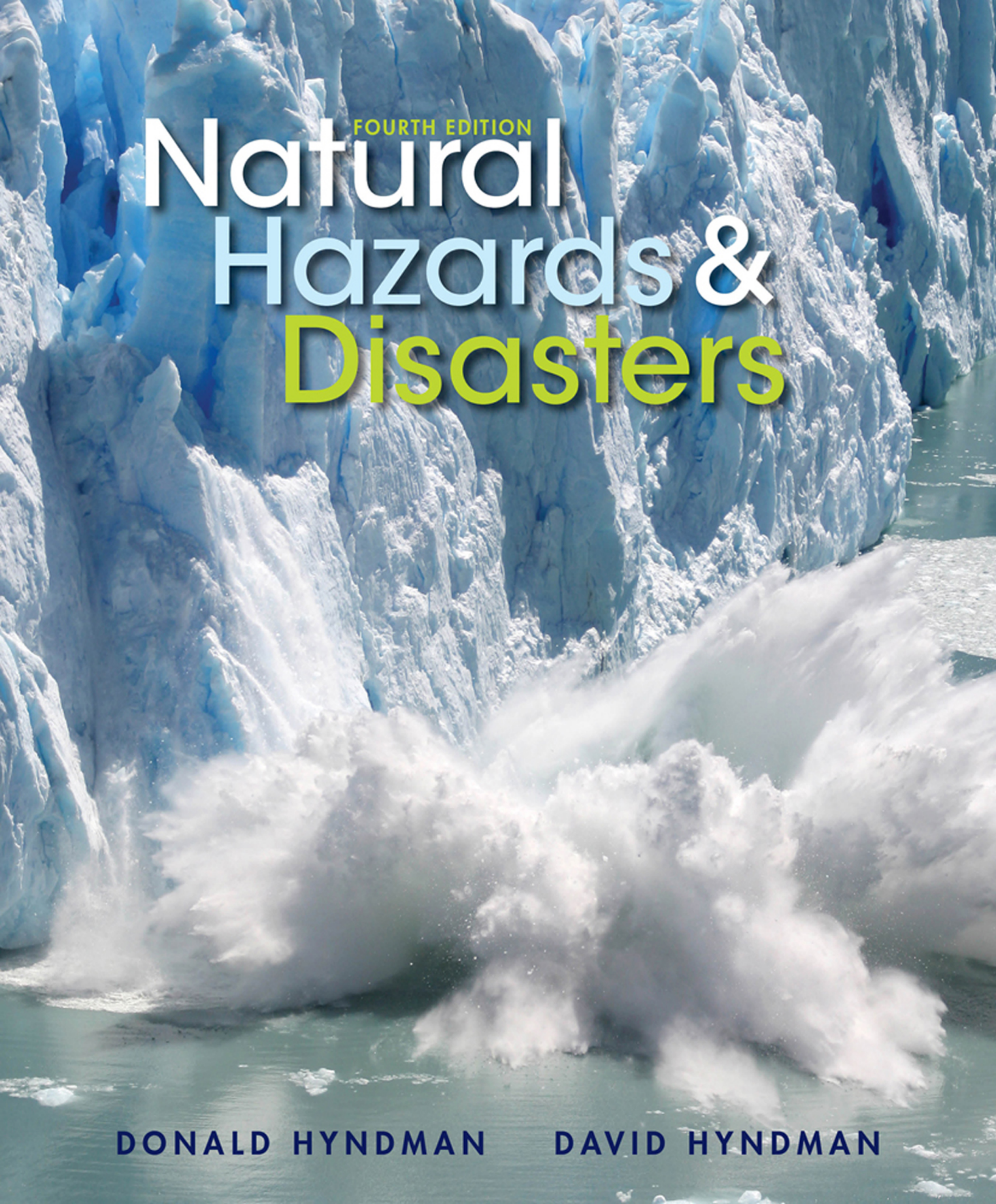

FOURTH EDITION

Natural Hazards & Disasters

DONALD HYNDMAN DAVID HYNDMAN

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To Shirley and Teresa

for their endless encouragement and patience

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Domenico Pellegriti/Photos.com

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Appendix 1: Geological Time Scale, and Appendix 2: Mineral and Rock Characteristics Related to Hazards, can be found online at www.cengagebrain.com/shop/isbn/9781133590811

Preface

The further you are from the last disaster,
the closer you are to the next.

Why We Wrote This Book

In teaching large introductory environmental and physical geology courses for many years—and, more recently, natural hazards courses—it has become clear to us that topics involving natural hazards are among the most interesting for students. Thus, we realize that employing this thematic focus can stimulate students to learn basic scientific concepts, to understand how science relates to their everyday lives, and to see how such knowledge can be used to help mitigate both physical and financial harm. For all of these reasons, natural hazards and disasters courses should achieve higher enrollments, have more interested students, and be more interesting and engaging than those taught in a traditional environmental or physical geology framework.

A common trend is to emphasize the hazards portions of physical and environmental geology texts while spending less time on subjects that do not engage the students. Students who previously had little interest in science can be awakened with a new curiosity about Earth and the processes that dramatically alter it. Science majors experience a heightened interest, with expanded and clarified understanding of natural processes. In response to years of student feedback and discussions with colleagues, we have reshaped our courses to focus on natural hazards.

Students who take a natural hazards course greatly improve their knowledge of the dynamic Earth processes that will affect them throughout their lives. They should be able to make educated choices about where to live and work. Perhaps some who take this course will become government officials or policy makers who can change some of the current culture that contributes to major losses from natural disasters.

Undergraduate college students, including nonscience majors, should find the writing clear and stimulating. Our emphasis is to provide them a basis for understanding important hazard-related processes and concepts. This book encourages students to grasp the fundamentals while still appreciating that most issues have complexities that are beyond the current state of scientific knowledge and involve societal aspects beyond the realm of science. Students not majoring in the geosciences may find motivation to continue studies in related areas and to share these experiences with others.

Natural hazards and disasters can be fascinating and even exciting for those who study them. Just don't be on the receiving end!

Living with Nature

Natural hazards, and the disasters that accompany many of them, are an ongoing societal problem. We continue to put ourselves in harm's way, through ignorance or a naïve belief that a looming hazard may affect others but not us. We choose to live in locations that are inherently unsafe.

The expectation that we can control nature through technological change stands in contrast to the fact that natural processes will ultimately prevail. We can choose to live *with* nature or we can try to fight it. Unfortunately, people who choose to live in hazardous locations tend to blame either "nature on the rampage" or others for permitting them to live there. People do not often make such poor choices willfully, but rather through their lack of awareness of natural processes. Even when they are aware of an extraordinary event that has affected someone else, they somehow believe "it won't happen to me." These themes are revisited throughout the book, as we relate principles to societal behavior and attitudes.

People often decide on their residence or business location based on a desire to live and work in scenic environments without understanding the hazards around them. Once they realize the risks, they often compound the hazards by attempting to modify the environment. Students who read this book should be able to avoid such decisions. Toward the end of the course, our students sometimes ask, "So where is a safe place to live?" We often reply that you can choose hazards that you are willing to deal with and live in a specific site or building that you know will minimize impact of that hazard.

It is our hope that by the time students have finished reading this textbook, they should have the basic knowledge to evaluate critically the risks they take and the decisions they make as voters, homeowners, and world citizens.

Our Approach

This text begins with an overview of the dynamic environment in which we live and the variability of natural processes, emphasizing the fact that most daily events are small and generally inconsequential. Larger events are less frequent, though most people understand that they can happen. Fortunately, giant events are infrequent; regrettably, most people are not even aware that such events can happen. Our focus here is on Earth and atmospheric hazards that appear rapidly, often without significant warning.

The main natural hazards covered in the book are earthquakes and volcanic eruptions; extremes of weather, including hurricanes; and floods, landslides, tsunami, wildfires, and asteroid impacts. For each, we examine the nature of the hazard, the factors that influence it, the dangers associated with the hazard, and the methods of forecasting or predicting such events. Throughout the book, we emphasize interrelationships between hazards, such as the fact that building dams on rivers often leads to greater coastal erosion. Similarly, wildfires generally make slopes more susceptible to floods, landslides, and mudflows.

The book includes chapters on dangers generated internally, including earthquakes, tsunami, and volcanic eruptions. Society has little control over the occurrence of such events but can mitigate their impacts through a deeper understanding that can afford more enlightened choices. The landslides section addresses hazards influenced by a combination of in-ground factors and weather, a topic that forms the basis for many of the following chapters. A chapter on sinkholes, subsidence, and swelling soils addresses other destructive in-ground hazards that we can, to some extent, mitigate and that are often subtle yet highly destructive.

The following hazard topics depend on an understanding of the dynamic variations in weather, thunderstorms and tornadoes, so we begin with a chapter to provide that background. The next chapter on climate change addresses the overarching atmospheric changes imposed by increasing carbon dioxide and other greenhouse gases that affect weather and many hazards described in the following chapters. Chapters on streams and floods begin with the characteristics and behavior of streams and how human interaction affects both a stream and the people around it. Chapters follow on wave and beach processes, hurricanes and Nor'easters, and wildfires. The final chapters discuss asteroid impacts and future concerns related to natural hazards.

The book is up-to-date and clearly organized, with most of its content derived from current scientific literature and from our own personal experience. It is packed with relevant content on natural hazards, the processes that control them, and the means of avoiding catastrophes. Numerous excellent and informative color photographs, many of them our own, illustrate scientific concepts associated with natural hazards. Diagrams and graphs are clear, straightforward, and instructive.

Extensive illustrations and Case in Point examples bring reality to the discussion of principles and processes. These cases tie the process-based discussions to individual cases and integrate relationships between them. They emphasize the natural processes and human factors that affect disaster outcomes. Illustrative cases are placed at the chapter end to not interrupt continuity of the discussion. We attempt to provide balanced coverage of natural hazards across North America and the rest of the world. As our global examples illustrate, although the same fundamental processes lead to natural hazards around the world, the impact of natural disasters can be profoundly different depending on factors such as economic conditions, security, and disaster preparedness.

End-of-chapter material also includes Critical View photos with paired questions, a list of Key Points, Key Terms, Questions for Review, and Critical Thinking Questions.

New to the Fourth Edition

With such a fast-changing and evolving subject as natural hazards, we have extensively revised and added to the content, with emphasis not only on recent events but also on those that best illustrate important issues. We have endeavored to keep breaking material as up-to-date as possible, both with new Cases in Point and in changes in governmental policy that affect people and their hazardous environments. For the first time in this edition we have added Critical Thinking Questions to focus on important issues related to each Case in Point. To make space for new Cases in Point, some older cases have been moved online, where they can be accessed in the CourseMate available at cengagebrain.com.

In recognition of the rapid advances in understanding of climate change and its increasing importance, we now present this important topic in a separate chapter. That material is thoroughly reorganized, rewritten, and revised, with numerous new graphs and photos. Graphs have been updated with the most recently available information. The weather content in the previous edition is now merged into a new chapter on Weather, Thunderstorms, and Tornadoes.

In addition to these overall changes, some significant additions to individual chapters include the following:

- **Chapter 1, Natural Hazards and Disasters**, is reedited and brought up-to-date, with new photos.
- **Chapter 2, Plate Tectonics and Physical Hazards**, is reorganized with improved diagrams, dramatic new photos, and improved descriptions.
- **Chapters 3** and **4, Earthquakes**, has new photos and diagrams, including one illustrating the likelihood of collapse of buildings constructed of different types of materials, and a new discussion of earthquake predictions and their ramifications. A new comparison looks

at the consequences of moderate-size earthquakes in developing countries in contrast to similar magnitude earthquakes in developed countries. It also has new Cases in Point on the giant 2011 subduction zone earthquake in northern Japan, and on Eastern North American Earthquakes, with emphasis on the northeastern United States and eastern Canada.

- **Chapter 5, Tsunami**, has important new coverage of the tragic March 2011 tsunami that obliterated much of the coastal zone onshore from the giant magnitude 9 subduction-zone earthquake offshore from northern Japan. It includes new tectonic maps and dramatic new photos.
- **Chapters 6** and **7, Volcanoes**, has tightened up and clarified text, with improved diagrams and photos.
- **Chapter 8, Landslides and Other Downslope Movements**, has dramatic new photos and new discussion of political issues that hinder notification of landslide hazards. A new Case in Point focuses on Los Angeles–area landslides.
- **Chapter 9, Sinkholes, Land Subsidence, and Swelling Soils** has been edited throughout.
- **Chapter 10, Weather, Thunderstorms, and Tornadoes**, newly combines material on weather with material that previously appeared in Chapter 15. The new chapter is completely reorganized and rewritten, with newly expanded sections such as Regional Winds including monsoons and Santa Ana winds. Violent tornado outbreaks in April 2011 across Oklahoma to Arkansas, Alabama, and North Carolina are discussed in the Chapter Opener and in a Case in Point. Another new Case in Point addresses the tragic tornado superoutbreak that struck Joplin, Missouri, and nearby areas in May 2011. Information is updated to most recent figures. The 2011 extreme drought in Texas is highlighted in a new Case in Point. Deadly heat waves are covered in a new Case in Point. There are many new photos and new and improved pieces of art.
- **Chapter 11, Climate Change**, is completely revised, reorganized, updated, and rewritten.

  New write-ups cover Earth's climate history, how the long-term temperature record is established, and how greenhouse gases force changes in thermal radiation passing through Earth's atmosphere. Studies of Greenland and Antarctic ice cores document hundreds of thousands of years of variation in atmospheric temperatures and carbon dioxide. New discussions cover oceanic carbon dioxide and their effect on ocean acidity, and feedback effects. New Cases in Point prompted by the Japanese tsunami and nuclear reactor meltdown include one on the Pros and Cons of Nuclear Energy.

  Many new photos, much better illustrations, and new and updated graphs.
- **Chapters 12** and **13, Streams and Floods**, have new and more illustrative photos, and two important new Cases in Point. One addresses the devastating August 2010 monsoon-driven floods in Pakistan at the foot of the Himalayas. The other examines the 2011 lower Mississippi Valley flood that threatened to either flood New Orleans or possibly lead to avulsion, which would drain much of the Mississippi flow down the Atchafalaya River to the Gulf of Mexico.
- **Chapter 14, Waves, Beaches, and Coastal Erosion**, has many new and improved photos and annotations.
- **Chapter 15, Hurricanes and Nor'easters**, is reorganized and has many new photos and updated tables and diagrams. Discussions are tightened up to provide better emphasis of important points. The ongoing uncertainty in predicting storm strength is addressed in the August 2011 example of Hurricane Irene.
- **Chapter 16, Wildfires**, has a new focus on the central Texas wildfires of 2011. It elaborates details of the Fire Triangle and has many new and more illustrative photos and wildfire maps.
- **Chapter 17, Impact of Asteroids and Comets,** has new photos and edits.
- **Chapter 18, The Future**, has new photos and updated graphs and maps. It has a new section on the 2011 catastrophic earthquake and tsunami in Japan and implications for other areas.

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Donald Hyndman and David Hyndman
September 2012

FOURTH EDITION

Natural Hazards & Disasters

Hurricane Irene weakened to a tropical storm before a final landfall at Brooklyn, New York, in August, 2011. Heavy rain from the storm caused widespread flooding. This home, built 20 m from the stream in Woodford Valley, Vermont, was among many destroyed.

Angela Drexel, FEMA.

Natural Hazards and Disasters

1

Living in Harm's Way

> Those who cannot remember the past are condemned to repeat it.
>
> —George Santayana (Spanish philosopher), 1905

Why would people choose to put their lives and property at risk? Large numbers of people around the world live and work in notoriously dangerous places—near volcanoes, in floodplains, or on active fault lines. Some are ignorant of potential disasters, but others even rebuild homes destroyed in previous disasters. Sometimes the reasons are cultural or economic. Because volcanic ash degrades into richly productive soil, the areas around volcanoes make good farmland. Large floodplains attract people because they provide good agricultural soil, inexpensive land, and natural transportation corridors. Some people live in a hazardous area because of their job. For understandable reasons, such people live in the wrong places. Hopefully they recognize the hazards and understand the processes involved so they can minimize their risk.

But people also crowd into dangerous areas for frivolous reasons. They build homes at the bases or tops of large cliffs for scenic views, not realizing that big sections can give way in landslides or rockfalls. They choose to live along edges of sea bluffs where they can enjoy ocean views, or on the beach to experience the ocean more intimately. But in these locations they also expose themselves to coastal storms. Others build beside picturesque streams without realizing they have put themselves in a flood zone. Far too many people build houses in the woods because they enjoy the seclusion and scenery of this natural setting without understanding their risk from wildfires.

Some natural catastrophe experts say these people have chosen to live in "idiot zones." But people don't usually reside in hazardous areas knowingly—they generally don't understand or recognize the hazards. However, they might as well choose to park their cars on a rarely used railroad track. Trains don't come frequently, but the next one might come any minute.

Catastrophic natural hazards are much harder to avoid than passing freight trains; we may not recognize the signs of imminent catastrophes because these events are infrequent. So many decades or centuries may pass between eruptions of a large volcano that most people forget it is active. Many people live so long on a valley floor without seeing a big flood that they forget it is a floodplain. The great disaster of a century ago is long forgotten, so folks move into the path of a calamity that may not arrive today or tomorrow, but it is just a matter of time.

Catastrophes in Nature

Everyday geologic processes, like erosion, have produced large effects over the course of Earth's vast history, carving out valleys or changing the shape of coastlines. While some processes operate slowly and gradually, infrequent catastrophic events have sudden and major impacts.

While streams may experience a few days or weeks of flooding each year, major floods occurring once every few decades do far more damage than all of the intervening floods put together. Soil moves slowly downslope by creep, but occasionally a huge part of a slope may slide. Pebbles roll down a rocky slope daily, but every once and a while a giant boulder comes crashing down (**FIGURE 1-1**). Mountains grow higher, sometimes slowly, but more commonly by sudden movements. During an earthquake, a mountain can abruptly rise several meters above an adjacent valley.

Some natural events involve disruption of a temporary *equilibrium*, or balance, between opposing influences. Unstable slopes, for example, may hang precariously for thousands of years, held there by friction along a slip surface until some small perturbation, such as water soaking in from a large rainstorm, sets them loose. Similarly, the opposite sides of a fault may stick until continuing stress finally tears them loose, triggering an earthquake. A bulge may form on a volcano as molten magma slowly rises into it; then it collapses as the volcano erupts. The behavior of these natural systems is somewhat analogous to a piece of plastic wrap that can stretch up to a point, until it suddenly tears.

People watching Earth processes move at their normal and unexciting pace rarely pause to imagine what might happen if that slow pace were suddenly punctuated by a major event. The fisherman enjoying a quiet afternoon trout fishing in a small stream can hardly imagine how a 100-year flood might transform the scene. Someone gazing at a serene, snow-covered mountain can hardly imagine it erupting in an explosive blast of hot ash followed by destructive mudflows racing down its flanks (**FIGURE 1-2**). Large or even gigantic events are a part of nature. Such abrupt events produce large results that can be disastrous if they affect people.

FIGURE 1-1 THE UNEXPECTED

BOB ZELLAR/Gazette Staff.

On October 9, 2010, a huge mass of sandstone separated from the Rimrocks cliffs in Billings, Montana, to destroy this house. Fortunately the owner was in another room. Note people in lower right.

FIGURE 1-2 **A LOOMING CATASTROPHE**

Donald Hyndman.

Orting, Washington, with spectacular views of Mt. Rainier, is built on a giant, ancient mudflow from the volcano. If mudflows happened in the past, they almost certainly will happen again.

FIGURE 1-3 **A DISASTER TAKES A HIGH TOLL**

REUTERS/UN Photo Logan Abassi/Handout.

Searchers dig for survivors of the Haiti earthquake of January 12, 2010, which killed more than 316,000, mostly in concrete and cinder block buildings with little or no reinforcing steel.

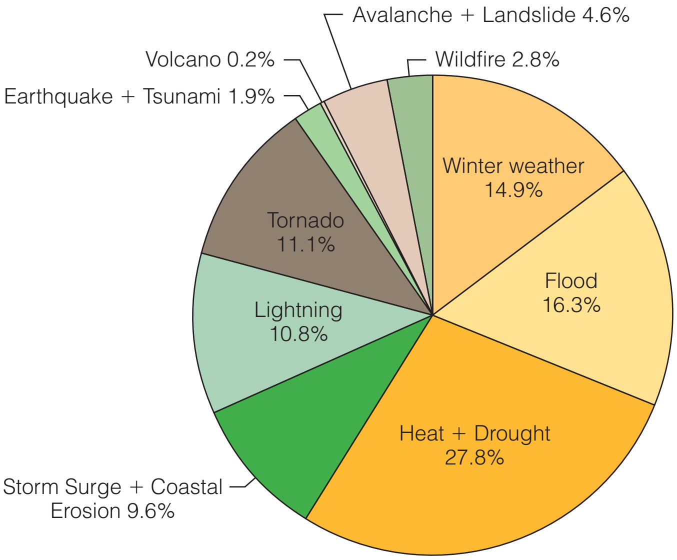
Human Impact of Natural Disasters

When a natural process poses a threat to human life or property, we call it a **natural hazard**. Many geologic processes are potentially hazardous. For example, streams flood as part of their natural process and become a hazard to those living nearby. A hazard is a **natural disaster** when the event causes significant damage to life or property. A moderate flood that spills over a floodplain every few years does not often wreak havoc, but when a major flood strikes, it may lead to a disaster that kills or displaces many people. When a natural event kills or injures large numbers of people or causes extensive property damage, it is called a **catastrophe**.

The potential impact of a natural disaster is related not only to the size of the event but also to its effect on the public. A natural event in a thinly populated area can hardly pose a major hazard. For example, the magnitude 7.6 earthquake that struck the southwest corner of New Zealand on July 15, 2009, was severe but posed little threat because it happened in a region with few people or buildings. In contrast, the much smaller January 12, 2010, magnitude 7.0 earthquake in Haiti killed more than 46,000 (**FIGURE 1-3**). In another example, the eruption of Mt. St. Helens in 1980 caused few fatalities and remarkably little property damage simply because the area surrounding the mountain is sparsely populated. On the other hand, a similar eruption of Vesuvius, in the heavily populated outskirts of Naples, Italy, could kill hundreds of thousands of people and cause property damage beyond reckoning.

You might assume that more fatalities occur as a result of dramatic events, such as large earthquakes, volcanic eruptions, hurricanes, or tornadoes. However, some of the most dramatic natural hazards occur infrequently or in restricted areas, so they cause fewer deaths than more common and less dramatic hazards such as floods or droughts. **FIGURE 1-4** shows the approximate

FIGURE 1-4 **HAZARD-RELATED DEATHS**



Compiled from many sources, including NOAA-NWS, USGS, USFS, and the NW Avalanche Center.

Approximate percentages of U.S. fatalities due to different groups of natural hazards from 1986 to 2008, when such data are readily available. For hazardous events that are rare or highly variable from year to year (earthquakes and tsunami, volcanic eruptions, and hurricanes), a 69-year record from 1940–2008 was used.

proportions of fatalities caused by typical natural hazards in the United States.

In the United States, heat and drought together account for the largest numbers of deaths. In fact, there were more U.S. deaths from heat waves between 1997 and 2008 than from any other type of natural hazard. In addition to heat stress, summer heat wave fatalities can result from dehydration and other factors; the very young, the very old, and the poor are affected the most. The same populations are vulnerable during winter weather, the third most deadly hazard in the United States. Winter deaths often involve hypothermia, but some surveys include, for example, auto accidents caused by icy roads.

Flooding is the second most deadly hazard in the United States, accounting for 16% of fatalities between 1986 and 2008. Fatalities from flooding can result from hurricane-driven floods; some surveys place them in the hurricane category rather than floods.

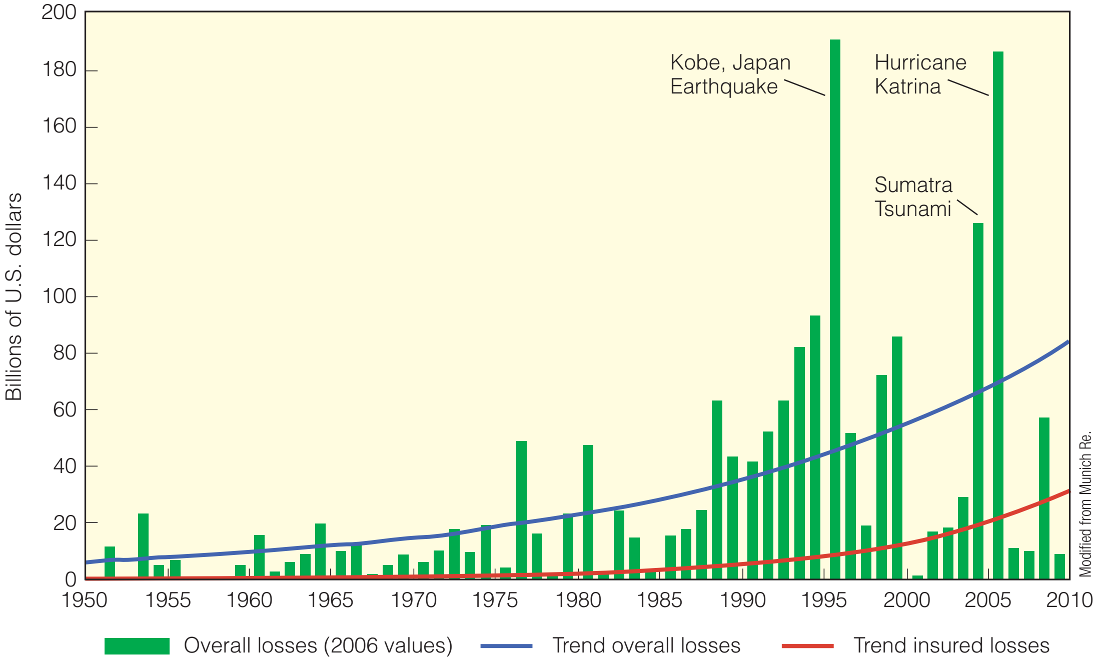
The number of deaths from a given hazard can vary significantly from year to year due to rare, major events. For example, there were about 1800 hurricane-related deaths in 2005 when Hurricane Katrina struck, compared with zero in other years. The rate of fatalities can also change over time as a result of safety measures or trends in leisure activities. Lightning deaths were once among the most common hazard-related causes of death, but associated casualties have declined significantly over the past 50 years, due in part to satellite radar and better weather forecasting. In contrast, avalanche deaths have increased significantly over a similar period, a change that seems to be associated with increased snowmobile use and skiing in mountain terrains.

Some natural hazards can cause serious physical damage to land or manmade structures, some are deadly for people, and others are destructive to both. The type of damage sustained as a result of a natural disaster also depends on the economic development of the area where it occurs. In developing countries, there are increasing numbers of deaths from natural disasters, whereas in developed countries, there are typically greater economic losses. This is because developing countries show dramatic increases in populations relegated to marginal and hazardous land on steep slopes and near rivers. Such populations also live in poorly constructed buildings and have less ability to evacuate as hazards loom; many lack transportation and financial ability to survive away from their homes.

For an example of this phenomenon, in 2010 earthquakes of similar sizes (magnitude 7.0) struck Haiti, a poor, developing country, and New Zealand, a prosperous, developed country. In Haiti, between 46,000 and 316,000 people were killed (U.S. government versus Haitian government estimates), mostly in the collapse of poorly built masonry buildings. Total damages were estimated to be about U.S. $7.8 billion. In contrast, only 185 people died in the New Zealand earthquake, which also occurred near a populous area. New Zealand's buildings were generally well constructed. Despite this, damages were still estimated to be about U.S. $6.5 billion.

The average annual cost of natural hazards has increased dramatically over the last several decades (**FIGURE 1-5**). This is due in part to the increase in world population, which

FIGURE 1-5 INCREASING COSTS OF NATURAL HAZARDS



Modified from Munich Re.

The cost of natural hazards is increasing worldwide. The 2011 earthquake and tsunami in Japan alone caused losses of about $210 billion, contributing to a record annual total of approximately $380 billion (not shown on the graph).

doubled in the 40 years between 1959 and 1999. By the end of 2011 it reached 7.05 billion. It is also a function of the increased value of properties at risk and to human migration to more hazardous areas. Overall losses have increased even faster than population growth. Population increases in urban and coastal settings result in more people occupying land that is subject to major natural events. In effect, people place themselves in the path of unusual, sometimes catastrophic events. Economic centers of society are increasingly concentrated in larger urban areas that tend to expand into regions previously considered undesirable, including those with greater exposure to natural hazards.

Predicting Catastrophe

A catastrophic natural event is unstoppable, so the best way to avoid it would be to predict its occurrence and get out of the way. Unfortunately, there have been few well-documented cases of accurate prediction, and even the ones on record may have involved luck more than science. Use of the same techniques in similar circumstances has resulted in false alarms and failure to correctly predict disasters.

Many people have sought to find predictable cycles in natural events. Those that occur at predictable intervals are called *cyclic events*. However, most recurrent events are not really cyclic; too many variables control their behavior. Even with cyclic events, overlapping cycles make resultant extremes noncyclic, which affects the predictability of a specific event. So far as anyone can tell, most episodes, large and small, occur at seemingly random and essentially unpredictable intervals.

Although scientists cannot predict exactly when an event will occur, based on past experience they can often **forecast** the occurrence of a hazardous event in a certain area within decades with an approximate percentage probability. For example, they can forecast that there will be a large earthquake in the San Francisco Bay region over the next several decades, or that Mt. Shasta will likely erupt sometime in the next few centuries. In many cases, their advice can greatly reduce the danger to lives and property.

Ask a stockbroker where the market is going, and you will probably hear that it will continue to do what it has done during recent weeks. Ask a scientist to forecast an event, and he or she will probably look to the geologically recent past and forecast more of the same; in other words, *the past is the key to the future*. Most forecasts are based on linear projections of past experience. However, we must be careful to look at a long enough sample of the past to see prospects for the future. Many people lose money in the stock market because *short-term* past experience is not always a good indicator of what will happen in the future.

Similarly, statistical forecasts are simply a refinement of past recorded experiences. They are typically expressed as **recurrence intervals** that relate to the probability that a natural event of a particular size, or **magnitude**, will happen within a certain period of time, or with a certain **frequency**. For example, the history of movement along a fault may indicate that it is likely to produce an earthquake of a certain size once every hundred years on average.

A recurrence interval is not, however, a fixed schedule for events. Recurrence intervals can tell us that a 50-year flood is likely to happen sometime in the next several decades but not that such floods occur at intervals of 50 years. Many people do not realize the inherent danger of an unusual occurrence, or they believe that they will not be affected in their lifetimes because such events occur infrequently. That inference often incorrectly assumes that the probability of another severe event is lower for a considerable length of time after a major event. In fact, even if a 50-year flood occurred last year, that does not indicate that there will not be another one this year or for the next ten years.

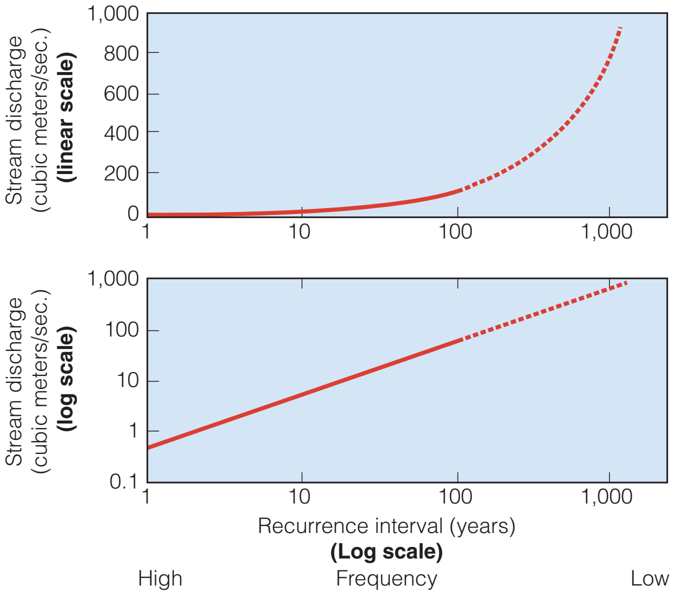
To understand why this is the case, take a minute to review probabilities. Flip a coin, and the chance that it will come up heads is 50%. Flip it again, and the chance is again 50%. If it comes up heads five times in a row, the next flip still has a 50% chance of coming up heads. So it goes with floods and many other kinds of apparently random natural events. The chance that someone's favorite fishing stream will stage a 50-year flood this year and every year is 1 in 50, regardless of what it may have done during the last few years.

As an example of the limitations of recurrence intervals, consider the case of Tokyo. This enormous city is subject to devastating earthquakes that for more than 500 years came at intervals of close to 70 years. The last major earthquake ravaged Tokyo in 1923, so everyone involved awaited 1993 with considerable consternation. The risk steadily increased during those years as both the population and the strain across the fault zone grew. Nearly 20 years later, no large earthquake has occurred. Obviously, the recurrence interval does not predict events at equal intervals, in spite of the 500-year Japanese historical record. Nonetheless, the knowledge that scientists have of the pattern of occurrences here helps them assess risk and prepare for the eventual earthquake. Experts forecast that there is a 70% chance that a major quake will strike that region in the next 30 years.

To estimate the recurrence interval of a particular kind of natural event, we typically plot a graph of each event size versus the time interval between sequential individual events. Such plots often make curved lines that cannot be reliably extrapolated to larger events that might lurk in the future (**FIGURE 1-6**). Plotting the same data on a logarithmic scale often leads to a straight-line graph that can be extrapolated to values larger than those in the historical record. Whether the extrapolation produces a reliable result is another question.

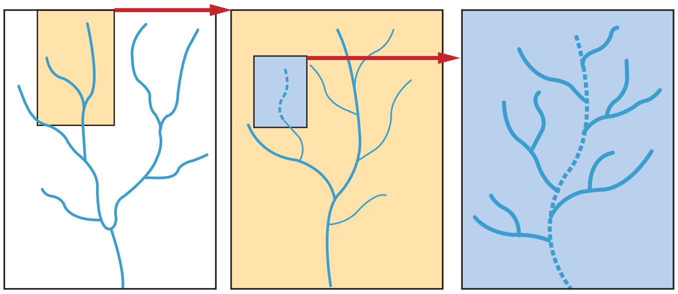
The probability of the occurrence of an event is related to the magnitude of the event. We see huge numbers of small events, many fewer large events, and only a rare giant

FIGURE 1-6 RECURRENCE INTERVAL



If major events are plotted on a linear scale (top graph, vertical axis), the results often fall along a curve that cannot be extrapolated to larger possible future events. If the same events are plotted on a logarithmic scale (bottom graph), the results often fall along a straight line that can use historical data to forecast what to expect in future events.

FIGURE 1-7 FRACTAL SYSTEMS



The general style of a branching stream looks similar regardless of scale—from a less-detailed map on the left to the most-detailed map on the right.

By the Numbers 1-1

Relationship between Frequency and Magnitude

$M \propto 1/f$

Magnitude (M) of an event is inversely proportional to **frequency (f)** of the type of event.

event (**By the Numbers 1-1:** Relationship between Frequency and Magnitude). The infrequent occurrence of giant events means it is hard to study them, but it is often rewarding to study small events because they may well be smaller-scale models of their uncommon larger counterparts that may occur in the future.

Many geologic features look the same regardless of their size, a quality that makes them **fractal**. A broadly generalized map of the United States might show the Mississippi River with no tributaries smaller than the Ohio and Missouri rivers. A more detailed map shows many smaller tributaries. An even more detailed map shows still more. The number of tributaries depends on the scale of the map, but the general branching pattern looks *similar across a wide range of scales* (**FIGURE 1-7**). Patterns apparent on a small scale quite commonly resemble patterns that exist on much larger scales that cannot be easily perceived. This means that small events may provide insight into huge ones that occurred in the distant past but are larger than any seen in historical time; we may find evidence of these big events if we search. The geologic record provides evidence for massive natural catastrophes in the Earth's distant past, such as the impact of a large asteroid that caused the extinction of the dinosaurs. We need to be aware of the potential for such extreme events in the future.

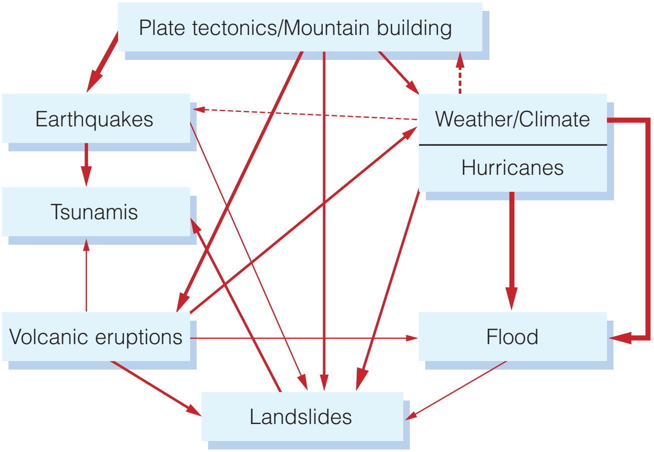
It is impossible in our current state of knowledge to predict most natural events, even if we understand in a general way what controls them. The problem of avoiding natural disasters is like the problem drivers face in avoiding collisions with trains. They can do nothing to prevent trains, so they must look and listen. We have no way of knowing how firm the natural restraints on a landslide, fault, or volcano may be. We also do not generally know what changes are occurring at depth. But we can be confident that the landslide or fault will eventually move or that the volcano will erupt. And we can reasonably understand what those events will involve when they finally happen.

Relationships among Events

Although randomness is a factor in forecasting disasters, most natural events do not occur as randomly as tosses of a coin. Some events are directly related to others—formed as a direct consequence of another event (**FIGURE 1-8**). For example, the slow movement of Earth's huge outer layers colliding or sliding past one another clearly explains the driving forces behind volcanic eruptions and earthquakes. Heavy or prolonged rainfall can cause a flood or a landslide. But are some events unrelated? Could any of the arrows in Figure 1-8 be reversed?

Past events can also create a contingency that influences future events. It is certainly true, for example, that sudden movement on a fault causes an earthquake. But the same movement also changes the stress on other parts of the fault and probably on other faults in the region, so the next earthquake will likely differ considerably from the last. Similar complex relationships arise with many other types of destructive natural events.

FIGURE 1-8 INTERACTIONS AMONG NATURAL HAZARDS



Some natural disasters are directly related to others. The bolder arrows in this flowchart indicate stronger influences. Can you think of others?

Some processes result in still more rapid changes—a **feedback effect**. For example, global warming causes more rapid melting of Arctic sea ice. The resulting darker sea water absorbs more of the sun's energy than the white ice, which in turn causes even more sea ice melting. Similarly, global warming causes faster melting of the Greenland and Antarctic ice sheets. More meltwater pours through fractures to the base of the ice, where it lubricates movement, accelerating the flow of ice toward the ocean. This leads to more rapid crumbling of the toes of glaciers to form icebergs that melt in the ocean.

In other cases, an increase in one factor may actually lead to a decrease in a related result. Often as costs of a product or service go up, usage goes down. With increased costs of hydrocarbon fuels, people conserve more and thus burn less. A rapid increase in the price of gasoline in 2008 led people to drive less and to trade in large SUVs and trucks for smaller cars. In some places, commuter train, bus, and bicycle use increased dramatically. With the rising cost of electricity, people are switching to compact fluorescent bulbs and using less air conditioning. These changes had a noticeable effect on greenhouse gases and their effect on climate change (discussed in Chapter 11).

Sometimes major natural events are preceded by a series of smaller **precursor events**, which may warn of the impending disaster. Geologists studying the stirrings of Mt. St. Helens, Washington, before its catastrophic eruption in 1980 monitored swarms of earthquakes and decided that most of these recorded the movements of rising magma as it squeezed upward, expanding the volcano. Precursor events alert scientists to the potential for larger events, but events that appear to be precursors are not always followed by a major event.

The relationships among events are not always clear. For example, an earthquake occurred at the instant Mt. St. Helens exploded, and the expanding bulge over the rising magma collapsed in a huge landslide. Neither the landslide nor the earthquake caused the formation of molten magma, but did they trigger the final eruption? If so, which one triggered the other—the earthquake, the landslide, or the eruption? One or more of these possibilities could be true in different cases.

Events can also overlap to amplify an effect. Most natural disasters happen when a number of unrelated variables overlap in such a way that they reinforce each other to amplify an effect. If the high water of a hurricane storm surge happens to arrive at the coast during the daily high tide, the two reinforce each other to produce a much higher storm surge (**FIGURE 1-9**). If this occurs on a section of coast that happens to have a large population, then the situation can become a major disaster. Such a coincidence caused the catastrophic hurricane that killed 8000 people in Galveston, Texas, in 1900.

Mitigating Hazards

Because natural disasters are not easily predicted, it falls to governments and individuals to assess their risk and prepare for and mitigate the effects of disasters. **Mitigation** refers to efforts to prepare for a disaster and reduce its damage. Mitigation can include engineering projects such as levees, as well as government policies and public education efforts. In each chapter of this book, we examine mitigation strategies related to specific disasters.

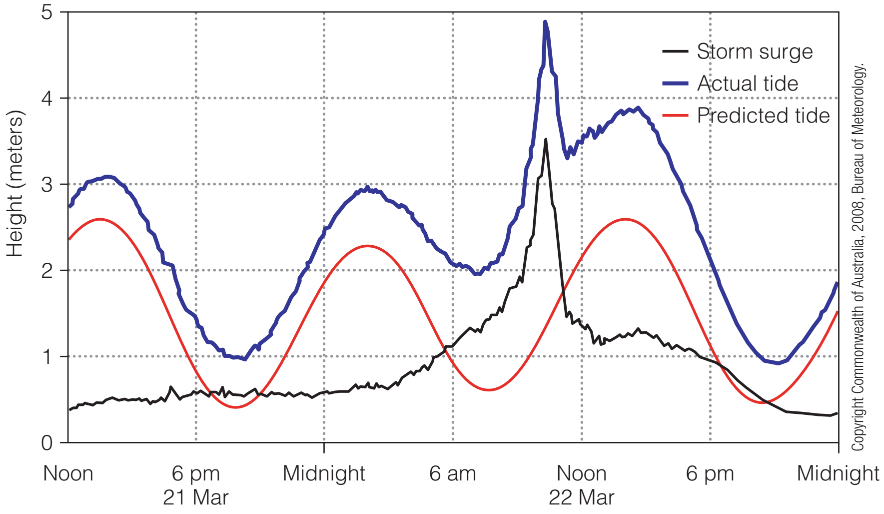
Land-Use Planning

One way to reduce losses from natural disasters is to find out where disasters are likely to occur and restrict development there, using **land-use planning**. Ideally, we would prevent development along major active faults by reserving that land for parks and natural areas. We should also limit housing and industrial development on floodplains to minimize flood damage and along the coast to reduce hurricane and coastal erosion losses. Limiting building near active volcanoes and the river valleys that drain them can curtail the hazards associated with eruptions.

It is hard, however, to impose land-use restrictions in many areas because such imposition tends to come too late. Many hazardous areas are already heavily populated, perhaps even saturated with inhabitants. Many people want to live as close as they can to a coast or a river and resent being told that they cannot; they oppose attempts at land-use restrictions because they feel it infringes on their property rights. Almost any attempt to regulate land use in the public interest is likely to ignite intense political and legal opposition.

Developers, companies, and even governments often aggravate hazards by allowing—or even encouraging—people to move into hazardous areas. Many developers and private individuals view restrictive zoning as an infringement

FIGURE 1-9 **AMPLIFICATION OF OVERLAPPING EFFECTS**



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If events overlap, their effects can amplify one another. In this example, a storm surge (black line) can be especially high if it coincides with high tide (red line). The blue line shows the much higher tide that resulted when the tide overlapped with the storm surge.

on their rights to do as they wish with their land. Developers, real estate agents, and some companies are reluctant to admit the existence of hazards that may affect a property for fear of lessening its value and scaring off potential clients (**FIGURE 1-10**). Most local governments consider news of hazards bad for growth and business. They shun restrictive zoning or minimize possible dangers for fear of inhibiting improvements in their tax base. As in other venues, different groups have different objectives. Some are most concerned with economics, others with safety, still others with the environment.

FIGURE 1-10 **RISKY DEVELOPMENT**

David Hyndman.

Some developers seem unconcerned with the hazards that may affect the property they sell. High spring runoff floods this proposed development site in Missoula, Montana.

Insurance

Some mitigation strategies are designed to help with recovery once a disaster occurs. **Insurance** is one way to lessen the financial impact of disasters after the fact. People buy property insurance to shield themselves from major losses they cannot afford. Insurance companies use a formula for risk to establish premium rates for policies. **Risk** is essentially a hazard considered in the light of its recurrence interval and expected costs (**By the Numbers 1-2:** Assessing Risk). The greater the hazard and the shorter its recurrence interval, the greater the risk.

In most cases, a company can estimate the cost of a hazard event to a useful degree of accuracy, but they can only guess at its recurrence interval. The history of experience with a given natural hazard in any area of North America is typically less than 200 years. Large events recur, on average, only every few decades or few hundred years or even more rarely. In some cases, most notably floods, the hazard and its recurrence interval are both firmly enough established to support a rational estimate of risk. But the amount of risk

By the Numbers 1-2

Assessing Risk

Insurance costs are actuarial: they are based on past experience. For insurance, a “hazard” is a condition that increases the severity or frequency of a loss.

Risk is proportional to [probability of occurrence] × [cost of the probable loss from the event].

and the potential cost to a company can be so large that a catastrophic event would put the company out of business.

The uncertainties of estimating risk make it impossible for private insurance companies to offer affordable policies that protect against many kinds of natural disasters. As a result, insurance is generally available for events that present relatively little risk, mainly those with more or less dependably long recurrence intervals. In high-risk areas for a particular hazard, for example Florida or Louisiana for hurricanes and sinkholes, insurance companies may either charge very high insurance premiums to cover their risks or refuse to cover such hazards. In those states, non-profit state programs have been formed to provide insurance that is not otherwise available. In California, where the risks and expected costs of earthquake damages are very high, insurance companies are required by law to provide earthquake coverage. As a result, companies now make insurance available through the California Earthquake Authority, a consortium of companies, in order to spread out their risks.

Insurance for some natural hazards is simply not available. Landslides, most mudflows, and ground settling or swelling are too risky for companies, and each potential hazard area would have to be individually studied by a scientist or engineer who specialized in such a hazard. The large number of variables makes the risk too difficult to quantify; it is too expensive to estimate the different risks for the relatively small areas involved.

People who lose their houses in landslides may not only lose what they have already paid into the mortgage or home loan, but can be obligated to continue paying off a loan on a house that no longer exists. In some states, such as California, there are laws preventing what are called "deficiency judgments" against such mortgage holders. This permits home owners to walk away from their destroyed homes, and the bank cannot go after them for the remainder of the loan.

The Role of Government

The U.S. and Canadian governments are involved in many aspects of natural hazard mitigation. They conduct and sponsor research into the nature and behavior of many kinds of natural disasters. They attempt to forecast hazardous events and mitigate the damage and loss of life they cause. Governmental programs are split among several agencies.

The U.S. Geological Survey (USGS) and Geological Survey of Canada (GSC) are heavily involved in earthquake and volcano research, as well as in studying and monitoring stream behavior and flow. The National Weather Service monitors rainfall and severe weather and uses this and the USGS data to try to forecast storms and floods.

The Federal Emergency Management Agency (FEMA) was created in 1979, primarily to bring order to the chaos of relief efforts that seemed invariably to emerge after natural disasters. After the hugely destructive Midwestern floods of 1993, it has increasingly emphasized hazard reduction. Rather than pay victims to rebuild in their original unsafe locations, such as floodplains, the agency now focuses on relocating them. Passage of the Disaster Mitigation Act in 2000 signals greater emphasis on identifying and assessing risks before natural disasters strike and taking steps to minimize potential losses. The act funds programs for hazard mitigation and disaster relief through FEMA, the U.S. Forest Service, and the Bureau of Land Management.

To determine risk levels and estimate loss potential from earthquakes, federal agencies such as FEMA use a computer system called HAZUS (Hazard United States). It integrates a group of interdependent modules that include potential hazards, inventories of the hazards, direct damages, induced damages, direct economic and social losses, and indirect losses.

Unfortunately, some government policies can be counterproductive, especially when politics enter the equation. In some cases, disaster assistance continues to be provided without a large cost-sharing component from states and local organizations. Thus, local governments continue to lobby Congress for funds to pay for losses but lack incentive to do much about the causes. FEMA is charged with rendering assistance following disasters; it continues to provide funds for victims of earthquakes, floods, hurricanes, and other hazards. It remains reactive to disasters, as it should be, but is only beginning to be proactive in eliminating the causes of future disasters. Congress continues to fund multimillion-dollar Army Corps of Engineers projects to build levees along rivers and replenish sand on beaches. The Small Business Administration disaster loan program continues to subsidize credit to finance rebuilding in hazardous locations. The federal tax code also subsidizes building in both safe and hazardous sites. Real estate developers benefit from tax deductions, and ownership costs, such as mortgage interest and property taxes, can be deducted from income. A part of uninsured "casualty losses" can still be deducted from a disaster victim's income taxes. Such policies do not discourage future damages from natural hazards.

The Role of Public Education

Much is now known about natural hazards and the negative impacts they have on people and their property. It would seem obvious that any logical person would avoid such potential damages or at least modify their behavior or their property to minimize such effects. However, most people are not knowledgeable about potential hazards, and human nature is not always rational.

Unfortunately, a person who has not been adversely affected in a serious way is much less likely to take specific steps to reduce the consequences of a potential hazard. Migration of the population toward the Gulf and Atlantic coasts accelerated in the last half of the twentieth century and still continues. Most of those new residents, including developers and builders, are not very familiar with the power of coastal storms. Even where a hazard is apparent, people are slow to respond. Is it likely to happen? Will I have a major loss? Can I do anything to reduce the loss? How much time will it take, and how much will it cost? Who else has experienced such a hazard?

Several federal agencies have programs to foster public awareness and education. The Emergency Management Institute—in cooperation with FEMA, the National Oceanic and Atmospheric Administration (NOAA), USGS, and other agencies—provides courses and workshops to educate the public and governmental officials. Some state emergency management agencies, in partnership with FEMA and other federal entities, provide workshops, reports, and informational materials on specific natural hazards.

In Japan, where the risk of earthquakes is high, the government places a strong emphasis on preparing the public through drills and education programs (**FIGURE 1-11**).

Some people are receptive to making changes in the face of potential hazards. Some are not. The distinction depends partly on knowledge, experience, and whether they feel vulnerable. A person whose house was badly damaged in an earthquake is likely to either move to a less earthquake-prone area or live in a house that is well braced for earthquake resistance. A similar person losing his home to a landslide is more likely to avoid living near a steep slope. The best window of opportunity for effective hazard reduction is immediately following a disaster of the same type. Studies show that this opportunity is short—generally, not more than two or three months.

FIGURE 1-11 **EARTHQUAKE DRILL**

YOSHIKAZU TSUNO/AFP/Getty Images.

In Japan, an earthquake drill is held every year on September 1. School children are trained to take cover under desks or tables when they feel an earthquake.

Living with Nature

Catastrophic events are natural and normal processes, but the most common human reaction to a current or potential catastrophe is to try to stop ongoing damage by controlling nature. In our modern world, it is sometimes hard to believe that scientists and engineers cannot protect us from natural disasters by predicting them or building barriers to withstand them.

Unfortunately, we cannot change natural system behaviors, because we cannot change natural laws. Most commonly, our attempts tend only to temporarily hinder a natural process while diverting its damaging energy to other locations. In other cases, our attempts cause energy to build up and produce more severe damage later.

If, through lack of forethought, you find yourself in a hazardous location, what can you do about it? You might build a levee to protect your land from flooding. Or you might build a rock wall in the surf to stop sand from leaving your beach and undercutting the hill under your house.

If you do any of these things, however, you merely transfer the problem elsewhere, to someone else, or to a later point in time. For example, if you build a levee to prevent a river from spreading over a floodplain and damaging your property, the flood level past the levee will be higher than it would have been without it. Constricting river flow with a levee also backs up floodwater, potentially causing flooding of an upstream neighbor's property. Deeper water also flows faster past your levee, so it may cause more erosion of a downstream neighbor's riverbanks.

Individually and as a society, we must learn to live with nature, not try to control it. Mitigation efforts typically seek to avoid or eliminate a hazard through engineering. Such efforts require financing from governments, individuals, or groups likely to be affected. Less commonly, but more appropriately, mitigation requires changes in human behavior. Behavioral change is usually much less expensive and more permanent than the necessary engineering work. In recent years, governmental agencies have begun to learn this lesson, generally through their own mistakes. In a few places along the Missouri and Sacramento Rivers, for example, some levees are being reconstructed back from the riverbanks to permit water to spread out on floodplains during future floods.

In reality, few places are completely free of all natural hazards. Given the constraints of health, education, and livelihood, we can minimize living in the most hazardous areas. We can avoid one type of hazard while tolerating a less ominous one. Above all, we can educate ourselves about natural hazards and their controls, how to recognize them, and how to anticipate increased chances of a disaster. Although prediction may not be realistic, we can forecast the likelihood of certain types of occurrence that may endanger our property or physical safety. This book provides the background you need to be knowledgeable about natural hazards.

Chapter Review

Key Points

Catastrophes in Nature

- Many natural processes that we see are slow and gradual, but occasional sudden or dramatic events can be hazardous to humans.
- Hazards are natural processes that pose a threat to people or their property.
- A large event becomes a disaster or catastrophe only when it affects people or their property. Large natural events have always occurred but do not become disasters until people place themselves in harm's way.
- More common and less dramatic hazards, such as heat, cold, and flooding, often have higher associated fatalities than rare but dramatic hazards, such as earthquakes and volcanoes. **FIGURE 1-4**.
- The cost of natural hazards is increasing worldwide as a result of growth in population and development. Developed countries suffer greater financial losses in a major disaster; poor countries suffer more fatalities. **FIGURE 1-5**.

Predicting Catastrophe

- Events are often neither cyclic nor completely random.
- Although the precise date and time for a disaster cannot be predicted, understanding the natural processes that control them allows scientists to forecast the probability of a disaster striking a particular area.
- Statistical predictions or recurrence intervals are average expectations based on past experience. **FIGURE 1-6**.
- There are numerous small events, fewer larger events, and only rarely a giant event. We are familiar with the common small events but, because they come along so infrequently, we tend not to expect the giant events that can create major catastrophes. **By the Numbers 1-1.**
- Many natural features and processes are fractal—that is, they have similarities across a broad range of sizes. Large events tend to have characteristics that are similar to smaller events. **FIGURE 1-7**.

Relationships among Events

- Different types of natural hazards often interact with or influence one another. **FIGURE 1-8**.
- Natural processes can sometimes trigger other, more rapid changes.
- Overlapping influences of multiple factors can lead to the extraordinarily large events that often become disasters. **FIGURE 1-9**.

Mitigating Hazards

- Mitigation involves efforts to avoid disasters rather than merely dealing with the resulting damages.
- Land-use planning can prevent development of hazardous areas, but it often faces opposition.
- Insurance can help people recover from a disaster by providing financial compensation for losses.
- Risk is proportional to the probability of occurrence and the cost from such an occurrence. **By the Numbers 1-2.**
- People need to be educated about natural processes and how to learn to live with and avoid the hazards around them.

Living with Nature

- Erecting a barrier to some hazard will typically transfer the hazard to another location or to a later point in time.
- Humans need to learn to live with some natural events rather than trying to control them.

Key Terms

catastrophe, p. 3
feedback effect, p. 7
forecast, p. 5
fractal, p. 6
frequency, p. 5
insurance, p. 8
land-use planning, p. 7
magnitude, p. 5
mitigation, p. 7
natural disaster, p. 3
natural hazard, p. 3
precursor event, p. 7
recurrence interval, p. 5
risk, p. 8

Questions for Review

1. What are some of the reasons people live in geologically dangerous areas?
2. Is the geologic landscape controlled by gradual and unrelenting processes or intermittent large events with little action in between? Provide an example to illustrate.
3. Some natural disasters happen when the equilibrium of a system is disrupted. What are some examples?
4. Contrast the general nature of catastrophic losses in developed countries versus poor countries. Explain why this is the case.
5. What are the three most deadly hazards in the United States?
6. What are the main reasons for the ever-increasing costs of catastrophic events?
7. Why are most natural events not perfectly cyclic, even though some processes that influence them are cyclic?
8. What is the difference between prediction and forecast?
9. Give an example of a feedback effect in natural processes.
10. Give an example of a fractal system.
11. Describe the general relationship between the frequency and magnitude of an event.
12. If the recurrence interval for a stream flood has been established at 50 years and the stream flooded last year, what is the probability of the stream flooding again this year?
13. When an insurance company decides on the cost of an insurance policy for a natural hazard, what are the two main deciding factors?
14. When people or governmental agencies try to restrict or control the activities of nature, what is the general result?

Critical Thinking Questions

1. If people should not live in especially dangerous areas, what beneficial uses could there be for those areas? What are some examples?
2. What responsibility does the government have to ensure that its citizens are safe from natural hazards? Conversely, what freedom should individuals have to choose where they want to live?
3. A small town suffering economic losses from the closure of a factory considers a plan to build a new housing development in an area where there is a record of infrequent flooding. Make a case for and against this development. In your case for the development, stipulate what measures need to be taken to minimize hazards.
4. Should people be permitted to build in hazardous sites? Should they expect government help in case of a disaster? Should they be required to pay for all costs incurred in a disaster?

The Himalayas of Tibet rise along the collision zone between the northward-moving tectonic plate containing India and the Eurasian plate.

Donald Hyndman

Plate Tectonics and Physical Hazards

2

The Big Picture

Why are mountain ranges commonly near coastlines? Why are some of these mountains volcanoes that erupt molten rocks? What causes giant tsunami waves, and why do most originate near mountainous coastlines? Why are most devastating earthquakes near those same coastlines? Why do the opposite sides of the Atlantic Ocean look like they would match? Giant areas of the upper part of Earth move around, grind sideways and collide, or sink into the hot interior of the planet, where they cause melting of rocks and formation of volcanoes. Those collisions between plates squeeze up and maintain high mountain ranges, even as landslides and rivers erode them away. Those same collisions can generate giant tsunami waves. To understand where and when these hazards occur, we need to understand the forces that drive them. Without the movements of Earth's plates, there would be no high mountain ranges to cause rockfalls and other landslides or for rivers to flow down. Those same mountain ranges even have a big effect on weather and climate. All of these processes ultimately drive natural hazards.

Earth Structure

At the center of Earth is its **core**, surrounded by the thick **mantle** and covered by the much thinner **crust** (**FIGURE 2-1A**). The distinction between the mantle and the crust is based on rock composition. We also distinguish between two zones of Earth based on rock rigidity or strength. The stiff, rigid outer rind of Earth is called the **lithosphere**, and the inner, hotter, more easily deformed part is called the **asthenosphere** (**FIGURE 2-1B**). Continental lithosphere includes silica-rich crust 30 to 50 km thick, underlain by the upper part of the mantle (see Appendix 2 online for detailed rock compositions). Oceanic lithosphere is generally only about 60 km thick; its top 7 km are a low-silica basalt-composition crust. Continental crust is largely composed of high-silica-content minerals, which give it the lowest density (2.7 g/cm^3) of the major regions on Earth. Oceanic crust is denser (3 g/cm^3) because it contains more iron- and magnesium-rich minerals.

Because we do not have direct observations of crustal thickness, scientists measure the gravitational attraction of Earth (which is greater over denser rocks) and analyze the velocity and timing of seismic waves as they radiate away from earthquake epicenters to provide indirect evidence of the density, velocity, and thickness of subsurface materials.

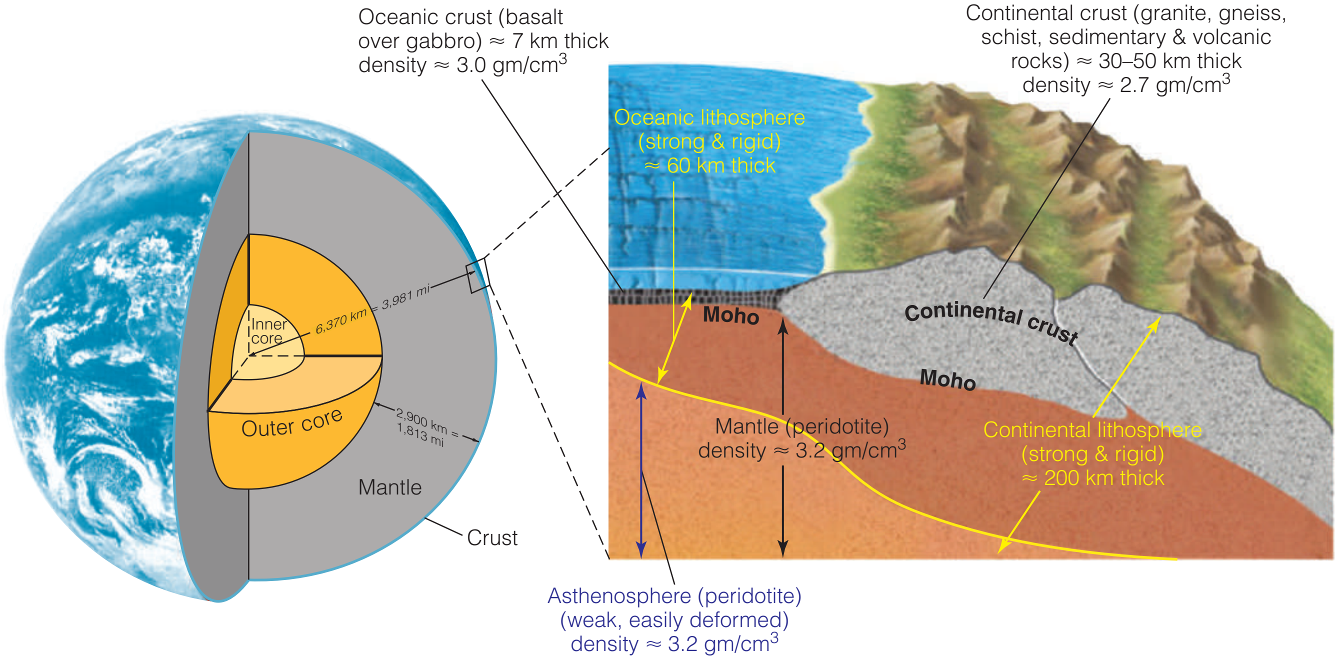
The boundary between Earth's crust and mantle has been identified as a major difference in density that we call the Mohorovičić discontinuity or *Moho*. It marks the base of the continental crust.

Deeper in the mantle, the next major change in material properties occurs at the boundary between the strong, rigid lithosphere above and the weak, deformable asthenosphere below. This boundary was first identified as a near-horizontal zone of lower velocity earthquake waves that move at several kilometers per second. The so-called low-velocity zone is concentrated at the top of the asthenosphere and may contain a small amount of molten basalt over a zone a few hundred kilometers thick. The cold, rigid lithosphere rides on that asthenosphere made weak by its higher temperatures and perhaps also by small melt contents.

Earth's topography clearly shows the continents standing high relative to the ocean basins (**FIGURE 2-2**). The thin lithosphere of the ocean basins stands low; the continents with their thick lower-density lithosphere float high and sink deep into the asthenosphere.

The elevation difference between the continental and oceanic crusts is explained by the concept of **isostacy**, or buoyancy. A floating solid object displaces an amount of liquid with the same mass. Although Earth's mantle is not liquid, its high temperature (above 450°C or 810°F)

FIGURE 2-1 EARTH STRUCTURE

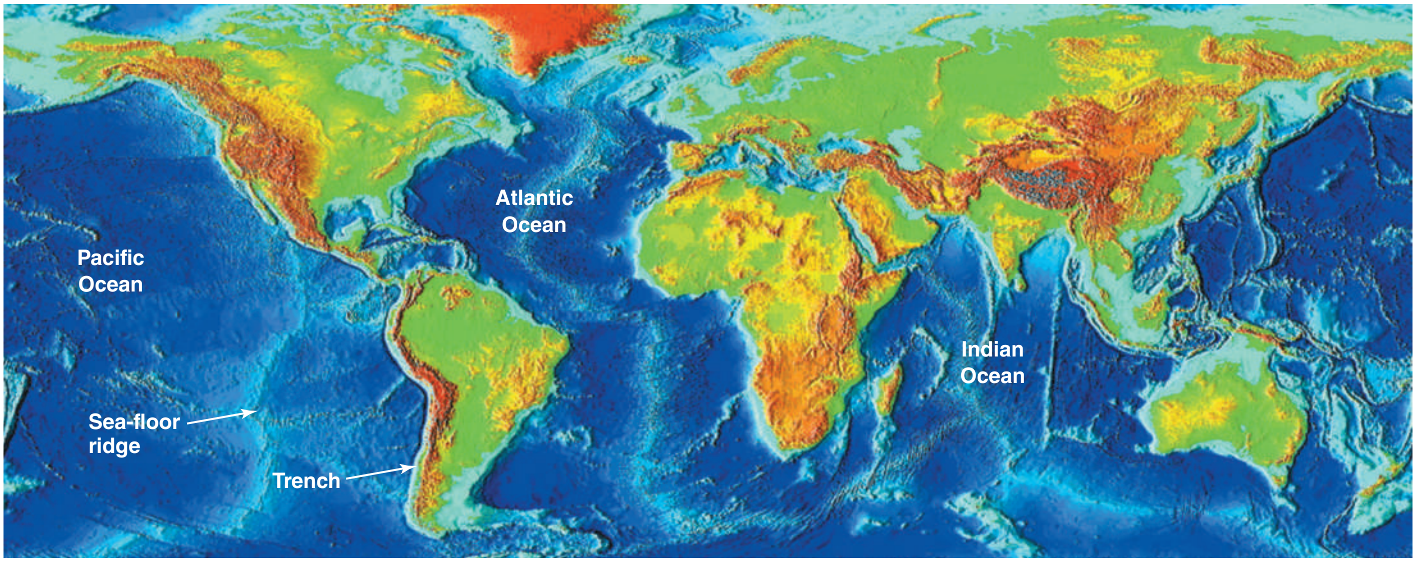


Modified from Garrison.

A. A slice into Earth shows a solid inner core and a liquid outer core, both composed of nickel-iron. Peridotite in Earth's mantle makes up most of the volume of Earth. Earth's crust, on which we live, is as thin as a line at this scale.

B. This expanded view shows the relative thickness and density of different parts of Earth's mantle and crust. The boundary between the mantle and crust is called the *Moho*.

FIGURE 2-2 MOUNTAIN TOPOGRAPHY



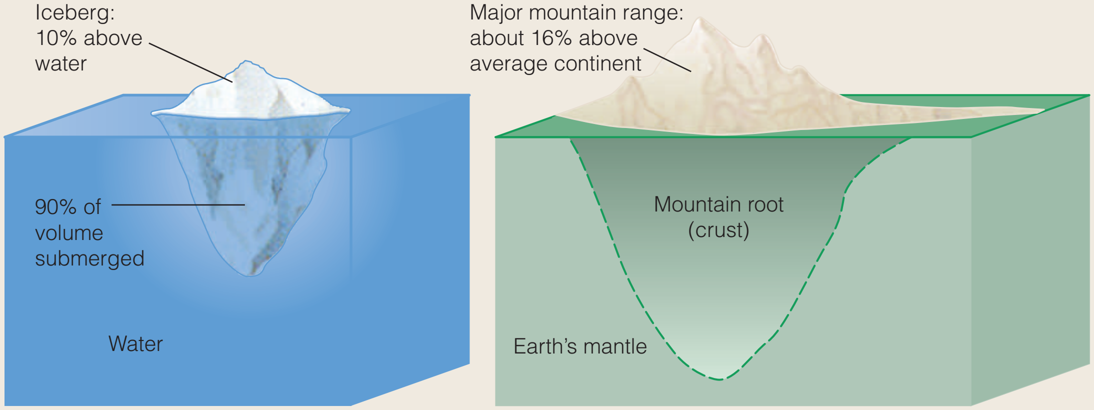
This shaded relief map shows the continents standing high. Mountain ranges in red tones concentrate at some continental margins. Deep blue areas are the deep ocean floor. Light blue ridges in oceans are mountain ranges on the ocean floor.

permits it to flow slowly as if it were a viscous liquid. As a result, the proportion of a mass immersed in the liquid can be calculated from the density of the floating solid divided by the density of the liquid (**By the Numbers 2-1:** Height of a Floating Mass). Similarly, where the weight of an extremely large glacier is added to a continent, the crust and upper mantle slowly sink deeper into the mantle. That happened during the last ice age when thick ice covered most of Canada and the northern United States. As the ice melted, these areas gradually rose back toward their original heights.

Almost 150 years ago, measurements showed that gravitational attraction of the huge mountain mass of the Himalayas pulled plumb bobs of very precise surveying instruments toward the mountain range more than would be expected based on the height of the mountains above sea

By the Numbers 2-1

Height of a Floating Mass



The height to which a floating block of ice rises above water depends on the density of water compared with the density of ice. For example, when water freezes, it expands to become less dense (ice density is 0.9 g/cm^3, liquid water is 1.0 g/cm^3). Thus, 90% of an ice cube or iceberg will be underwater. Similarly, for many large mountain ranges, approximately 84% of a mountain range of continental rocks (2.7 g/cm^3) will submerge into the mantle (3.2 g/cm^3) as a deep mountain root. Note that 2.7/3.2 = 0.84 or 84%. That is, Earth's crust rocks are about 84% as dense as Earth's mantle rocks.

level. A scientist, George Airy, inferred that the mountains must be thicker than they appeared, not merely standing on Earth's crust but extending deeper into it. Based on measurements of the density and velocity of earthquake waves through the crust, it now seems that many major mountain ranges do in fact have roots, and their crust is much thicker than adjacent older crust. As the mountains grew higher, their roots sank deeper into a fluid Earth, like a block of wood floating in water.

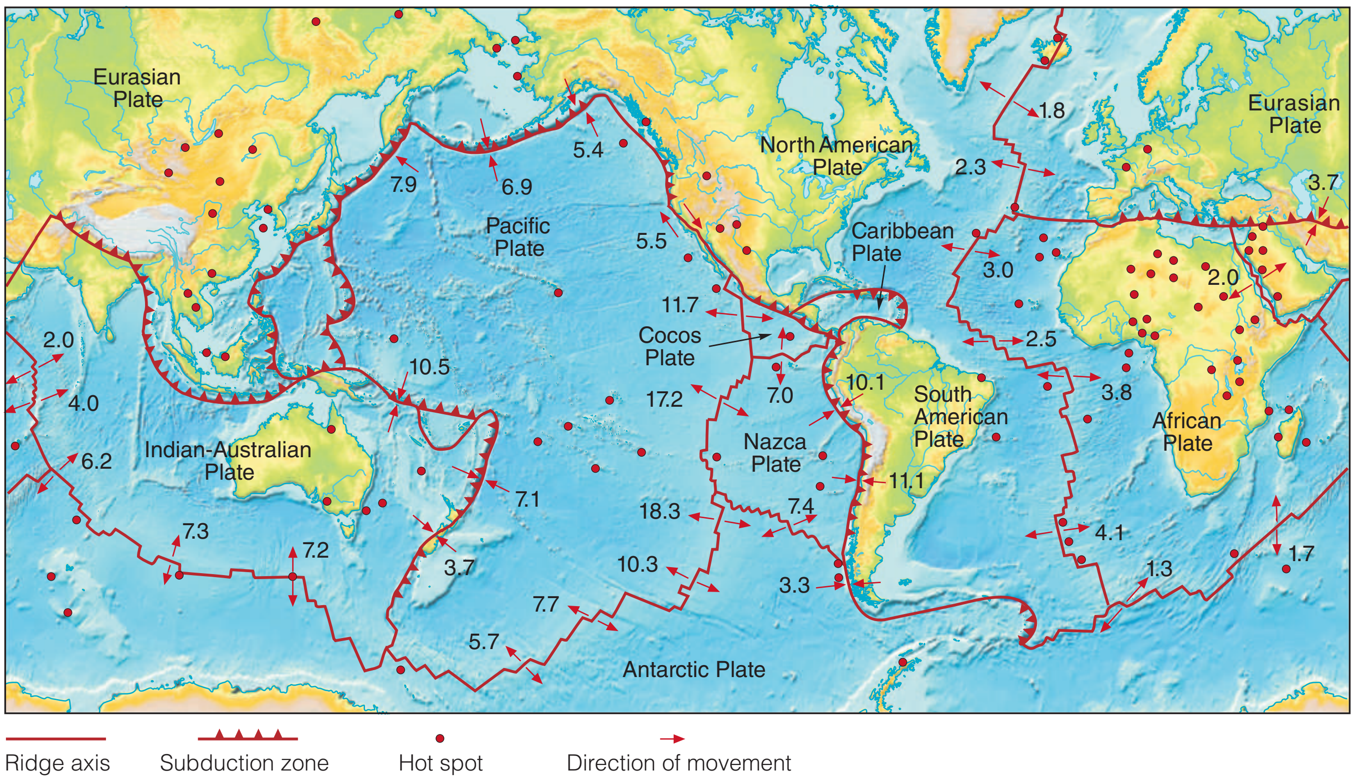
The temperature of the crust also affects its elevation. The crust of the mountainous Cordillera of western Canada and the northwestern United States is no thicker than the 40-km-thick continental crust to the east, and in some areas it is even thinner. Why then does it rise higher above sea level? Measurement of the temperature of the deep crust shows it to be hotter than old, cold continental crust to the east. In certain mountain ranges such as the Cordillera, the hot, more expanded, crust of the mountain range is less dense, so it floats higher than old, dense continental crust on the underlying asthenosphere. Heat in the thin crust may have been provided from the hot underlying mantle asthenosphere that stands relatively close to Earth's surface.

Plate Movement

The lithosphere is not continuous like the rind on a melon. It is broken into a dozen or so large **lithospheric plates** and about another dozen much smaller plates (**FIGURE 2-3**). Even though they are uneven in size and irregular in shape, the plates fit neatly together almost like a mosaic that covers entire surface of Earth. The plates do not correspond to continent versus ocean areas; most plates consist of a combination of the two. The South American Plate is about half below the Atlantic Ocean and half continent. Even the Pacific Plate, which is mostly ocean, includes a narrow slice of western California and part of New Zealand.

The lithospheric plates move over the weak, deforming asthenosphere at the rate of up to 11 cm (4.2 in.) per year, as confirmed by satellite Global Positioning System (GPS) measurements. Many move in roughly an east-west direction, but some don't. **Plate tectonics** is the big picture theory that describes the movements of Earth's plates. We will present the evidence for plate tectonics at the end of this chapter.

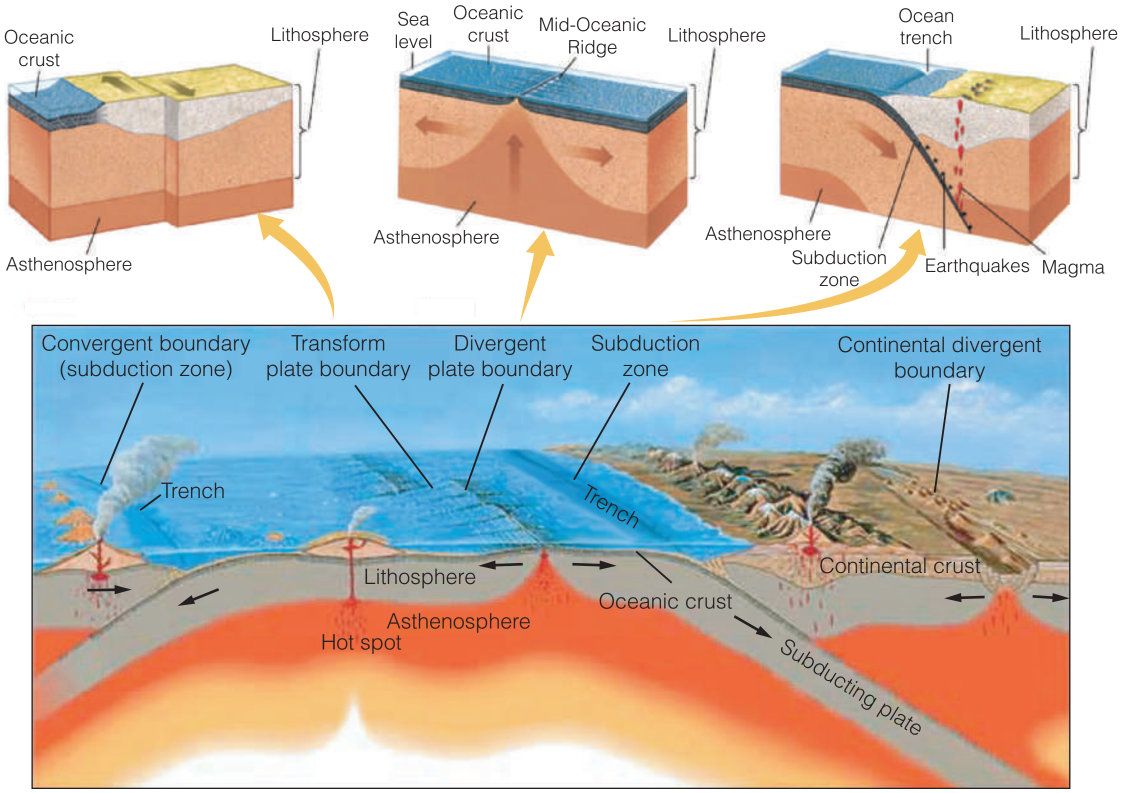
FIGURE 2-3 LITHOSPHERIC PLATES



Monroe and Wicander, modified from NOAA.

Most large lithospheric plates consist of both continental and oceanic areas. Although the Pacific Plate is largely oceanic, it does include parts of California and New Zealand. General direction and velocities of plate movement (compared with hotspots that are inferred to be anchored in the deep mantle), in centimeters per year, are shown with red arrows.

FIGURE 2-4 PLATE BOUNDARIES



Modified from Garrison.

USGS.

This three-dimensional cutaway view shows a typical arrangement of the different types of lithospheric plate boundaries: transform, divergent, and convergent.

Some plates separate, others collide, and still others slide under, over, or past one another (**FIGURE 2-4**). In some cases, their encounters are head on; in others, the collisions are more oblique. Plates move away from each other at **divergent boundaries**. Plates move toward each other at collision or **convergent boundaries**. In cases where one or both of the converging plates are oceanic lithosphere, the denser plate will slide down, or be *subducted*, into the asthenosphere, forming a **subduction zone**. When two continental plates collide, neither side is dense enough to be subducted deep into the mantle, so the two sides typically crumple into a thick mass of low-density continental material. This type of convergent boundary is where the largest mountain ranges on Earth, such as the Himalayas, are built. In the remaining category of plate interactions, two plates slide past each other at a **transform boundary**, such as the San Andreas Fault.

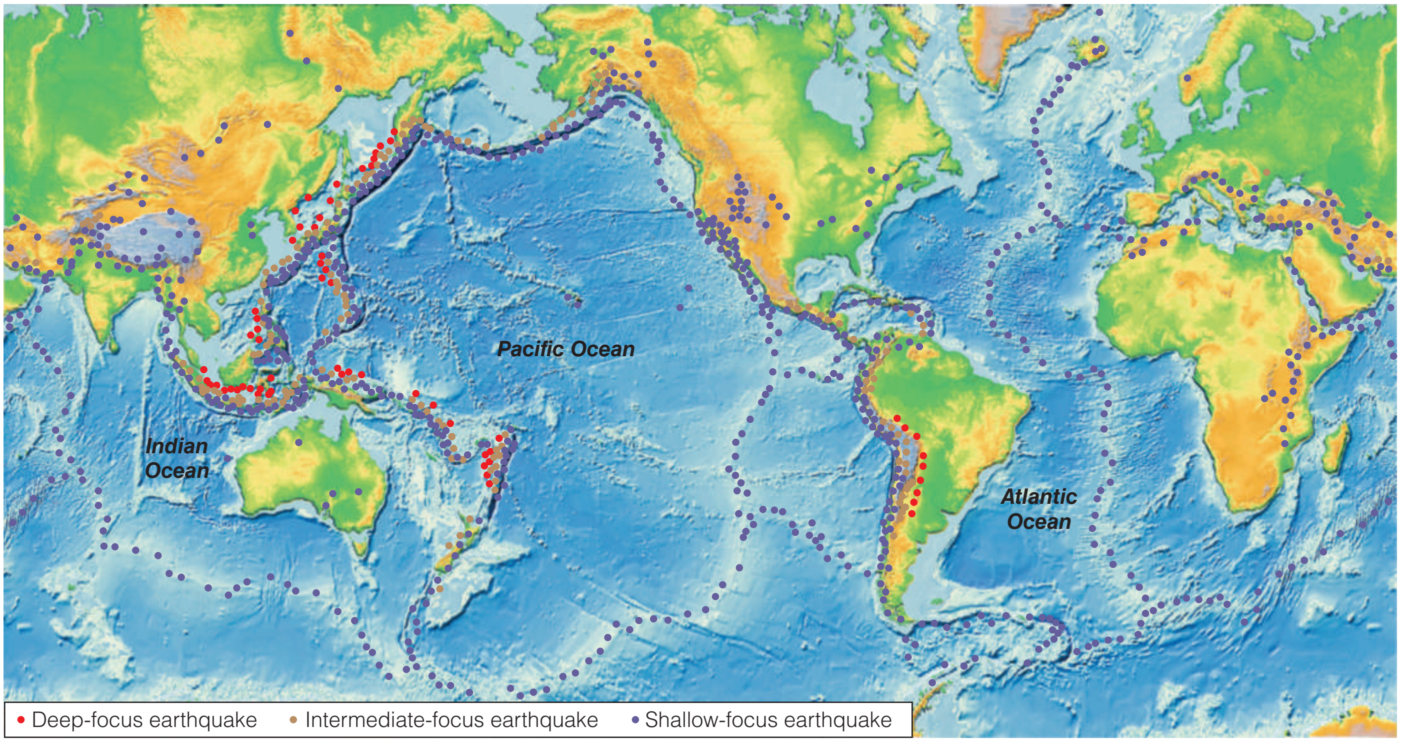
Plate motion is driven by **seafloor spreading**. Magma wells up at **mid-oceanic ridges** to form new oceanic crust. As the crust spreads out from the ridge, older crust moves away from the ridge until it finally sinks into the deep oceanic **trenches** along the edges of some continents. Plates continue to pull apart at the Mid-Atlantic Ridge, for example, making the ocean floor wider and moving North America and Europe farther apart. In the Pacific Ocean, the plates diverge at the East Pacific Rise; their oldest edges sink in the deep ocean trenches near the western Pacific continental margins.

In some places, different types of plate edges intersect. For example, at the Mendocino *triple junction* just off the northern California coast, the Cascadia subduction zone at the Washington-Oregon coast joins both the San Andreas transform fault of California and the Mendocino transform fault that extends offshore. The north end of the same subduction zone joins both the Juan de Fuca spreading ridge and the Queen Charlotte transform fault at a triple junction just off the north end of Vancouver Island.

Hazards and Plate Boundaries

Most of Earth's earthquake and volcanic activity occurs along or near plate boundaries (**FIGURES 2-5** and **2-6**). Most of the convergent boundaries between oceanic and

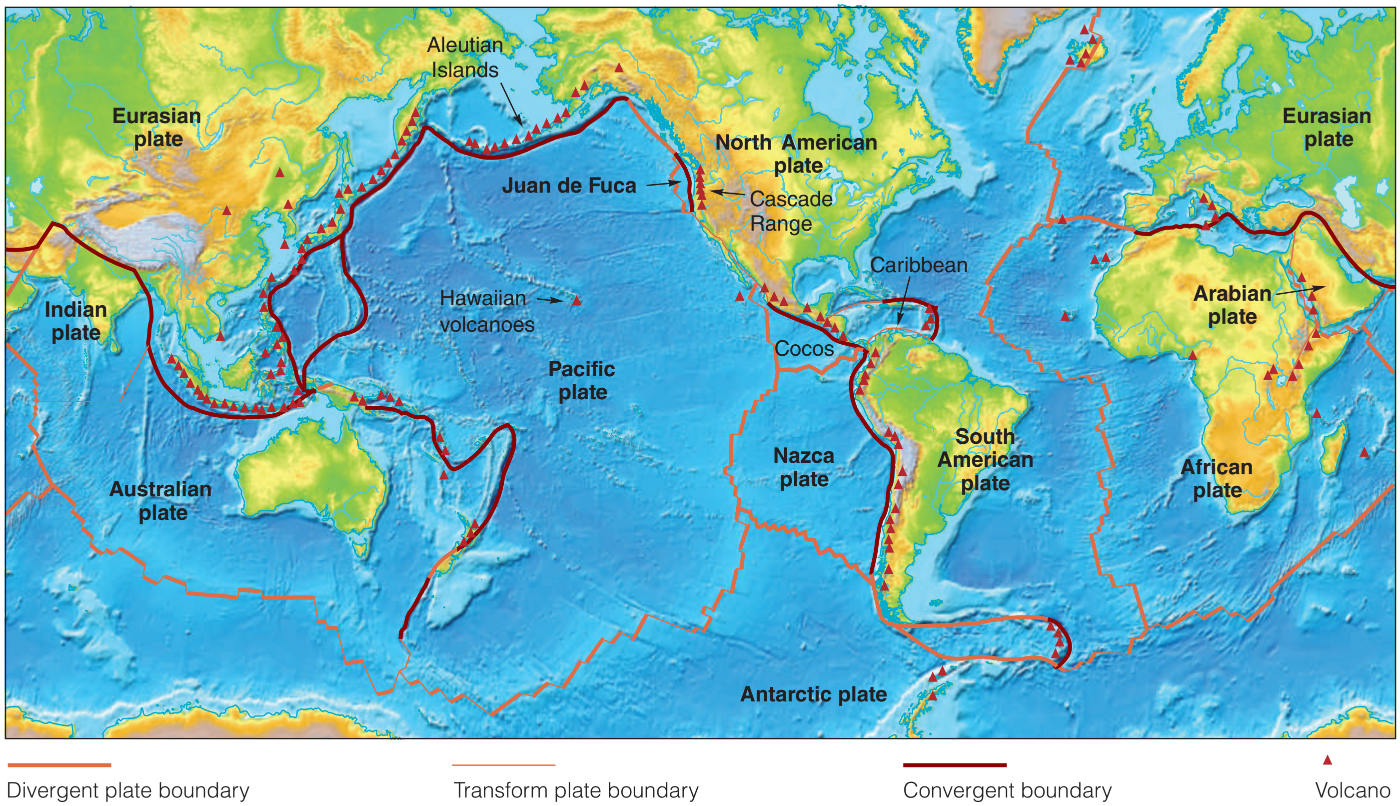
FIGURE 2-5 EARTHQUAKES AT PLATE BOUNDARIES



Monroe and Wincander, modified from NOAA.

Most earthquakes are concentrated along boundaries between major tectonic plates, especially subduction zones and transform faults, with fewer along spreading ridges.

FIGURE 2-6 VOLCANOES NEAR PLATE BOUNDARIES



Monroe and Wincander, modified from NOAA.

Most volcanic activity also occurs along plate tectonic boundaries. Eruptions tend to be concentrated along the continental side of subduction zones and along divergent boundaries, such as rifts and mid-oceanic ridges.

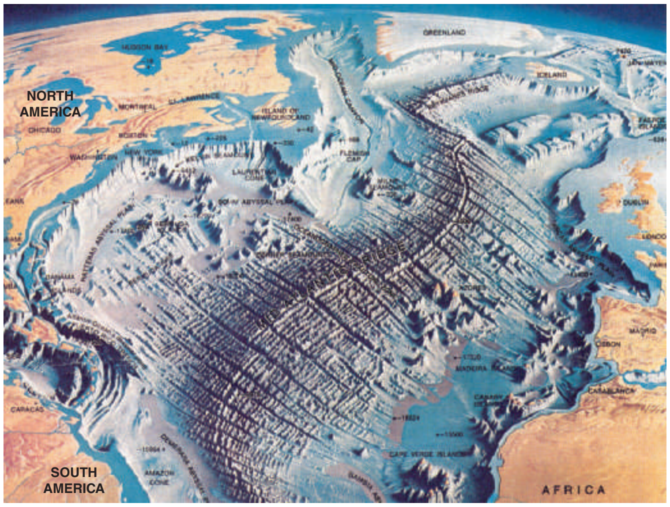
continental plates form subduction zones along the Pacific coasts of North and South America, Asia, Indonesia, and New Zealand. Collisions between continents are best expressed in the high mountain belts extending across southern Europe and Asia. Most rapidly spreading divergent boundaries follow oceanic ridges. In some cases, slowly spreading continental boundaries, such as the East African Rift zone, pull continents apart. Each type of plate boundary has a distinct pattern of natural events associated with it.

Divergent Boundaries

As plates pull apart, or *rift*, at divergent boundaries, magma wells up at the **spreading centers** between the plates to form a ridge with a central rift valley (**FIGURE 2-7**). A system of more-or-less connected ridges winds through the ocean basins like the seams on a baseball. These **rift zones** are associated with volcanic activity in the form of basalt lava flows as well as earthquakes.

These spreading centers are the source of the basalt lava flows that cover the entire ocean floor, roughly two-thirds of Earth's surface, to an average depth of several kilometers. The molten basalt magma rises to the surface, where it comes in contact with water. It then rapidly cools to form pillow-shaped blobs of lava with an outer solid rind initially encasing molten magma. As the plate moves away from the spreading center, it cools, shrinks, and thus increases in density. This explains why the hot spreading centers stand high on the subsea topography. New ocean floor continuously moves away from the oceanic ridges as the oceans grow wider by several centimeters every year.

FIGURE 2-7 MID-OCEANIC RIDGE



Aluminium Company of America.

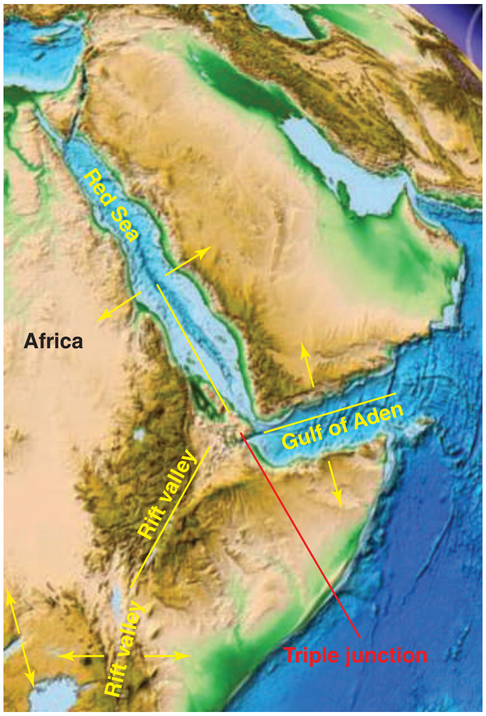
The spreading Mid-Atlantic Ridge, fracture zones, and transform faults are dramatically exhibited in this exaggerated topography of the ocean floor.

The only place where frequent earthquakes and volcanic eruptions along oceanic ridges pose a danger to people or property is in Iceland, where the oceanic ridge rises above sea level. Repeated surveys over several decades have shown that Iceland's cental valley is growing wider at a rate of several centimeters per year. The movement is the result of the North American and Eurasian Plates pulling away from each other, making the Atlantic Ocean grow wider at this same rate.

Iceland's long recorded history shows that a broad fissure opens in the floor of its central valley every 200 to 300 years. It erupts a large basalt lava flow that covers as much as several thousand square kilometers. The last fissure opened in 1821. Finally in April 2010, rifting under a glacier again erupted basalt magma. The hot magma melted the ice causing flooding and an immense ash cloud that spread over most of northern Europe, curtailing air traffic for days. Another such event could happen anytime. Fortunately, the sparse population of the region limits the potential for a great natural disaster.

Spreading centers in the continents pull apart at much slower rates and do not generally form along plate boundaries. The East African Rift zone that extends north-south through much of that continent (**FIGURE 2-8**) may be the

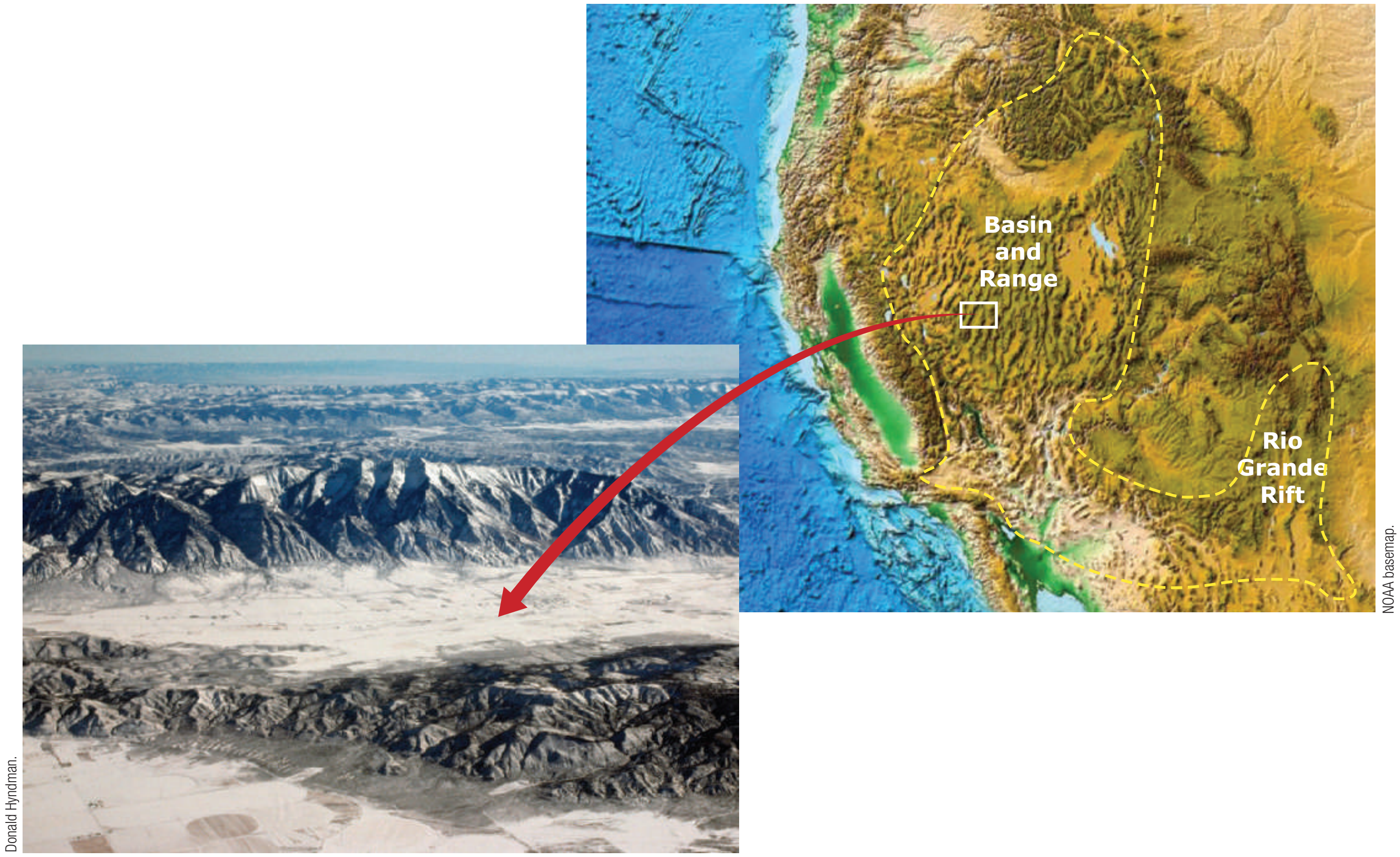
FIGURE 2-8 BEGINNING OF AN OCEAN



NOAA basemap.

The East African Rift Valley spreads the continent apart at rates 100 times slower than typical oceanic rift zones. This rift forms one arm of a triple junction, from which the Red Sea and the Gulf of Aden form somewhat more rapidly spreading rifts.

FIGURE 2-9 **CONTINENTAL SPREADING**



NOAA basemap.

Donald Hyndman.

The Basin and Range terrain is found southwest of Salt Lake City, Utah. This broad area of spreading in the western United States is marked by prominent basins and mountain ranges. Centered in Nevada and western Utah, it gradually decreases in spreading rate to the north across the Snake River Plain, near its north end. Its western boundary includes the eastern edge of the Sierra Nevada Range, California, and its main eastern boundary is at the Wasatch Front in Utah. An eastern branch includes the Rio Grande Rift of central New Mexico.

early stage of a future ocean. Continental rifts, such as the Rio Grande Rift of New Mexico and the Basin Range of Nevada and Utah, spread so slowly that they cannot split the continental plate to form new ocean floor (**FIGURE 2-9**). Continental spreading was responsible for creating the Atlantic Ocean long ago (**FIGURE 2-10**).

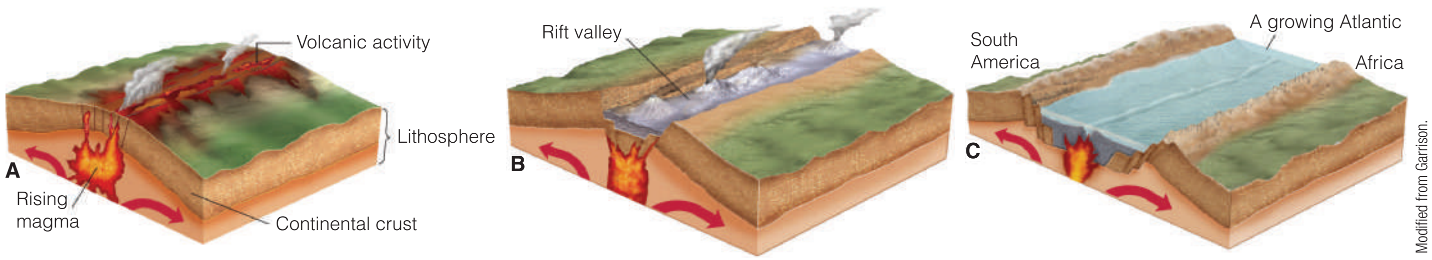
Continental spreading centers experience a few earthquakes—sometimes large—and volcanic eruptions accompany the up-and-down, “normal fault” movements. Volcanic activity is varied, ranging from large rhyolite calderas in the Long Valley Caldera of the Basin and Range region of southeastern California and the Valles Caldera of the Rio Grande Rift of New Mexico, to small basaltic eruptions at the edges of the spreading center.

Most of the magmas that erupt in continental rift zones are either ordinary rhyolite or basalt with little or no intermediate andesite (see Appendix 2 online). But some of the magmas, as in East Africa, are peculiar, with high sodium or potassium contents. Some of the rhyolite ash deposits in the Rio Grande Rift and in the Basin and Range provide evidence of extremely large and violent eruptions of giant rhyolite volcano activity. But those events appear to be infrequent, and much of the region is sparsely populated, so they do not pose much of a volcanic hazard.

Convergent Boundaries

Convergent boundaries, where plates come together, consist of both subduction zones and continental collision zones. Both zones are associated with earthquakes; volcanoes are more common at subduction zones.

FIGURE 2-10 EVOLUTION OF A SPREADING RIDGE



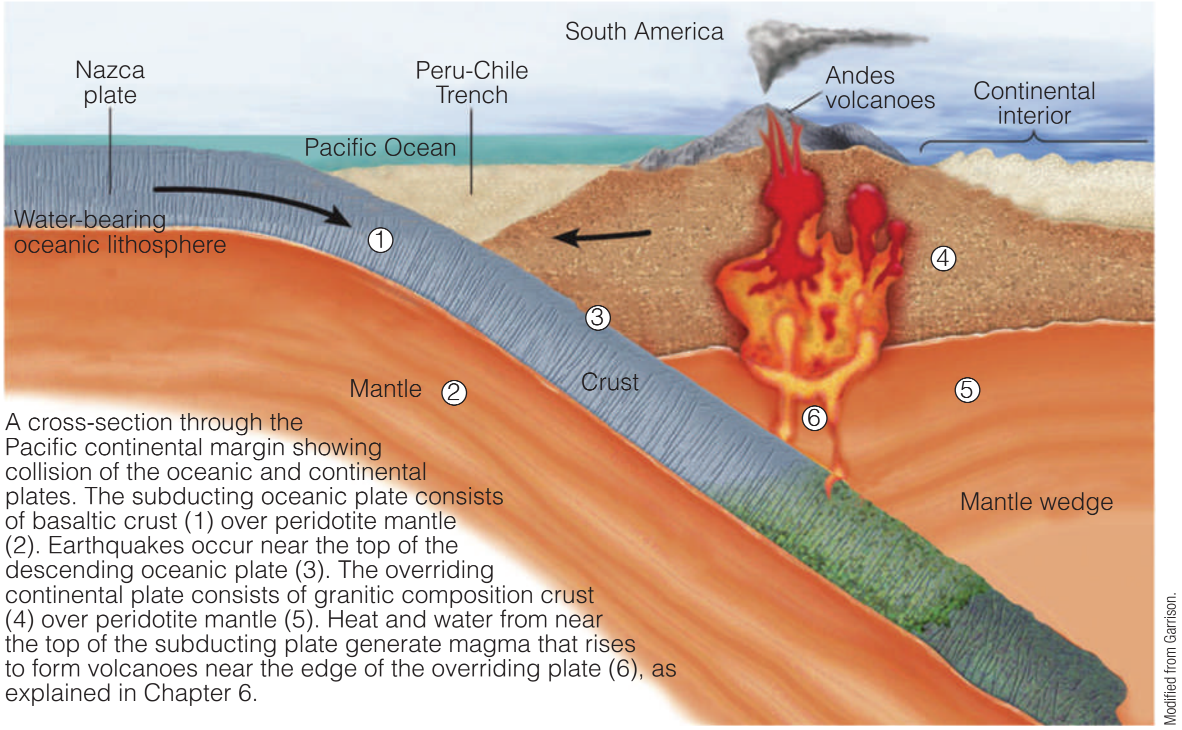
Modified from Garrison.

A spreading center forms as a continent is pulled apart to form new oceanic lithosphere. This process separated the supercontinent of Pangaea into South America and Africa, thereby forming the Atlantic Ocean.

SUBDUCTION ZONES As Earth generates new oceanic crust at boundaries where plates pull away from each other, it must destroy old oceanic crust somewhere else. It swallows this old crust in subduction zones, where one plate slides beneath the other and dives into the hot interior. The plate that sinks is the denser of the two, the one with oceanic crust on its outer surface. It absorbs heat as it sinks into the much hotter rock beneath. The subduction of one plate under another results in volcanic activity and earthquakes (**FIGURE 2-11**).

Where an oceanic plate sinks in a subduction zone, a line or *arc* of picturesque volcanoes rises inland from the trench. The process begins at the oceanic spreading ridge, where fractures open in the ocean floor. Seawater penetrates the dense peridotite of the upper mantle, where the two react to make a greenish rock called serpentinite. That altered ocean floor eventually sinks through an oceanic trench and descends into the upper mantle, where the serpentinite heats up, breaks down, releases its water, and reverts back to peridotite. The water rises into the overlying mantle, which it partially melts to make basalt magma that rises toward the surface. If the basalt passes through continental crust, it can heat and melt some of those rocks to make rhyolite magma. The basalt and rhyolite may

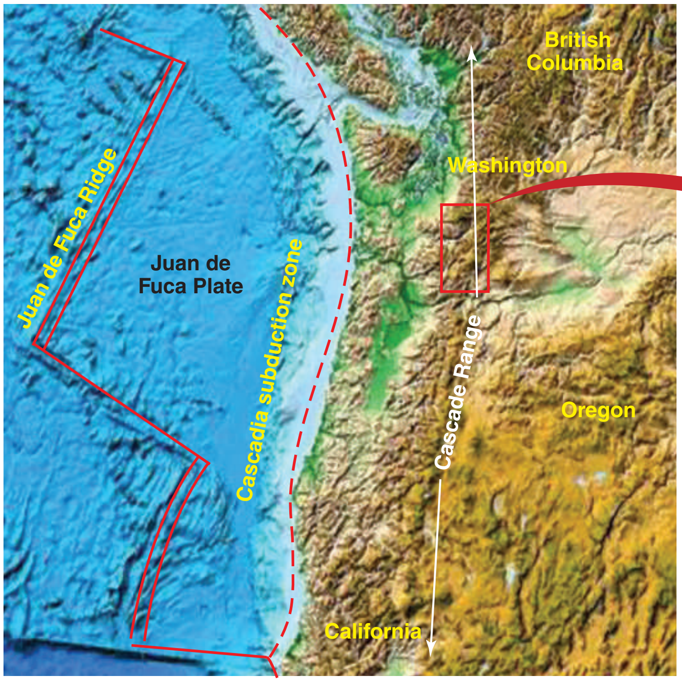
FIGURE 2-11 SUBDUCTION ZONE HAZARDS



A cross-section through the Pacific continental margin showing collision of the oceanic and continental plates. The subducting oceanic plate consists of basaltic crust (1) over peridotite mantle (2). Earthquakes occur near the top of the descending oceanic plate (3). The overriding continental plate consists of granitic composition crust (4) over peridotite mantle (5). Heat and water from near the top of the subducting plate generate magma that rises to form volcanoes near the edge of the overriding plate (6), as explained in Chapter 6.

Modified from Garrison.

FIGURE 2-12 VOLCANOES NEAR SUBDUCTION ZONES



NOAA basemap.

John Pallister, USGS.

The Cascade volcanic chain forms a prominent line of peaks parallel to the oceanic trench and 100 to 200 km inland. Mt. St. Helens (in foreground) and Mt. Rainier (behind) are two of the picturesque active volcanoes that lie inland from the Cascadia subduction zone.

erupt separately or mix in any proportion to form andesite and related rocks, the common volcanic rocks in stratovolcanoes. The High Cascades volcanoes in the Pacific Northwest are a good example; they lie inland from an oceanic trench, the surface expression of the active subduction zone (**FIGURE 2-12**).

Recall that most mountain ranges stand high. They stand high because they are either hot volcanoes of the volcanic arc or part of the hot *backarc*, the area behind the arc, above the descending subduction slab. The backarc environment stands high because it weakens, perhaps due to circulating hot-water-bearing rocks of the asthenosphere that spread, expand, and rise. In some cases, an oceanic plate descends beneath another section of oceanic plate attached to a continent. The same melting process described previously generates a line of basalt volcanoes because there is no overlying continental crust to melt and form rhyolite.

Volcanoes above a subducting slab present hazards to nearby inhabitants and their property. Deterring people from settling near these hazards can be difficult, because volcanoes are very scenic, and the volcanic rocks break down into rich soils that support and attract large populations. Volcanoes surrounded by people are prominent all around the Pacific basin and in Italy and Greece, where the African Plate collides with Europe.

The sinking slab of lithosphere also generates many earthquakes, both shallow and deep. Grinding rock against rock, the slippage zone sticks and occasionally slips, with an accompanying earthquake. Earth's largest earthquakes are generated along subduction zones; some of these cause major natural catastrophes. Somewhat smaller—but still dangerous—earthquakes occur in the overlying continental plate between the oceanic trench and the line of volcanoes.

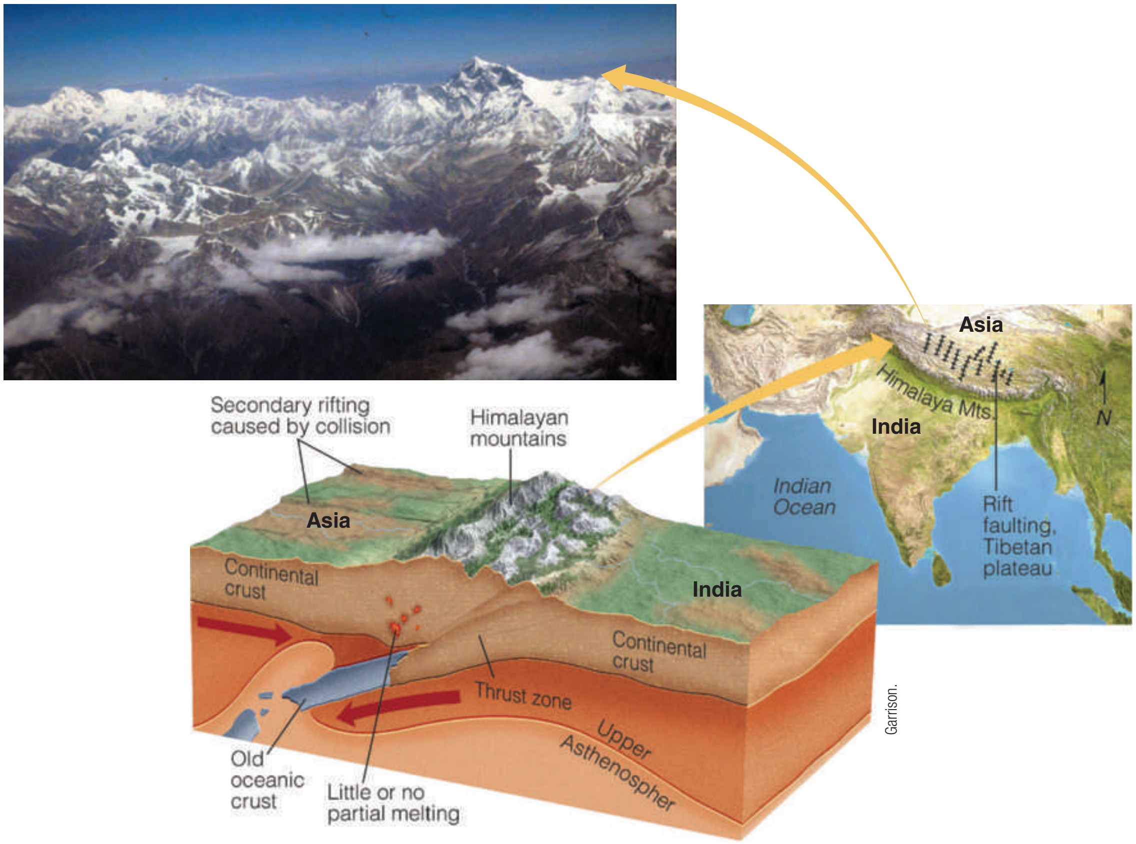
Sudden slippage of the submerged edge of the continental plate over the oceanic plate during a major earthquake can cause rapid vertical movement of a lot of water, which creates a huge tsunami wave. The wave both washes onto the nearby shore and races out across the ocean to endanger other shorelines.

COLLISION ZONES Where two continental plates collide, called a continental **collision zone**, neither plate sinks, so high mountains, such as the Himalayas, are pushed up in fits and starts, accompanied by large earthquakes (**FIGURE 2-13**). During the continuing collision of India against Asia to form the Himalayas, and between the Arabian Plate and Asia to form the Caucasus range farther west, earthquakes regularly kill thousands of people. These earthquakes are distributed across a wide area because of the thick, stiff crust in these mountain ranges.

Transform Boundaries

At transform boundaries, or transform faults, plates simply slide past each other without pulling apart or colliding. Some transform boundaries offset the mid-oceanic ridges. Because the ridges are spreading zones, the plates move

FIGURE 2-13 CONTINENTAL COLLISION ZONES



Geoff Edwards.

Garrison.

Garrison.

The Himalayas, which are the highest mountains on any continent, were created by collision between the Indian and Eurasian Plates. Collision of two continental plates generally occurs after subduction of oceanic crust. The older, colder, denser plate may continue to sink, or the two may merely crumple and thicken. Collision promotes thickening of the combined lithospheres and growth of high mountain ranges.

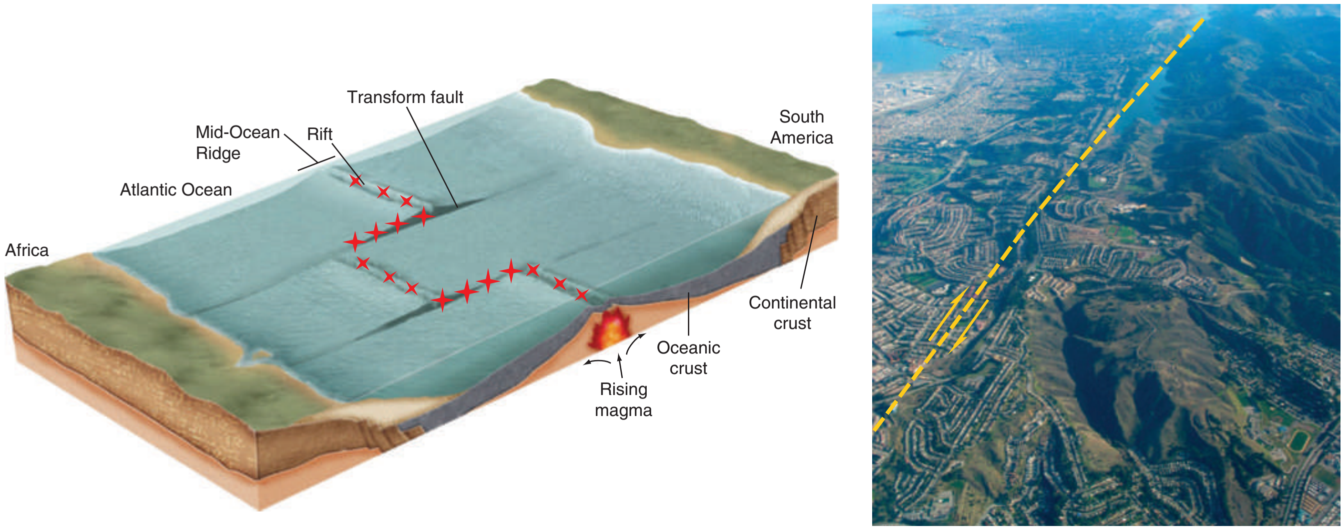
away from them. The section of the fault between the offset ends of the spreading ridge has significant relative movement (**FIGURE 2-14**). Lateral movement between the ridge ends occurs in the opposite direction compared to beyond the ridges, where there is no relative movement across the same fault. Note also that the offset between the two ridge segments does not indicate the direction of relative movement on the transform fault.

Oceanic transform faults generate significant earthquakes without causing casualties because no one lives on the ocean floor. On continents it is a different story. The San Andreas Fault system in California (**FIGURE 2-14**) is a well-known continental example. The North Anatolian Fault in Turkey is another that is even more deadly. The San Andreas Fault is the dominant member of a swarm of more-or-less parallel faults that move horizontally. Together, they have moved a large slice of western California, part of the Pacific Plate, north more than 350 km so far.

Transform plate boundaries typically generate large numbers of earthquakes, a few of which are catastrophic. A sudden movement along the San Andreas Fault caused the devastating San Francisco earthquake of 1906, with its large toll of casualties and property damage. The San Andreas system of faults passes through the metropolitan areas south of San Francisco and just east of Los Angeles. Both areas are home to millions of people, who live at risk of major earthquakes that have the potential to cause enormous casualties and substantial property damage with little or no warning. Even moderate earthquakes in 1971 and 1994 near Los Angeles, in 1989 near San Francisco, and in 2003 near Paso Robles, between them, killed almost 200 people. The threat of such sudden havoc in a still larger event inspires much public concern and major scientific efforts to find ways to predict large earthquakes.

For reasons that remain mostly unclear, some transform plate boundaries are also associated with volcanic activity. Several large volcanic fields have erupted along the San Andreas system of faults during the last 16 million or so years. One of those, in the Clear Lake area north of San

FIGURE 2-14 TRANSFORM FAULT



Modified from Garrison.

David Hyndman.

A. In this perspective view of an oceanic spreading center, earthquakes (stars) occur along spreading ridges and on transform faults offsetting the ridge.

B. The San Andreas Fault, indicated with a yellow, dashed line, is an example of a continental transform fault. Shown here is the heavily populated area that straddles the fault just south of San Francisco.

Francisco, erupted recently enough to suggest that it may still be capable of further eruptions.

Hotspot Volcanoes

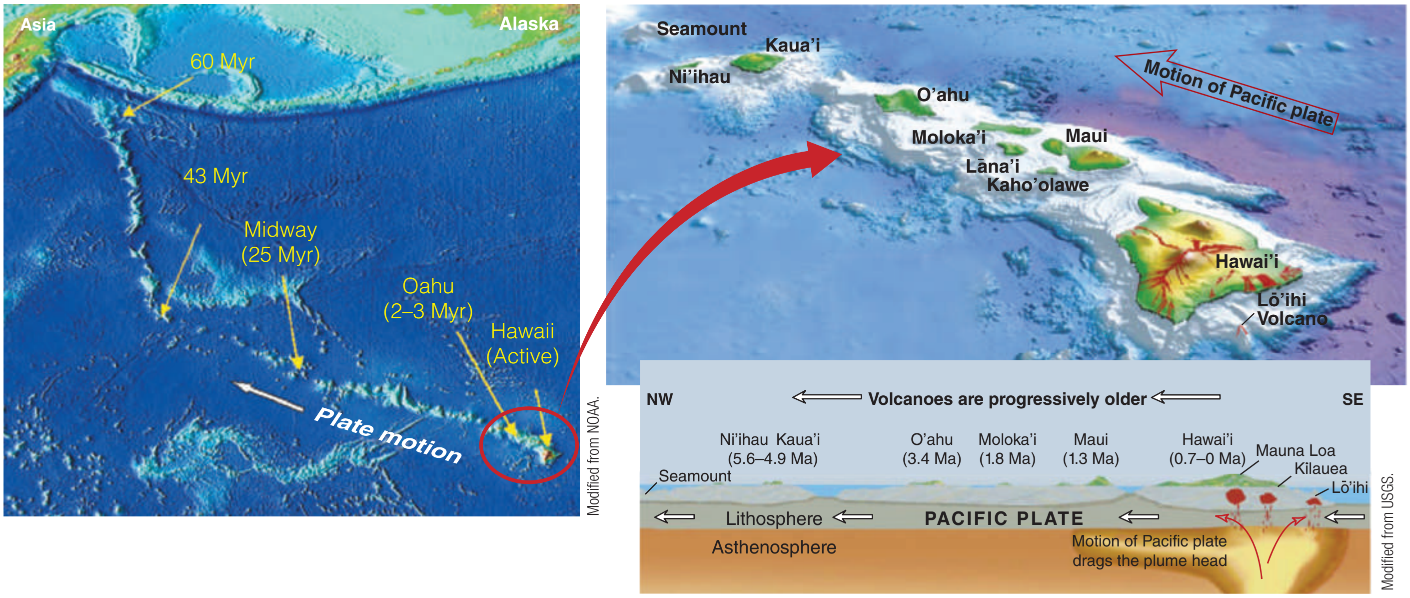
Despite being remote from any plate boundary, **hotspot volcanoes** provide a record of plate tectonic movements. Hotspots are the surface expressions of hot columns of partially molten rock anchored (at least relative to plate movements) in the deep mantle. Their origin is unclear, but many scientists infer that they arise from deep in the mantle, perhaps near the boundary between the core and the mantle. At a hotspot, plumes of abnormally hot but solid rock rising within Earth's mantle begin to melt as the rock pressure on them drops. Wherever peridotite of the asthenosphere partially melts, it releases basalt magma that fuels a volcano on the surface. If the hotspot is under the ocean floor, the basalt magma erupts as basalt lava. If the hot basalt magma rises under continental rocks, it partially melts those rocks to form rhyolite magma; that magma often produces violent eruptions of ash.

The melting temperature of basalt is more than 300°C hotter than rhyolite, so a small amount of molten basalt can melt a large volume of rhyolite. The molten rhyolite rises in large volumes, which may erupt explosively through giant rhyolite calderas, such as those in Yellowstone National Park in Wyoming and Idaho, Long Valley Caldera in eastern California, and Taupo Caldera in New Zealand.

The rising column or plume of hot rock appears to remain nearly fixed in its place as one of Earth's plates moves over it, creating a track of volcanic activity. The movement of the plate over an oceanic hotspot is evident in a chain of volcanoes, where the oldest volcanoes are extinct, and possibly submerged, while newer, active volcanoes are created at the end of the chain. Mauna Loa and Kilauea, for example, erupt at the eastern end of the Hawaiian Islands, a chain of extinct volcanoes that become older westward toward Midway Island (**FIGURE 2-15**). Beyond Midway, the Hawaiian-Emperor chain doglegs to a more northerly course. It continues as a long series of defunct volcanoes that are now submerged. They form seamounts to the western end of the Aleutian Islands west of Alaska. So far as anyone knows, the hotspot track of dead volcanoes will continue to lengthen until eventually the volcanoes and the plate carrying them slide into a subduction zone and disappear.

Hotspot volcanoes leave a clear record of the direction and rate of movement of the lithospheric plates. Remnants of ancient hotspot volcanoes show the direction of movement in the same way that a saw blade cuts in the opposite direction of movement of a board being cut. The ages of those old volcanoes provide the rate of movement of the lithospheric plate. The assumption, of course, is that the mantle containing the hotspot is not itself moving. Comparison of different hotspots suggests that this is generally valid

FIGURE 2-15 OCEANIC HOTSPOTS



Modified from NOAA.

Modified from USGS.

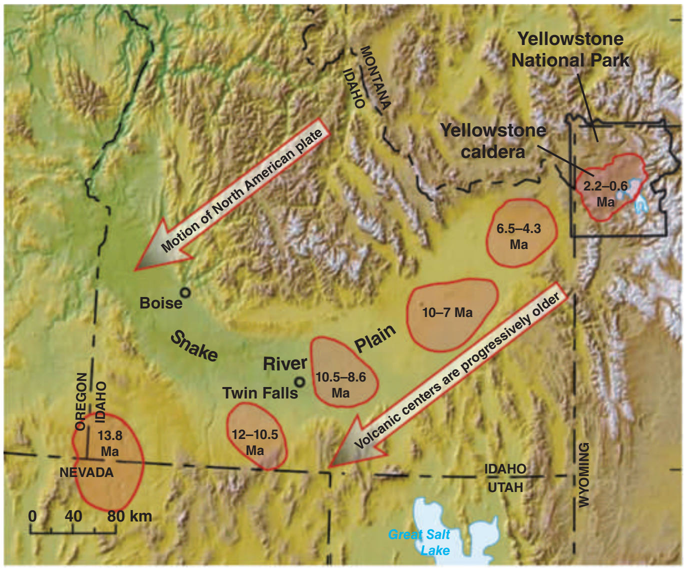
The relief map of the Hawaiian-Emperor chain of volcanoes clearly shows the movement of the crust over the hotspot that is currently below the Big Island of Hawaii, where there are active volcanoes. Two to three million years ago, the part of the Pacific plate below Oahu was over the same hotspot. The approximate rate and direction of plate motion can be calculated using the common belief that the hotspot is nearly fixed in space through time. The distance between two locations of known ages divided by the time (age difference) indicates a rate of movement of about 9 cm per year. The lithospheric plate, moving across a stationary hotspot in Earth's mantle (moving to the left in this diagram), leaves a track of old volcanoes. The active volcanoes are over the hotspot.

compared with migration of the tectonic plates, but many researchers suggest that it is not absolutely so.

The Snake River Plain of southern Idaho is probably the best example of a continental hotspot track. Along this track is a series of extinct *resurgent calderas*, depressions where the erupting giant volcano collapsed. Those volcanoes began to erupt some 14 million years ago. They track generally east and northeast in southern Idaho, becoming progressively younger northeastward as the continent moves southwestward over the hotspot (**FIGURE 2-16**). They are a continental hotspot track that leads from its western end near the border between Idaho and Oregon to the Yellowstone resurgent caldera at its active northeastern end in northwestern Wyoming.

Hotspot tracks provide clear evidence that Earth's plates are in motion. Plate tectonic theory has been confirmed by repeated wide-ranging studies, tests, and many predictions, all of which confirm its validity. What was once a series of **hypotheses** or ideas, which remained to be confirmed, has been so thoroughly examined and tested that it has been elevated to the category of **theory**—that is, it is now considered to be *fact*. What prompted the original hypotheses and how did it finally lead to the present understanding?

FIGURE 2-16 CONTINENTAL HOTSPOTS



Modified from USGS, Pierce & Morgan, 1992; Beranek and others, 2006.

This shaded relief map of the Snake River Plain shows the outlines of ancient resurgent calderas leading northeast to the present-day Yellowstone caldera. Caldera ages are shown in millions of years before present.

Development of a Theory

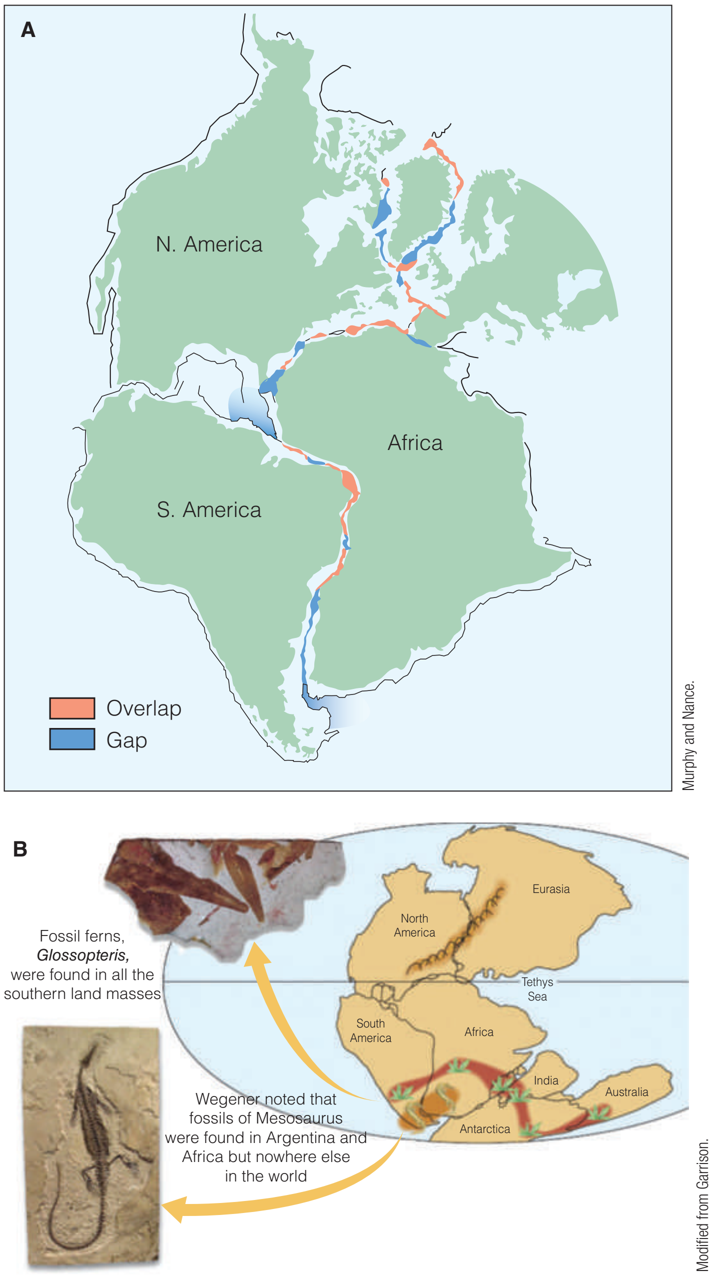
When you look at a map of the world, you may notice that the continents of South America and Africa would fit nicely together like puzzle pieces. In fact, as early as 1596, Abraham Ortelius, a Dutch mapmaker, noted the similarity of the shapes of those coasts and suggested that Africa and South America were once connected and had since moved apart. In 1912, Alfred Wegener detailed the available evidence and proposed that the continents were originally part of one giant supercontinent that he called **Pangaea** (**FIGURE 2-17A**). Wegener noted that the match between the shapes of the continents is especially good if we use the real edge of the continents, including the shallowly submerged continental shelves.

To test this initial hypothesis, Wegener searched for connections between other aspects of geology across the Atlantic Ocean: mountain ranges, rock formations and their ages, and fossil life forms. Continued work showed that ancient rocks, their fossils, and their mountain ranges also matched on the other side of the Atlantic (**FIGURE 2-17B**). This analysis is similar to what you would use to put a jigsaw puzzle together; the pieces fit and the patterns match across the reconnected pieces. With confirmation of former connections, he hypothesized that the continents had moved apart; North and South America separated from Europe and Africa, widening the Atlantic Ocean in the process. He suggested that the continents drifted through the oceanic crust, forming mountains along their leading edges. This hypothesis, called **continental drift**, remained at the center of the debate about large-scale Earth movements into the 1960s.

As research has continued, other lines of evidence supported the continental drift hypothesis. Exposed surfaces of ancient rocks in the southern parts of Australia, South America, India, and Africa show grooves carved by immense areas of continental glaciers (**FIGURE 2-18**). The grooves show that glaciers with embedded rocks at their bases may have moved from Antarctica into India, eastern South America, and Australia. The rocks were once buried under glacial ice, yet many of these areas now have warm to tropical climates. In addition, the remains of fossils that formed in warm climates are found in areas such as Antarctica and the present-day Arctic: coal with fossil impressions of tropical leaves, the distinctive fossil fern *Glossopteris*, and coral reefs.

Despite this evidence, many scientists rejected Wegener's whole hypothesis because they could show that his proposed mechanism was not physically possible. English geophysicist Harold Jeffreys argued that the ocean floor rocks were far too strong to permit the continents to plow through them. Others who were willing to consider different possibilities eventually came up with a mechanism that fit all of the available data.

FIGURE 2-17 CONTINENTS ONCE FIT TOGETHER



Fossil ferns, *Glossopteris*, were found in all the southern land masses

Wegener noted that fossils of Mesosaurus were found in Argentina and Africa but nowhere else in the world

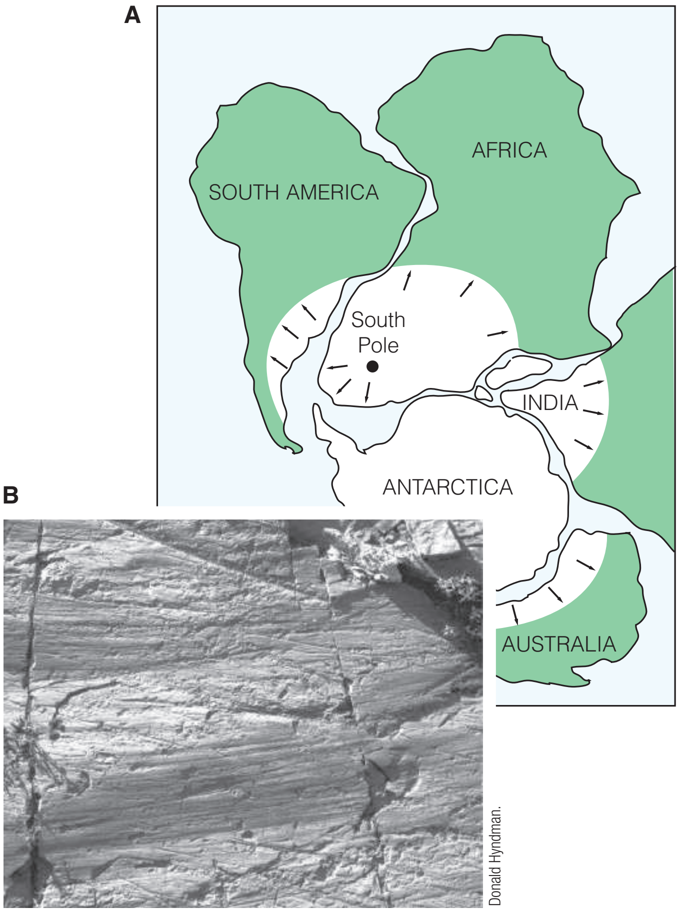
Murphy and Nance.

Modified from Garrison.

A. Before continental drift a few hundred million years ago, the continents were clustered together as a giant "supercontinent" that has been called Pangaea. The Atlantic Ocean had not yet opened. The pale blue fringes on the continents are continental shelves, which are part of the continents. The areas of overlap and gap (in red and darker blue) are small. **B.** Some distinctive fossils and mountain ranges lie in belts across the Atlantic and Indian oceans.

The first step in understanding how the continents were separating was to learn more about the topography of the ocean floor, what it looked like, and how old it was.

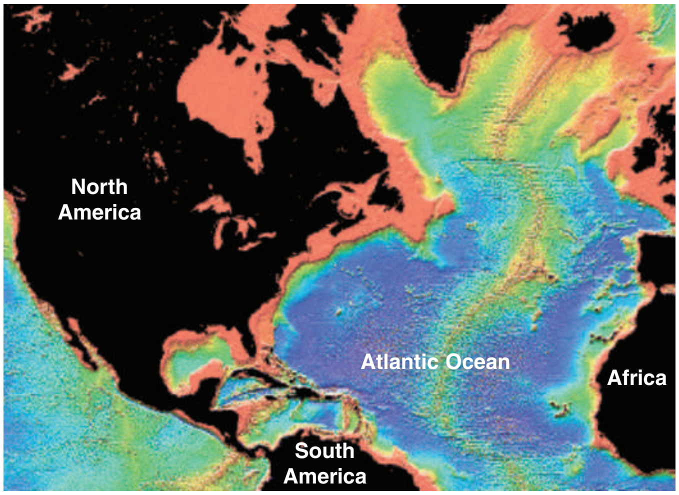
FIGURE 2-18 GLACIATION IN WARM AREAS



Donald Hyndman.

A. Continental masses of the southern hemisphere appear to have been parts of a supercontinent 300 million years ago, from which a continental ice sheet centered on Antarctica spread outward to cover adjacent parts of South America, Africa, India, and Australia. After separation, the continents migrated to their current positions. **B.** The inset photo shows glacial grooves like those found in the glaciated areas of those continents.

FIGURE 2-19 OCEAN-BOTTOM TOPOGRAPHY



NOAA/NGDC.

In this seafloor topographic map for the Atlantic Ocean, shallow depths at the oceanic ridges are shown in orange to yellow, deeper water off the ridge crests are in green, and deep ocean is blue. Shallow continental shelves are shown in red.

Oceanographers from Woods Hole Oceanographic Institute in Massachusetts, who were measuring depths from all over the Atlantic Ocean in the late 1940s and 1950s, found an immense mountain range down the center of the ocean, extending for its full length—a mid-oceanic ridge (**FIGURE 2-19**). Later, scientists recognized that most earthquakes in the Atlantic Ocean were concentrated in that central ridge.

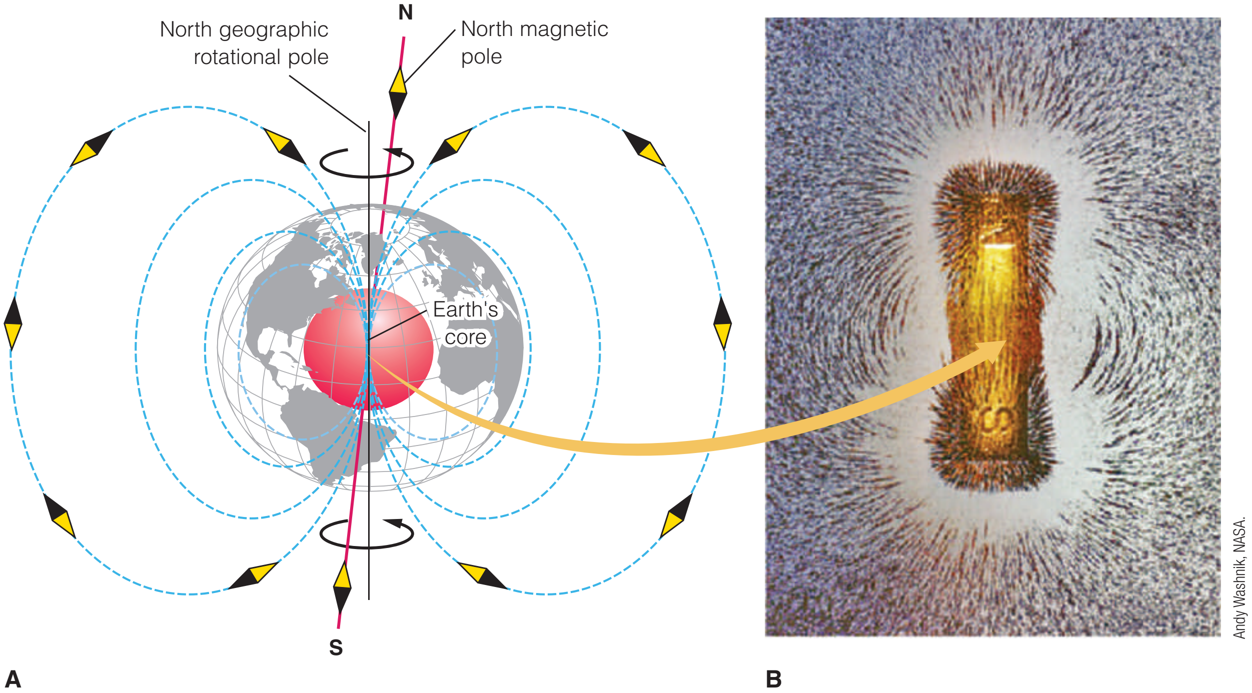
Although the anti-continental drift group dominated the scientific literature for years, in 1960 Harry Hess of Princeton University conjectured that the ocean floors acted as giant conveyor belts carrying the continents. Hess calculated the spreading rate to be approximately 2.5 cm (1 in.) per year across the Mid-Atlantic Ridge. If that calculation was correct, the whole Atlantic Ocean floor would have been created in about 180 million years.

Confirmation of seafloor spreading finally came in the mid-1960s through work on the magnetic properties of ocean floor rocks. We are all aware that Earth has a **magnetic field** because a magnetized compass needle points toward the north magnetic pole. Slow convection currents in Earth's molten nickel-iron outer core are believed to generate that magnetic field (**FIGURE 2-20**). Because of changes in those currents, this field reverses its north-south orientation every 10,000 to several million years (every 600,000 years on average).

The ocean floor consists of basalt, a dark lava that erupted at the mid-oceanic ridge and solidified from molten magma. Iron atoms crystallizing in the magma orient themselves like tiny compass needles, pointing toward the north magnetic pole. As a result, the rock is slightly magnetized with an orientation like the compass needle. When the magnetic field reverses, that reversed magnetism is frozen into rocks when they solidify. A compass needle at the equator remains nearly horizontal but one at the north magnetic pole points directly down into Earth. At other latitudes in between, the needle points more steeply downward as it approaches the poles. Thus we can tell the latitude at which the rock formed when it solidified by the inclination of its magnetism.

British oceanographers Frederick Vine and Drummond Matthews, studying the magnetic properties of ocean-floor rocks in the early 1960s, discovered a striped pattern parallel to the mid-oceanic ridge

FIGURE 2-20 **EARTH'S MAGNETIC FIELD**



A. The shape of Earth's magnetic field suggests the presence of a huge bar magnet in Earth's core. But instead of a magnet, Earth's rotation is thought to cause currents in the liquid outer core. Those currents create a magnetic field in a similar way in which power plants generate electricity when steam or falling water rotates an electrical conductor in a magnetic field. **B.** Metal filings align with the magnetic field lines from this bar magnet.

(**FIGURE 2-21**). Some of the stripes were strongly magnetic; adjacent stripes were weakly magnetic. They realized that the magnetism was stronger where the rocks solidified while Earth's magnetism was oriented parallel to the present-day north magnetic pole. Where the rock magnetism was pointing toward the south magnetic pole, the recorded magnetism was weak—it was partly canceled by the present-day magnetic field. Because it reversed from time to time, Earth's magnetic field imposed a pattern of magnetic stripes as the basalt solidified at the ridge. As the ridge spread apart, ocean floor formed under alternating periods of north- versus south-oriented magnetism to create the matching striped pattern on opposite sides of the ridge.

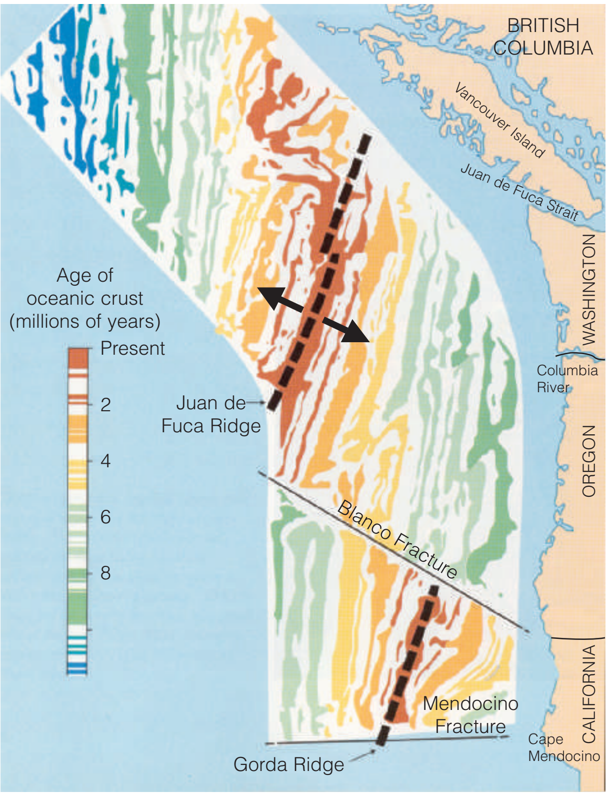
These magnetic anomalies provide the relative ages of the ocean floor; their mapped widths match across the ridge, and the rocks are assumed to get progressively older as they move away from mid-oceanic ridges. Determination of the true ages of ocean-floor rocks eventually came from drilling in the deep-sea floor by research ships of the Joint Oceanographic Institute for Deep Earth Sampling (JOIDES), funded by the National Science Foundation. The ages of basalts and sediments dredged and drilled from the ocean floor showed that those near the Mid-Atlantic Ridge were young (up to 1 million years old) and had only a thin coating of sediment. Both results contradicted the prevailing notion that the ocean floor was extremely old. In contrast, rocks from deep parts of the ocean floor far from the ridge were consistently much older (up to 180 million years) (**FIGURE 2-22**).

All of this evidence supports the modern theory of plate tectonics, the big picture of Earth's plate movements. We now know that the world's landmasses once formed one giant supercontinent, called Pangaea, 225 million years ago. As the seafloor spread, Pangaea began to break up, and the plates slowly moved the continents into their current positions (**FIGURE 2-23**).

As it turns out, Wegener's hypothesis that the continents moved apart was confirmed by the data, although his assumption that they plowed through the ocean was not. The evolution of this theory is a good example of how the scientific method works.

The **scientific method** is based on logical analysis of data to solve problems. Scientists make observations and develop tentative explanations—that is, hypotheses—for their observations. A hypothesis should always be testable, because science evolves through continual testing with new observations and experimental analysis. Alternate hypotheses should be developed to test other potential explanations for observed behavior. If observations are inconsistent with a hypothesis, it can either be rejected or revised. If a hypothesis continues to be supported by all available data over a

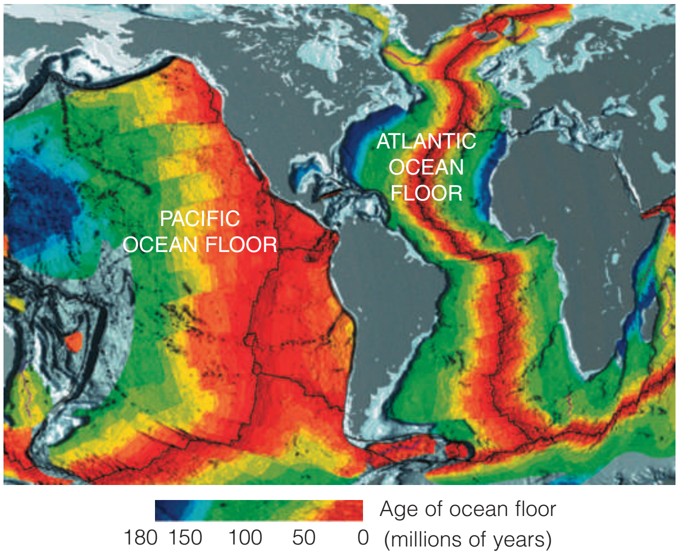
FIGURE 2-21 MAGNETIC RECORD OF OCEAN-FLOOR SPREADING



W. J. Kious and R. I. Tilling, USGS.

The magnetic polarity, or orientation, across the Juan de Fuca Ridge in the Pacific Ocean shows a symmetrical pattern, as shown in this regional survey (a similar nature of stripes exists along all spreading centers). Basalt lava erupting today records the current northward-oriented magnetism right at the ridge; basalt lavas that erupted less than 1 million years ago recorded the reversed, southward-oriented magnetic field at that time. The south-pointing magnetism in those rocks is largely canceled out by the present-day north-pointing magnetic field, so the ocean floor shows alternating strong (north-pointing) and weak (south-pointing) magnetism in the rocks.

FIGURE 2-22 AGES OF OCEAN FLOOR



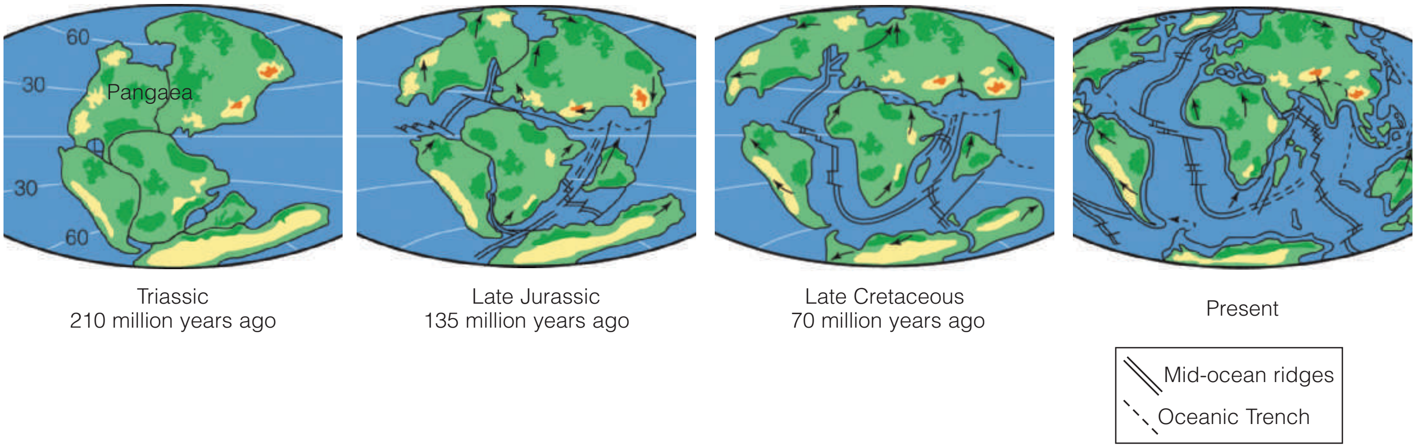
NOAA/NGDC.

Ocean-floor ages are determined by their magnetic patterns. Red colors at the oceanic spreading ridges grade to yellow at 48 million years ago, to green 68 million years ago, and to dark blue some 155 million years ago.

long period of time, and if it can be used to predict other aspects of behavior, it becomes a theory.

After a century of testing, Wegener's initial hypothesis of continental drift was modified to be the foundation for the modern theory of plate tectonics. Plate tectonics is supported by a large mass of data collected over the last century. Modern data continue to support the concept that plates move, substantiate the mechanism of new oceanic plate generation at the mid-oceanic ridges, and support the concept of plate destruction at oceanic trenches. This theory is a fundamental foundation for the geosciences and important for understanding why and where we have a variety of major geologic hazards, such as earthquakes and volcanic eruptions.

FIGURE 2-23 CONTINENTS SPREAD APART



Triassic
210 million years ago

Late Jurassic
135 million years ago

Late Cretaceous
70 million years ago

Present

Modified from Garrison.

The supercontinent Pangaea broke up into individual continents starting approximately 225 million years ago.

Chapter Review

Key Points

Earth Structure and Plates

- Earth is made up of an inner and outer core, surrounded by a thick mantle and covered by a much thinner crust. The crust and stiff outer part of the underlying mantle is called the lithosphere. The inner, hotter region is the asthenosphere. **FIGURE 2-1.**
- The concept of isostacy explains why the lower-density continental rocks stand higher than the higher density ocean-floor rocks and sink deeper into the underlying mantle. This behavior is analogous to ice (lower density) floating higher in water (higher density). **FIGURE 2-2** and **By the Numbers 2-1.**
- A dozen or so nearly rigid lithospheric plates make up the outer 60 to 200 km of Earth. They slowly slide past, collide with, or spread apart from each other. **FIGURES 2-3** and **2-4**.

Hazards and Plate Boundaries

- Much of the tectonic action, in the form of earthquakes and volcanic eruptions, occurs near the boundaries between the lithospheric plates. **FIGURES 2-5** and **2-6**.
- Where plates diverge from each other, new lithosphere forms. If the plates are continental material, a continental rift zone forms. As this process continues, a new ocean basin can develop, and the spreading continues from a mid-oceanic ridge, where basaltic magma pushes to the surface. **FIGURES 2-7** to **2-10**.
- Subduction zones, where ocean floors slide beneath continents or beneath other slabs of oceanic crust, are areas of major earthquakes and volcanic eruptions. These eruptions form volcanoes on the overriding plates. **FIGURES 2-11** and **2-12**.
- Continent–continent collision zones, where two continental plates collide, are regions with major earthquakes and the tallest mountain ranges on Earth. **FIGURE 2-13**.
- Transform faults involve two lithospheric plates sliding laterally past one another. Where these faults cross continents, such as along the San Andreas Fault through California, they cause major earthquakes. **FIGURE 2-14**.
- Hotspots form chains of volcanoes within individual plates rather than near plate boundaries. Because lithosphere is moving over hotspots fixed in Earth's underlying asthenosphere, hotspots grow as a trailing track of progressively older extinct volcanoes. **FIGURES 2-15** and **2-16**.

Development of a Theory

- The hypothesis of continental drift was supported by matching shapes of the continental margins on both sides of the Atlantic Ocean, as well as the rock types, deformation styles, fossil life forms, and glacial patterns. **FIGURES 2-17** and **2-18**.
- Continental drift evolved into the modern theory of plate tectonics based on new scientific data, including the existence of a large ridge running the length of many deep oceans, matching alternating magnetic stripes in rock on opposite sides of the oceanic spreading ridges, and age dates from oceanic rocks that confirmed a progressive sequence from very young rocks near the rifts to older oceanic rocks toward the continents. **FIGURES 2-19** and **2-20**.
- The scientific method involves developing tentative hypotheses that are tested by new observations and experiments, which can lead to confirmation or rejection.
- When hypotheses are confirmed by multiple sources of data over a long time, they become a theory—a widely accepted scientific fact.