, tsunami, hurricanes, and coastal erosion.

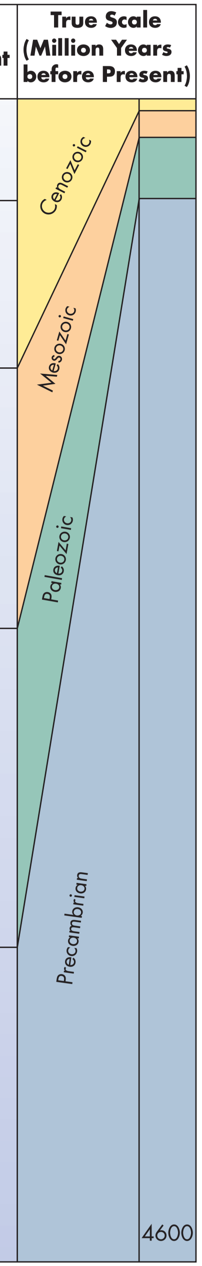
Scientists have identified where hazardous processes occur, their magnitude, and their frequency. They have also mapped the types and extents of different hazards. Coupled with knowledge of the frequency of past events, they use such maps to predict when and where floods, landslides, earthquakes, and other disasters will happen in the future. Scientists also search for types and patterns of precursor events. For example, *foreshocks* may precede a large earthquake, and a change in gas emissions may signal an imminent volcanic eruption.

Hazardous Processes Are Natural

Throughout history, people have had to adjust to events that make their lives difficult, such as earthquakes, tsunami, floods, volcanic eruptions, and severe storms. These events have occurred against a backdrop of major climate change. Humans are a product of the *Pleistocene Epoch*, which started about 2.6 million years ago (Table 1.3). The Pleistocene Epoch was

TABLE 1.3 Geologic Time with Some Important Events

Era	Period	Epoch	Million Years before Present	Events: Life	Events: Earth	Million Years before Present
Cenozoic	Quaternary	Holocene	0.01	• Extinction event • Modern humans	Ice Age Rise of St. Elias Mountains	
		Pleistocene	1.8	• Early humans		1.8
	Tertiary	Pliocene	5.3		Formation of Andes Mountains	
		Miocene	23	• Grasses • Whales	Collision of India with Asia forming Himalayan Mountains and Tibetan Plateau	
		Oligocene	34	• Extinction event		
		Eocene	56	• Mammals expand	Rocky Mountains form	
		Paleocene	65			65
Mesozoic	Cretaceous		146	• Dinosaur extinction,[1] extinction event • Flowering plants • Birds	Alberta and Saskatchewan are covered by the sea	
	Jurassic		200		• Supercontinent Pangaea begins to break up	
	Triassic		251	• Mammals • Dinosaurs		251
Paleozoic	Permian		299	• Extinction event • Reptiles	• Ice Age	
	Carboniferous		359	• Coal swamps	Appalachian Mountains form	
	Devonian		416	• Extinction event • Trees		
	Silurian		444	• Land plants		
	Ordovician		488	• Extinction event		
	Cambrian		542	• Fish • Explosion of organisms with shells		542
Precambrian time			2500 3500 4000 4600	• Multicelled organisms • Free oxygen in atmosphere and ozone layer in stratosphere • Primitive life (first fossils)	• Ice Age • Ice Age • Oldest rocks • Age of Earth	4600



[1] Some scientists believe that not all dinosaurs became extinct but that some evolved into birds.

a time of large fluctuations of climate—from cold, harsh glacial conditions as recently as 12 000 years ago to the relatively benign interglacial conditions we enjoy today. Adjusting to harsh and changing climatic conditions has been necessary for our survival from the very beginning.

Hazardous Earth processes are natural and thus are not the direct result of human activity. Nothing that people do, for example, changes the behaviour of volcanoes. However, because these processes are natural, we face fundamental philosophical issues when making choices about how to minimize their adverse effects. We realize, for example, that flooding is a natural part of river dynamics and must ask ourselves if it is wiser to attempt to control floods or to make sure that people and property are protected when they occur.

Although we can, to a degree, control some hazards, many are completely beyond our control. For example, we have some success in preventing damage from wildfires by using controlled burns and advanced firefighting techniques, but we will never be able to prevent earthquakes. In fact, we may actually worsen the effects of some natural processes simply by labelling them as hazardous. Efforts to suppress wildfires, for example, have interfered with ecosystems in forests in which fire is a natural process and, in some cases, have increased the severity of subsequent fires. Rivers will always flood, but because we choose to live and work on floodplains, we have labelled floods as hazards, which has led to efforts to control them. Unfortunately, as we will discuss later, some flood-control measures intensify the effects of flooding, thereby increasing the risk of the event we are trying to prevent (Chapter 9). The best approach to hazard reduction is to identify hazardous processes and delineate the geographic areas where they occur. Every effort should be made to avoid putting people and property in harm's way, especially for hazards we cannot control, such as earthquakes.

Prediction, Forecast, and Warning

A **prediction** of a hazardous event such as an earthquake involves specifying the date and size of the event. In contrast, a **forecast** is less precise and has uncertainty. A meteorologist may forecast a 40 percent chance of rain tomorrow, but she is not predicting the weather. Learning how to forecast disasters so that we can minimize loss of life and property is an important endeavour. In some cases, we have enough information to accurately forecast events. However, when information is insufficient to make accurate forecasts, the best we can do is identify areas where disasters can be expected in the future based on past history. If we know both the probability and the possible consequences of an event at a particular location, we can quantify the risk of the event, even if we cannot accurately predict when it will occur.

Damage inflicted by a natural disaster can be reduced if the event can be forecast and a warning issued. This process involves the following elements:

- Identifying the location of a hazard
- Determining the probability that an event of a given magnitude will occur
- Identifying any precursor events
- Forecasting the event
- Issuing a warning

Location We can identify areas at risk from different hazardous processes. Major zones of earthquakes and volcanic eruptions have been identified by mapping (1) where earthquakes have occurred historically, (2) areas of young volcanic rocks, and (3) locations of active and recently active volcanoes. We can use past volcanic eruptions to identify areas that are likely to be affected by future ones. Volcanic hazard maps have been prepared for most Cascade volcanoes in the Pacific Northwest and for volcanoes in Japan, Italy, Colombia, and elsewhere. Detailed mapping of surface sediments, rocks, groundwater conditions, surface drainage, and evidence for ground instability can pinpoint slopes that are likely to fail. We can also predict where flooding is likely to occur by identifying floodplains and mapping the extent of recent floods.

Probability of Occurrence Determining the probability of a particular event at a specific site is an essential part of hazard analysis. We have sufficiently long discharge records for many rivers to develop probability models that can reasonably predict the number of floods of a given size that will occur within a particular period. Likewise, the probability of droughts can be determined from the history of past rainfall in the region, and the probability of earthquakes of specific magnitudes can be estimated from historic earthquake records. However, these probabilities are subject to the same elements of chance as throwing a particular number on a die or drawing to an inside straight in poker. For example, although a flood may occur only once every 10 years, on average, it is possible to have two or more or no floods of this magnitude in that time, just as it is possible to throw a six twice in a row with a die. Probabilities of rare events within a specific region—for example, volcanic eruptions, tsunami, and meteorite impacts—are much more difficult to estimate and are subject to large uncertainties.

Precursor Events Many disasters are preceded by *precursor events*. For example, the surface of the ground may creep for weeks, months, or years before a catastrophic landslide, and the rate of creep may increase just before final failure. Volcanoes sometimes swell or bulge before an eruption, accompanied by an increase in earthquake activity in the area. Foreshocks or unusual uplift of the land may precede an earthquake.

Identification of precursor events helps scientists predict when and where a disaster will occur. Documentation of landslide creep or swelling of a volcano may lead authorities to issue a warning and evacuate people from a hazardous area, as happened before the catastrophic eruption of Mount St. Helens in 1980, for example.

Forecasting With some natural processes, it is possible to forecast accurately when a possible damaging event will occur. Government agencies can generally accurately forecast when large rivers will reach a particular flood stage. We can also forecast when and where hurricanes will strike land by tracking them at sea. Arrival times of tsunami can be precisely predicted if a warning system detects the waves.

Warning Once a hazardous event has been predicted or a forecast made, the public must be warned. The flow of information leading to a public **warning** of a possible disaster, such as a large earthquake or flood, should move along a predefined path (Figure 1.19). However, the public does not always welcome such warnings, especially when the predicted event does not occur. In 1982, geologists issued an advisory that a volcanic eruption was likely near Mammoth Lakes, California. The advisory caused loss of tourist business and apprehension on the part of residents. The eruption did not occur and the advisory was eventually lifted. In July 1986, a series of earthquakes occurred over a four-day period near Bishop, California, in the eastern Sierra Nevada Mountains, beginning with a magnitude 3 event and culminating in a damaging magnitude 6.1 earthquake. Scientists concluded that there was a high probability that a larger earthquake would occur in the area in the near future and issued a warning. Local business owners, who feared the loss of summer tourism, felt that the warning was irresponsible; in fact, the predicted quake never occurred.

Incidents of this kind have led some people to conclude that scientific predictions are worthless and that advisory warnings should not be issued. Part of the problem is poor communication among scientists, the news media, and the public. Newspaper, television, and radio reports may fail to explain the evidence or the probabilistic nature of disaster forecasting and prediction, leading the public to expect black-and-white statements about what will happen. Although scientists are not yet able to predict volcanic eruptions and earthquakes accurately, they have a responsibility to publicize their informed judgments. An informed public is better able to act responsibly than is an uninformed public, even if the subject makes people uncomfortable. Ships' captains, who depend on weather advisories and warnings of changing conditions, do not suggest they would be better off not knowing about an impending storm, even though the storm might not materialize or might take an unexpected course. Just as weather warnings have proved very useful for planning, official warnings of earthquakes, volcanic eruptions, landslides, and floods are also useful to people when they decide where to live, work, or travel.

Let's consider again the prediction of a volcanic eruption in the Mammoth Lakes area. The location and depth of earthquakes suggested to scientists that magma was moving toward the surface. In light of the chance that the volcano could erupt, and the possible loss of life if it did, it would have been irresponsible for scientists not to have issued the advisory. Although the predicted eruption did not occur, the advisory led to the development of evacuation routes and a consideration of disaster preparedness. This planning may eventually prove useful, because the most recent eruption in the Mammoth Lakes area occurred only 600 years ago, and it is likely that one will occur in the future.

Forecasts and warnings are useful only if they provide people adequate time to respond in an appropriate manner. A minimum of several hours of warning is required in most instances, and much more time is needed if evacuation of urban areas is necessary. Warnings of many hours to days are possible for hurricanes, volcanic eruptions, large floods, and some tsunami, but earthquakes and landslides commonly occur without any warning at all.

CONCEPT 2

An understanding of hazardous processes is vital to evaluating risk.

Hazardous processes are amenable to risk analysis, which considers both the probability that a damaging event will occur and the consequences of that event. For example, if we were to estimate that, in any given year, Vancouver has a 1 percent chance of a moderate earthquake, and if we know

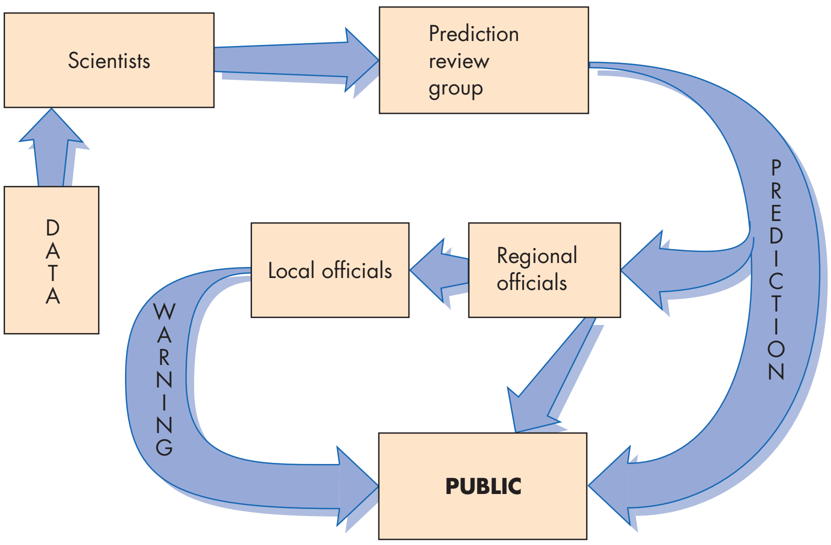


FIGURE 1.19 HAZARD PREDICTION OR WARNING Possible path for issuing a prediction or warning of a natural disaster.

the consequences of that earthquake in terms of loss of life and damage, we can then calculate the risk to society.

Determining *acceptable risk* is more complicated, because individuals, social groups, and countries have different attitudes about what level of risk is acceptable. Many people are willing to accept a level of risk that governments will not. A person may knowingly live on a floodplain, with the understanding that flooding of their property is a possibility. Governments, however, have a larger responsibility to society that requires a more cautious approach and a longer-term perspective. From their point of view, floodplain development, like a diamond, is forever, ensuring that losses ultimately will be incurred. Furthermore, governments are commonly left "holding the bag" after a disaster—they are essentially the insurer of last resort because individuals rarely have financial ability to cover their losses.

Acceptable risk also depends on the situation. Driving an automobile is fairly risky, but most of us accept that risk as part of living in a modern world. In contrast, for many people, the acceptable level of risk represented by a nuclear power plant is very low because they consider any possibility of radiation poisoning unacceptable. Nuclear power plants are controversial because many people perceive them as high-risk facilities. Even though the probability of an accident owing to a geologic hazard, such as an earthquake, might be very low, the consequences could be devastating; accordingly, the risk is relatively high.

Institutions such as governments, banks, and insurers commonly view acceptable risk from an economic perspective rather than a personal one. For example, an insurer may set policy premiums on the level of economic risk it faces from flooding or other natural hazards.

At the individual level, people have some control over the level of risk they are willing to accept. For the most part, you can choose where you live. If you choose to live in Vancouver, you may experience a damaging earthquake. If you move to Winnipeg, you should realize you will live on the floodplain of the Red River, which has a long history of damaging floods. So why do people choose to live in hazardous areas? Perhaps the allure of mountains and the ocean drew you to Vancouver, or you were offered an excellent job in Winnipeg. Whatever the case, individuals must weigh the pros and cons of living in a particular area and decide whether it is worth the risk. This assessment should consider such factors as the **frequency** of damaging events, the potential damage the events could cause, and the extent of the geographic area at risk. The assessment should compare these factors to the potential benefits of living in the high-risk area. In this way, we determine acceptable risk, which differs from person to person. In fact, a trade-off generally exists between risk acceptance and the cost of protection against hazards. Society may be willing to accept some risk in allowing people to live on a floodplain or in using the floodplain for business activity because of the economic benefits of doing so. More commonly, protective dykes are built to provide some protection, but at a cost, of course. An economic cost-benefit analysis can be an essential part of the decision-making process for determining the most appropriate level of protection against floods and other hazards.

A frequent problem in risk analysis is that the data required to determine the probability or consequences of an event are either inadequate or lacking. It can be difficult to assign probabilities to geologic events, such as earthquakes and volcanic eruptions, because the known record of past events is too short or is incomplete.[16] Similarly, it may not be possible to accurately determine the consequences of an event from sparse data. For example, if we are concerned about the consequences of a release of radiation into the environment, we need information about the local biology, geology, hydrology, and meteorology, all of which may be complex and difficult to analyze. We also need information about the infrastructure at risk and the numbers and distribution of people living and working in the area of concern. Despite these limitations, risk analysis is a step in the right direction. As we learn more about the probability and consequences of a hazardous event, we can make a more reliable assessment of risk for appropriate decision making.

CONCEPT 3

Hazards are commonly linked to each other and to the environment in which they occur.

Many hazardous natural processes are directly or indirectly linked. For example, intense precipitation and storm surges accompanying hurricanes cause flooding, coastal erosion, and landslides. Volcanic eruptions on land cause volcanic debris flows (*lahars*) and floods, and volcanic eruptions on islands can trigger tsunami.

Natural hazards also are affected by Earth materials. Slopes developed on shale or loose glacial sediments, for example, are prone to landslides. In contrast, massive granite slopes are generally stable, although jointed granite may fail along fractures within the rock.

CONCEPT 4

Population growth and socio-economic changes are increasing risk from natural hazards.

Over much of human history, our numbers were small and nomadic and losses from hazardous processes were not very significant (Table 1.4). As people began to cultivate crops and domesticate animals, populations increased and became more fixed, in many cases in hazardous areas. Concentration of people and resources in fixed settlements increased losses from periodic earthquakes, floods, and other natural disasters. The rate of population growth increased nearly tenfold during the Early Industrial period (A.D. 1600 to 1800). Since the Industrial Revolution, with modern sanitation and medicine, growth rates have increased another 10 times. The human population reached 6 billion in 2000, and by 2011 it will be 7 billion—that is, 1 billion new people in only 11 years![17] Most of the

TABLE 1.4 How We Became 7 Billion

40 000–9000 B.C.: HUNTERS AND GATHERERS

Population density about 1 person per 100 km^2 of habitable area*; total population probably less than a few million; average annual growth rate less than 0.0001% (doubling time about 700 000 years)

9000 B.C.–A.D. 1600: PREINDUSTRIAL AGRICULTURAL

Population density about 1 person per 1 km^2 of habitable area; total population several hundred million; average annual growth rate about 0.03% (doubling time about 2300 years)

A.D. 1600–1800: EARLY INDUSTRIAL

Population density about 7 persons per 1 km^2 of habitable area; total population by 1800 about 1 billion; annual growth rate about 0.1% (doubling time about 700 years)

A.D. 1800–2011: MODERN

Population density about 40 persons per 1 km^2 of habitable area; total population in 2011 about 7.1 billion; annual growth rate in 2000 about 1.4% (doubling time about 50 years)

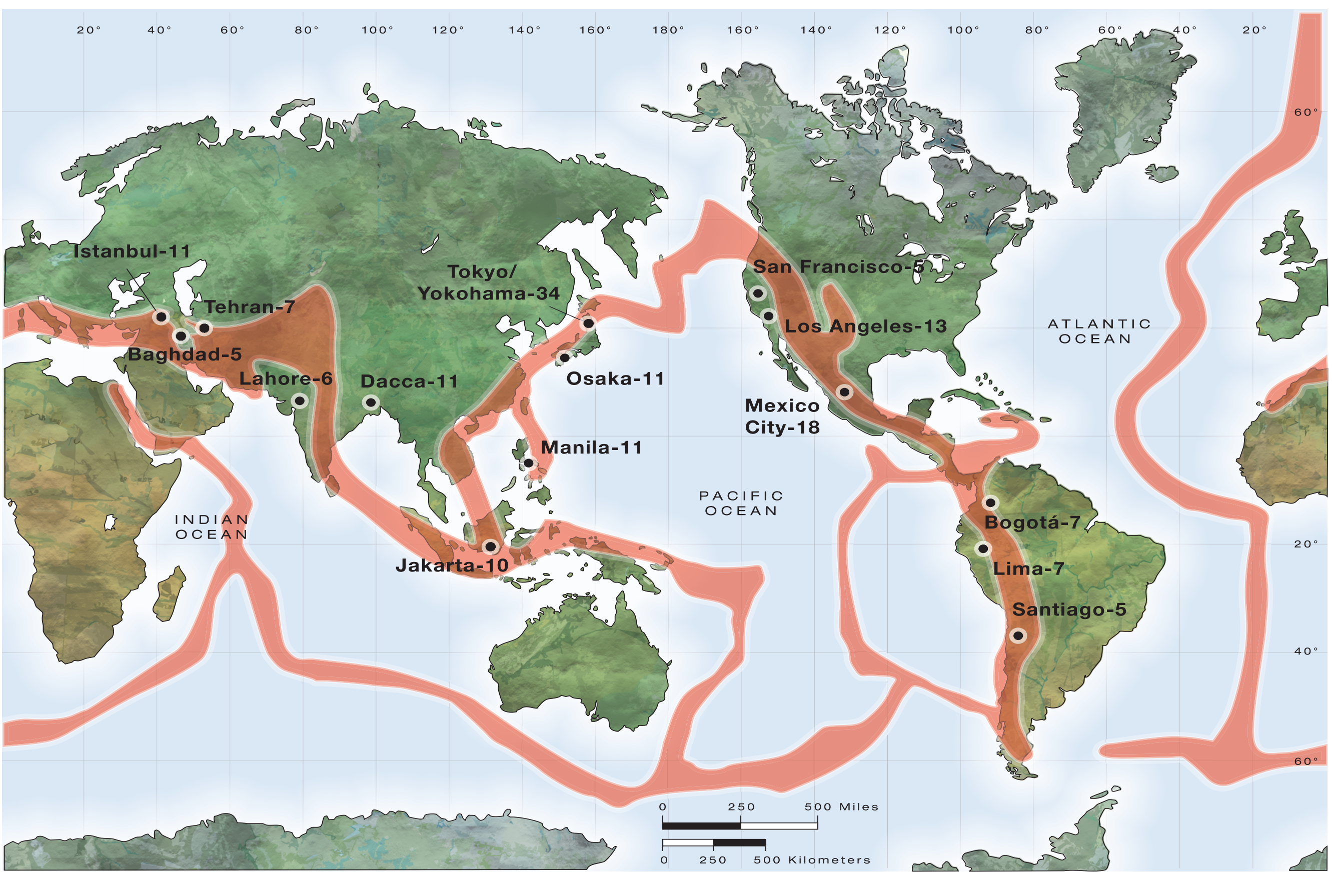
*Habitable area is assumed to be about 150 000 000 km^2.

Source: Modified from Botkin, D. B., and E. A. Keller. 2000. Environmental Science, 3rd ed. New York: John Wiley and Sons. 7 billion data from U.S. Census Bureau, International Data Base.

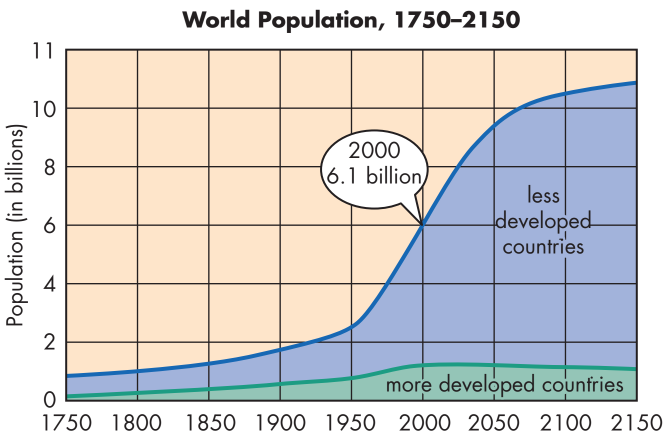
increase in population will be in developing nations. India will have the largest population of all countries by 2050, about 18 percent of the world total; China will have about 15 percent of the world total.

Today billions of people live in areas vulnerable to damage by hazardous Earth processes (Figure 1.20). In addition, much of our economic productivity and wealth are located in hazard zones. Because more and more people are living in hazardous areas, the need for planning to minimize losses from natural disasters is increasing.

This rapid increase in population has been *exponential*—the population grows each year, not by the addition of a constant number of people, but rather by the addition of a constant percentage of the current population (Figure 1.21). The exponential growth in population can be expressed by the following equation:



▲ **FIGURE 1.20 CONCENTRATION OF PEOPLE AND WEALTH IN HAZARDOUS AREAS.** Many of the world's largest cities and much of our economic activity are concentrated in areas vulnerable to large earthquakes. In this figure, numbers are populations in millions and orange zones are areas prone to damaging earthquakes.



▲ **FIGURE 1.21 POPULATION GROWTH** The growth in global population has been exponential, but the rate of increase is now declining. The world's population in 2011 was about 7 billion *(United Nations,* World Population Prospects, the 1998 Revision *(New York: UN, 1998); and estimates by the Population Reference Bureau)*

$$N_t = N_0 e^{rt} \text{ where } N_t$$

is the population at time t, N_0 is the starting population, r is the growth rate, and e is the base of the natural logarithm (2.71828).

This equation does not directly take into account changes in life expectancy, but it clearly shows that future population numbers are dependent on the *rate* of growth in population. At the current annual rate of growth, the population will increase from its current level of 7 billion to about 9.2 billion by 2050. In contrast, if the annual rate of increase were only half the present rate, the population in 2050 would be about the same as today.

An emerging issue related to natural hazards is the link between disasters and technological dependence. The ice storm in southern Quebec and Ontario in 1998 was a disaster mainly because electric power was lost when transmission lines failed. The storm would not have been a large disaster 100 years earlier when people did not use electricity to keep themselves warm in winter. Related to the issue of overdependence on complex and fallible technological systems is the interrelation of different technological systems. During the Quebec–Ontario ice storm, the loss of hydroelectric power required the use of generators to produce electricity. However, there were not enough generators to filter water at the same rate as is normally done, and the population came close to suffering a shortage of drinking water.

Inequities in health, education, and wealth between developed and developing countries aggravate these problems. Population growth in developing countries is far outstripping that in North America, Europe, Japan, and other wealthy jurisdictions. Most people in developing countries lack resources to protect themselves from hazardous events. Thus, when a disaster happens in a densely populated area in a developing country, the consequences are likely to be catastrophic. The same event in a fully developed country tends to kill far fewer people, although the economic cost is generally much greater.

CONCEPT 5

Damage and loss of life from natural disasters can be reduced.

We deal with natural hazards primarily in *reactive* ways—following a disaster, we engage in search and rescue, firefighting, and the provision of emergency food, water, and shelter. These activities reduce loss of life and property and must, of course, be continued. However, a higher level of hazard reduction requires a *proactive* approach in which we anticipate and prepare for disasters. Land-use planning that limits construction in hazardous areas; hazard-resistant construction; and hazard modification or control, such as flood control channels, are some of the proactive measures that can be taken before disastrous events occur in order to reduce our vulnerability to them.[7]

Reactive Response: Recovery from Disasters

The effects of a disaster on a population may be either direct or indirect. *Direct effects* include deaths, injuries, displacement of people, and damage to property and other infrastructure. *Indirect effects* are post-disaster impacts, including crop failure, starvation, emotional distress, loss of employment, reduction in tax revenues because of property loss, and higher taxes to finance the recovery. Many more people experience indirect effects than direct effects.[18,19] In our highly interconnected and interdependent world, a catastrophic natural disaster can have nearly global impacts. An example is the temporary loss of oil-refining capacity in Louisiana after Hurricane Katrina. The effect of this event was an immediate rise in gasoline prices throughout North America and Europe, an economic impact affecting hundreds of millions of people. A more serious interdependency can be seen in the potential impacts of global warming. An increase in average atmospheric temperature of more than about 2°C may lead to serious failures in some cereal crops in many countries, which would lead to food shortages that would threaten global food supply.[20] The same warming might cause sea levels to rise, flooding low-lying coastal areas where hundreds of millions of people live. The result would be massive human migrations, creating refugees that would likely overwhelm the coping ability of many countries and lead to strife and even war.

The stages of recovery following a disaster are emergency work, restoration of services and communication, and reconstruction (Figure 1.22). We can see the stages of recovery in the activities that followed the 1994 Northridge earthquake in the Los Angeles area. Emergency restoration began almost immediately with the repair of roads and utilities. Continuing restoration used funds from federal programs, insurance companies, and other sources that arrived in the first few weeks and months after the earthquake. Activity soon shifted from the restoration phase to the first phase of reconstruction, which lasted until about 2000. The effects of the earthquake on highway overpasses and bridges, buildings, and other

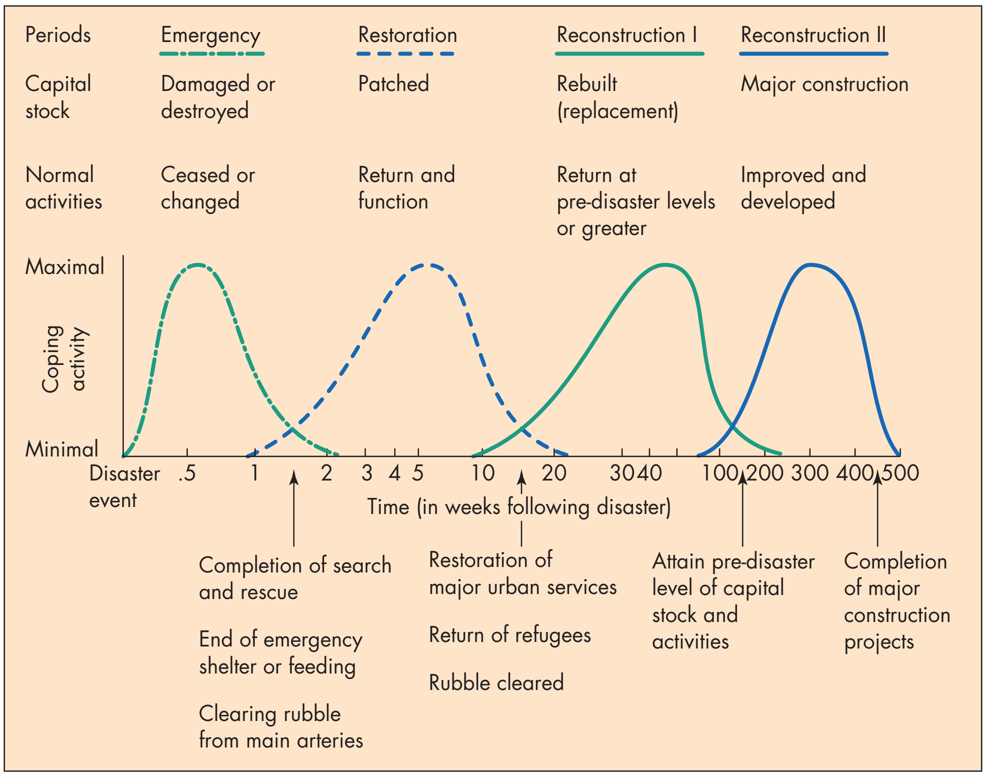


FIGURE 1.22 RECOVERY FROM DISASTER Generalized model of recovery following a disaster. The first two weeks after a disaster are the period of emergency during which normal activities cease or are changed. In the restoration phase, which typically lasts several months, normal activities return, although perhaps not at pre-disaster levels. Finally, during reconstruction, the capital stock is replaced, major new construction is completed, and normal activities return. *(From Kates, R. W., and D. Pijawka. 1977. "From rubble to monument: The pace of reconstruction. In* Disaster and Reconstruction,*" eds. J. E. Haas, R. W. Kates, and M. J. Bowden, pp. 1–23. Cambridge, MA: MIT Press)*

structures were carefully evaluated and new structures were built to a higher seismic standard. Large earthquakes are certain to occur again in the Los Angeles area; therefore, efforts to reduce the damage they cause must continue.

Now that Los Angeles is past the final phase of the reconstruction period, the lessons from two other disasters should be remembered: the Anchorage, Alaska, earthquake in 1964 and the flash flood that devastated Rapid City, South Dakota, in 1972. Restoration following the Anchorage earthquake began almost immediately with a tremendous influx of money from U.S. federal disaster programs, insurance companies, and other sources. Reconstruction was rapid and proceeded without much thought as everyone competed for the available funds. Apartments and other buildings were hurriedly constructed in areas that had suffered ground rupture. Building sites were prepared by simply filling in cracks and regrading the surface. By ignoring the potential benefits of careful **land-use planning**, Anchorage has made itself vulnerable to the same type of earthquake damage as it experienced in 1964. In contrast, in Rapid City, the restoration did not peak until approximately 10 weeks after the flood, and the community took time to carefully think through alternatives. As a result, Rapid City today uses the floodplain as a greenbelt, an entirely different use than before the 1972 flood. The change has reduced the flood risk substantially.[8,19,20]

The pace of recovery depends on several factors, the most important of which are the **magnitude** of the disaster and social and economic context. Recovery is more rapid following smaller disasters, such as the Northridge earthquake, than after catastrophes, such as Hurricane Katrina and the 2004 Indian Ocean tsunami. Recovery also proceeds more rapidly in resilient communities and in those that have prepared in advance for natural disasters. Lack of preparation leads to a protracted recovery, often with severe economic consequences that last years, sometimes even decades. The complete failure of the U.S. and Louisiana governments to respond in a timely fashion to the destruction wrought by Hurricane Katrina resulted in a depopulation of New Orleans, from which the city still has not yet recovered, six years later. Recovery normally proceeds more rapidly in wealthy countries, such as Canada, the United States, and Japan, than in countries that have few resources to deal with natural disasters, like Haiti (2010 earthquake), Pakistan (2005 earthquake) and Indonesia (2004 tsunami). The global community has a responsibility to provide both immediate and long-term assistance to countries that do not have the ability to deal with catastrophes themselves.

Proactive Response: Avoiding and Adjusting to Hazards

The decisions we make, individually and collectively, in preparing for natural disasters depend in part on our perception of risk. Much research has been done in recent years to try to understand how people perceive different natural hazards. This understanding is important because the success of risk-reduction programs depends on the attitudes of the people who are likely to be affected. Although there may be adequate awareness of hazard and risk at the government level, it may not filter down to the general population. Such a lack of awareness is particularly true for events that occur infrequently; people are more aware of hazards that occur every few years, such as forest fires. Standard procedures, as well as local ordinances, may already be in place to control damage from these events. For example, some expensive new homes in Pemberton, British Columbia, have been constructed on pads of artificial fill elevated above the adjacent floodplain to provide protection from the frequent floods that occur. Similarly, some landowners in tsunami-prone areas on the island of Hawaii have elevated their homes on piles anchored in the ground. In the latter case, tsunami have been sufficiently frequent in the past 100 years that the owners view the extra cost of elevating their homes as a good investment.

One of the most environmentally sound and cost-effective adjustments to hazards involves land-use planning. People can avoid building on floodplains, in areas where there are active landslides, or in places where tsunami or coastal erosion are likely to occur. In many Canadian and U.S. cities, floodplains have been delineated and zoned for a particular land use. Legal requirements for engineering geology studies at building sites may greatly reduce potential damage from landslides. Damage from tsunami and coastal erosion can be minimized by requiring adequate setback of buildings from the shoreline or sea cliff. Although it may be possible to control physical processes in some instances, land-use planning is often preferable to a technological fix that may or may not work.

Insurance is another option for dealing with natural hazards. Flood and earthquake insurance is available in many areas. However, huge insured losses stemming from recent hurricanes, earthquakes, and other disasters are forcing insurance companies to increase their premiums or deductibles in many hazard-prone areas or simply to discontinue some types of insurance.

Evacuation is a reaction to the hurricane hazard in states along the Gulf of Mexico and the eastern seaboard of the United States. Sufficient time is generally available for people to evacuate coastal areas, provided they heed warnings. However, if people do not react quickly or if the population in the affected area is large, evacuation routes may become clogged, as happened in Texas in September 2005 during Hurricane Rita.

Disaster preparedness is an option that individuals, families, cities, states, and entire nations can use to reduce risk. Of particular importance are public education and emergency preparedness training.

Attempts at *artificial control* of landslides, floods, lava flows, and other hazardous processes have met with mixed success. Seawalls have been constructed on pads of artificial fill elevated above the adjacent floodplain to provide protection from floods. Retaining walls and other structures may protect slopes from landslides if well designed. They are necessary where potentially unstable slopes are excavated or where buildings border steep slopes. Common methods of flood control are channelization and construction of dams and levees. Unfortunately, flood-control projects tend to provide residents with a false sense of security; no method can completely protect floodplain residents from extreme floods.

An option that is all too often chosen is to simply accept the risk and bear the loss in the event of a disaster. Many people are optimistic about their chances of making it through any disaster and will therefore take little action on their own. They also believe that governments will step in with relief following a disaster, which is commonly the case. The do-nothing response is particularly true for hazards that are rare in a given area, such as volcanic eruptions and earthquakes.

1.6 Many Hazards Provide a Natural Service Function

It is ironic that the same natural events that injure people and destroy property also provide important benefits, which we will refer to as *natural service functions*. The following examples illustrate this point. Floods add new sediment to floodplains, creating the fertile soils that support agriculture. They cause erosion but also deliver sediment to beaches and flush pollutants from coastal estuaries. Some volcanic eruptions create new land, as in the case of the Hawaiian Islands, which are completely volcanic in origin. Nutrient-rich volcanic ash enriches soils, making them more productive for crops and wild plants. Earthquakes contribute to mountain building and thus are responsible for many of the scenic landscapes of the world. Faults on which earthquakes occur may serve as paths for groundwater, creating springs that are important sources of water.

1.7 Climate Change and Natural Hazards

Global and regional climatic change may alter the incidence of some hazardous natural processes—notably storms, coastal erosion, landslides, drought, and fires (see Chapter 12). How might climatic change affect the magnitude and frequency of these events? With global warming, sea levels will rise as warmer surface-ocean waters expand and glaciers melt. Rising seas will induce or accelerate coastal erosion in some areas. Climate change may shift food production regions or force a change in the types of crops grown in specific areas. Deserts and semi-arid zones may expand, and warmer northern latitudes could become more productive. Permafrost is likely to degrade, causing problems for people who live at high latitudes. Some of these changes could force shifts in populations, which might bring about social and political upheaval.

Global warming will feed more energy from warmer ocean water into the atmosphere, which may increase the severity and frequency of thunderstorms, tornadoes, and hurricanes.[21] This trend may already be underway—2005 set a new record for direct economic losses from weather-related disasters, which cost at least US$200 billion worldwide. This figure represents more than a 100-percent increase over the previous record of US$100 billion, set in 1998.

Our ability to adjust to climate change will be determined in large part by the rate at which it happens. If the climate changes slowly, we should be able to adjust our agricultural practices and settlement patterns without major economic and social disruption. If, however, the change occurs rapidly, we may not have the capacity to easily adapt.

Summary

Natural hazards are responsible for significant damage and loss of life worldwide each year. Natural processes that cause disasters are driven by energy derived from three sources: (1) Earth's internal heat, which produces slow convection in the mantle and is ultimately responsible for volcanic eruptions and earthquakes; (2) energy from the sun, which warms Earth's atmosphere and surface and is responsible for violent storms, floods, and coastal erosion; and (3) the gravitational attraction of Earth, which is responsible for landslides, snow avalanches, and meteorite impacts.

Central to an understanding of natural hazards is awareness that disasters result from natural processes that have been operating for billions of years. These natural processes become hazards only when they threaten human life or property.

Natural disasters are repetitive events, and study of their history provides information required for risk reduction. A better understanding of hazardous events and the risks they pose can be obtained by integrating information on historic and prehistoric events, geomorphology, and land-use change.

Geologic conditions and materials govern the type, location, and intensity of some natural events. The geologic cycle creates, maintains, and destroys Earth materials by physical, chemical, and biological processes. This cycle comprises a number of self-regulating cycles, including the tectonic cycle, the rock cycle, the hydrologic cycle, and various biogeochemical cycles. The tectonic cycle describes large-scale geologic processes that deform Earth's crust, producing ocean basins, continents, and mountains. The rock cycle is a worldwide material recycling process driven by Earth's internal heat, which melts and metamorphoses crustal rocks. Weathering and the erosion of surface rocks produce sediments and, ultimately, sedimentary rocks, which are added to the crust, offsetting materials lost through subduction. The hydrologic cycle is driven by solar energy and operates through evaporation, precipitation, surface runoff, and subsurface flow. Biogeochemical cycles involve transfers of chemical elements through a series of storage compartments or reservoirs, such as air or vegetation.

Five fundamental concepts establish a philosophical framework for studying natural hazards:

1. Hazards can be understood through scientific investigation and analysis.
2. An understanding of hazardous processes is vital to evaluating risk.
3. Hazards are commonly linked to each other and to the environment in which they occur.
4. Population growth and socio-economic changes are increasing risk from natural disasters.
5. Damage and loss of life from natural disasters can be reduced.

Key Terms

biogeochemical cycle (p. 18)
catastrophe (p. 7)
disaster (p. 7)
forecast (p. 21)
frequency (p. 23)
geologic cycle (p. 11)
hazard (p. 7)
hydrologic cycle (p. 18)
hypothesis (p. 19)
land-use planning (p. 26)
magnitude (p. 26)
mitigation (p. 8)
prediction (p. 21)
residence time (p. 18)
risk (p. 7)
rock cycle (p. 16)
scientific method (p. 17)
tectonic cycle (p. 11)
warning (p. 22)

Review Questions

1. What forces drive Earth's internal and external processes?
2. What are the distinctions between a natural hazard and a disaster, and between a disaster and a catastrophe?
3. What is the difference between hazard and risk?
4. Why is history important in understanding natural hazards?
5. What kinds of information must be assembled to conduct a risk assessment?
6. What are the five fundamental concepts for understanding natural processes as hazards?
7. Explain the scientific method as it is applied to natural hazards.
8. What are the elements involved in making a hazard forecast and warning?
9. What is a precursor event? Give some examples.
10. Explain the magnitude-frequency concept.
11. How do risk and acceptable risk differ?
12. Explain how population growth increases risk.
13. What are the stages of disaster recovery? How do they differ?
14. Describe four common adjustments to natural hazards.
15. What are natural service functions of natural hazards?

Critical Thinking Questions

1. How would you use the scientific method to test the hypothesis that sand on the beach comes from nearby mountains?
2. It has been argued that we must curb human population growth because otherwise we won't be able to feed everyone. Even if we could feed 10 billion to 15 billion people, would we still want a smaller population? Why or why not?
3. The processes we call natural hazards have been occurring on Earth for billions of years and will happen for billions more. How, then, can we lessen loss of life and property damage from natural disasters?

Selected Web Resources

Natural Resources Canada
http://ess.nrcan.gc.ca/2002_2006/nher/index_e.php Homepage of NRCan's Natural Hazards and Emergency Response program

Canadian Centre for Emergency Preparedness
www.ccep.ca Nonprofit organization for emergency preparedness and disaster management

Public Safety Canada
www.psepc-sppcc.gc.ca From the Canadian federal agency responsible for natural hazard preparedness and mitigation

FEMA
www.fema.gov Homepage of the U.S. Federal Emergency Management Agency (FEMA)

United States Geological Survey
http://geology.usgs.gov/index.htm Hazard information from the U.S. Geological Survey

NASA Earth Observatory
http://earthobservatory.nasa.gov/NaturalHazards Information on recent natural hazard events from the National Aeronautics and Space Administration (NASA)

Earthweek
www.earthweek.com Weekly summary of natural disasters by an information service

International Strategy for Disaster Reduction
www.unisdr.org United Nations program to build disaster-resilient communities

CDC: Centers for Disease Control and Prevention
www.bt.cdc.gov/disasters/disease Information about health aspects of natural hazards from the U.S. Department of Health and Human Services

NOAA National Geophysical Data Center
www.ngdc.noaa.gov/hazard Natural hazards information from the National Oceanic and Atmospheric Administration National Geophysical Data Center

ABS Consulting Catastrophic Reports
www.absconsulting.com/catastrophe-reports.cfm Summaries of numerous natural disasters from ABS Consulting, an international insurance company

On the Companion Website

Test your knowledge in Hazard City. Analyze data and evaluate risk. This book has its own Companion Website where you will find Hazard City assignments which challenge you to make assessments and offer recommendations. You will also find animations on the Companion Website and additional resources, including reference material on minerals, rocks, maps, and geologic time.