Donald Hyndman | David Hyndman

Natural Hazards and Disasters

FIFTH EDITION

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***Natural Hazards and Disasters,* Fifth Edition**
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To Shirley and Teresa

for their endless encouragement and patience

About the Authors

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DAVID HYNDMAN is a professor in and the chair of the department of Geological Sciences at Michigan State University, where he has taught courses in natural hazards and disasters, the dynamic Earth, and advanced hydrogeology. His B.S. in hydrology and water resources is from the University of Arizona, and his M.S. in applied earth sciences and Ph.D. in geological and environmental sciences are from Stanford University. David was selected as a Lilly Teaching Fellow and has received the Ronald Wilson Teaching Award. He was the 2002 Darcy Distinguished Lecturer for the National Groundwater Association, is the 2016 Chair of the Board of Directors for the Consortium of Universities for the Advancement of Hydrologic Science, and is a Fellow of the Geological Society of America.

Brief Contents

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/9781305581692

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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 appear to 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 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, how to better recognize natural hazards, and to deal with those around them. 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 and understanding 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 errors. 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 critically evaluate 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 and processes that drive the hazard, the dangers associated with it, the methods of forecasting or predicting such events, and approaches to their mitigation. 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 within the Earth, 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, human actions, 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 two chapters on climate change address 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 chapter addresses asteroid impacts on Earth.

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. Coverage of natural hazards is balanced with excellent examples across North America and the rest of the world. As our global examples illustrate, although the same fundamental processes lead to natural hazards everywhere, 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 Fifth 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 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. New to this edition is a Survival Guide feature that highlights risk, preparedness, and safety information related to relevant hazards. 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 two separate chapters. That material is thoroughly reorganized, rewritten, and revised, with numerous new graphs and photos. Graphs have been updated with the most recent available information.

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

- **Chapters 3 and 4, Earthquakes**, include new coverage of the giant 2015 Nepal earthquake that killed more than 8600 people, destroyed most of the capital, Kathmandu and surrounding cities, and flattened most of its priceless ancient temples. We have added new insights on earthquakes associated with fracking, the latest way to drill for oil and gas. The moderate-size but destructive 2014 earthquake near Napa, California's iconic wine-growing area provides another wake-up call for this region.
- **Chapters 6 and 7, Volcanoes**, include an update on Hawaii's lava flows, which continued into 2015.
- **Chapter 8, Landslides**, features a new Case in Point on the tragic Oso landslide in western Washington, which occurred in a known hazard area that permitted building of a new subdivision.

- **Chapter 10, Weather, Thunderstorms, and Tornadoes**, has been significantly updated and revised. We have added coverage of the polar vortex, a process that is now better understood and more relevant to the public after millions of people in the northeastern United States lived through the bitterly cold winter of 2014. A new Case in Point focuses on the 2013 EF5 tornado that struck Moore, Oklahoma (the fourth in 14 years), killing many people who had no tornado shelters, in spite of federal support to partially pay for them. Another new Case is devoted to the severe California drought.
- **Chapters 11 and 12, Climate Change**, breaks the existing climate change coverage into two updated and expanded chapters. Chapter 11 focuses on processes related to climate change, whereas Chapter 12 focuses on the impacts of climate change and mitigation strategies. Coverage has been significantly expanded to encompass new data and illustrations from the 5th Intergovernmental Panel on Climate Change (IPCC).
- **Chapters 13 and 14, Streams and Floods**, features a new Case in Point about the disastrous 2013 flash floods in the Rocky Mountain foothills near Denver that provided a reminder of the Big Thompson canyon event almost 40 years before.
- **Chapter 16, Hurricanes and Nor'easters**, includes coverage of Hurricane Sandy in late 2012, which was a major wake-up call for those who view a "weak" hurricane as a minor inconvenience.
- **Chapter 17, Wildfires**, includes new Cases in Point about two large fires near Colorado Springs and the tragic Yarnell Hill fire in Arizona that killed 14 professional firefighters.
- **Chapter 18, Asteroid and Comet Impacts**, includes a new Case on the 2013 Chelyabinsk meteor in Russia, which was a frightening near miss that nearly became a catastrophe.

Ancillaries

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Donald Hyndman and David Hyndman

During Hurricane Sandy the east end of the Mantoloking Bridge, at left, was submerged, and houses on the barrier island battered. Some like the one in the lower left floated off their foundations.

Mark Olsen, NJ Army National Guard

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 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. Others 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. In October 2012, the devastating effects of Hurricane Sandy, only a Category 1 storm, reminded many people of the hazards of living on the Atlantic coast.

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

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.

Although 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 slowly building 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.

Donald Hyndman

Courtesy of the Utah Geological Survey (UGS)

FIGURE 1-1 **The Unexpected**

On December 12, 2013, a huge mass of sandstone separated from a prominent cliff above homes along Highway 9 in the community of Rockville, Utah, instantly killing the two home owners. This hazardous area of homes was highlighted in a Utah Geological Survey report in 2013. The same home was pictured as in a dangerous location in the previous edition of this textbook printed in late 2012, one year before the disaster.

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. Large or even gigantic events are a part of nature. Such abrupt events produce large results that can be disastrous if they affect people.

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 1-2**). 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 1-3** shows the approximate proportions of fatalities caused by typical natural hazards in the United States.

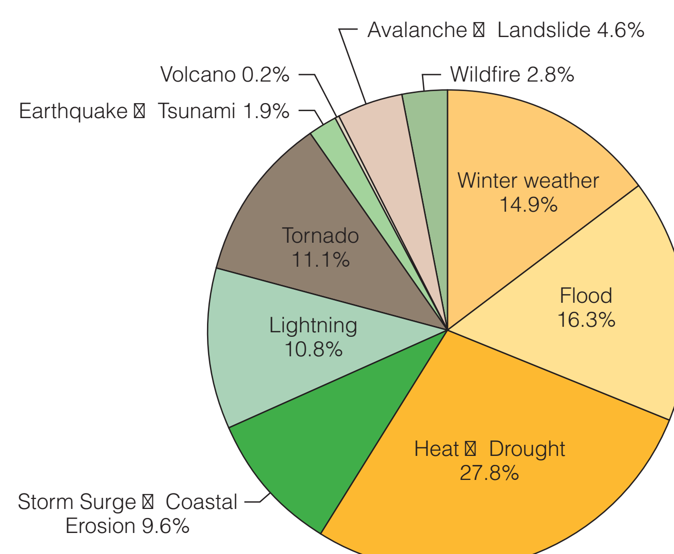
In the United States, heat and drought together account for the largest numbers of deaths. In fact, there were more U.S. deaths from heat waves between 1997 and 2008 than from any other type of natural hazard. In addition to heat stress, summer heat wave fatalities can result from dehydration and other 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 percent of fatalities between 1986 and 2008. Fatalities from flooding can result from

Ho new/UN Photo Logan Abassi/Handout/Reuters

FIGURE 1-2 A Disaster Takes a High Toll

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.



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

FIGURE 1-3 Hazard-Related Deaths

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 to 2008 was used.

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 man-made 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 1-4**). This is due in part to the increase in world population, which doubled in the 40 years between 1959 and 1999. By July 2015, it reached 7.3 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 crowding into 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.

The reality of climate change adds an additional dimension to these problems; it is one of the greatest challenges facing the human race. Scientists agree that global temperatures are rising. As world population grows and large numbers of people become more affluent and use larger amounts of resources, greenhouse gas emissions increase dramatically.

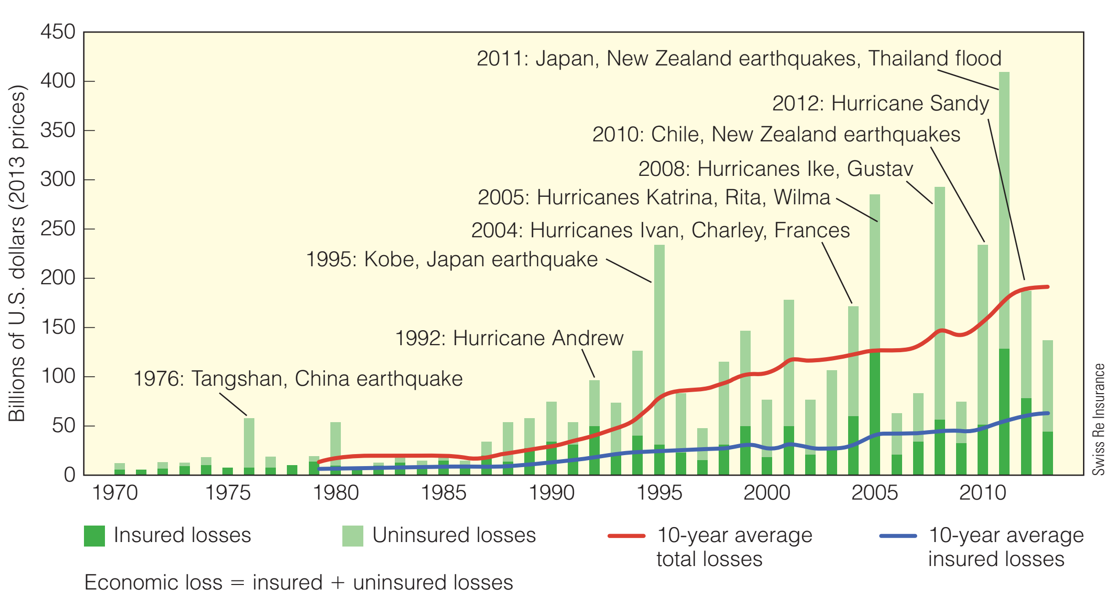


FIGURE 1-4 Increasing Costs of Natural Hazards

The cost of natural hazards is increasing worldwide. The 2011 earthquake and tsunami in Japan alone caused losses of about $235 billion.

Donald Hyndman

FIGURE 1-5 Homes at Risk

Homes along channels in the Mekong River delta in southern Vietnam are almost in the water under normal circumstances. They would be washed away in the next major cyclone.

Our generation of greenhouse gases seems likely to cause population collapse in some parts of the world, especially in poor areas most affected by natural hazards. People's living conditions will be severely disrupted. Millions will die from increased incidence of storms and coastal flooding, heat stroke, dehydration, famine, disease, and wars over water, food, heating fuel, and other resources.

Climate change is expected to lead to more rapid erosion of coastlines, along with more extreme weather events that cause landslides, floods, hurricanes, and wildfires. Some small islands in the Indian Ocean, far from the 2004 Sumatra earthquake's epicenter, were completely overwashed by tsunami waves. As sea level continues to rise, such low-lying islands will gradually submerge, even without a catastrophic event. Extensive low-lying coastal regions of major river deltas in Southeast Asia feed and are homes to millions of poor people. Deltas of the Ganges and Brahmaputra Rivers in Bangladesh, the Irrawaddy River in Myanmar, and the Mekong River in Vietnam and Cambodia are subject to 2-m ocean tides more than 200 km upstream (**FIGURE 1-5**). Major storms can submerge most of the deltas, including all of their rice fields and homes, under more than 2 m of water, with storm waves on top of that. Sea-level rise with climate change is expected to worsen those effects, killing thousands in major typhoons. The number of hurricanes has not increased significantly, but since 1990 the annual number of the most intense storms—Categories 4 and 5—nearly doubled to 18 worldwide in 2005 although the future trend remains unclear. Hurricane development and intensity depend on energy provided by higher sea-surface temperatures.

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 chance that a hazardous event will occur in a region within a few decades. 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 apprehension. The risk steadily increased during those years as the strain across the fault zone grew, as did the size of the population at risk. More than 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.

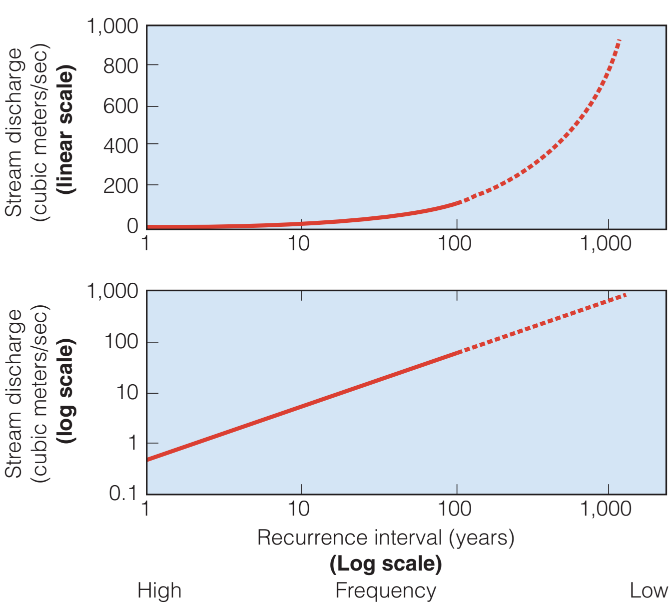


FIGURE 1-6 Recurrence Interval

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.

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.

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 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.

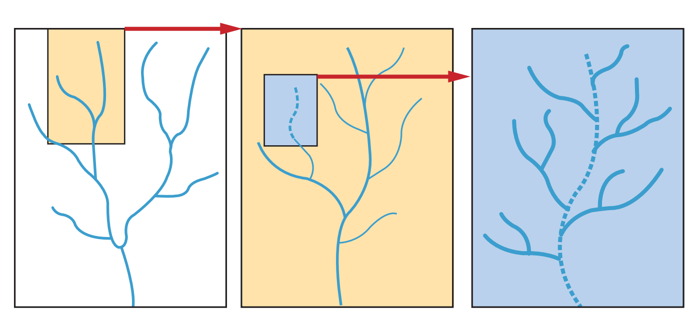


FIGURE 1-7 Fractal Systems

The general *pattern* 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.

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. What if, after an earthquake movement on a fault, one side of the fault is now across from a very slippery area of rock on the other side of the fault. Might then the fault break more easily and the next movement on the fault come sooner? Similar complex relationships arise with many other types of destructive natural events.

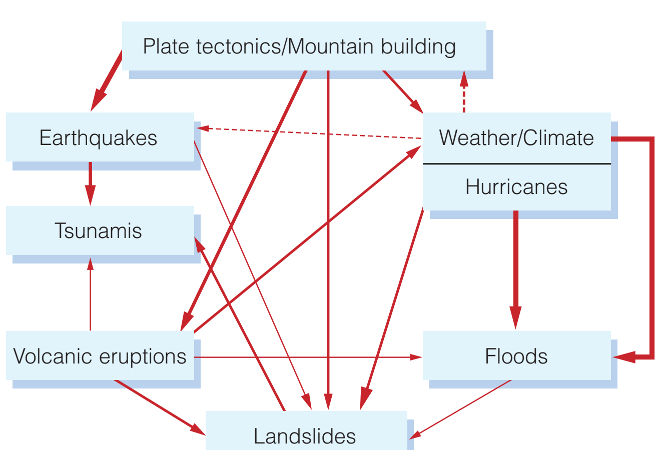


FIGURE 1-8 Interactions among Natural Hazards

Some natural disasters are directly related to others. The bolder arrows in this flowchart indicate stronger influences. Can you come up with words to describe these influences?

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 gas emissions and their effect on climate change (discussed in Chapter 12).

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.

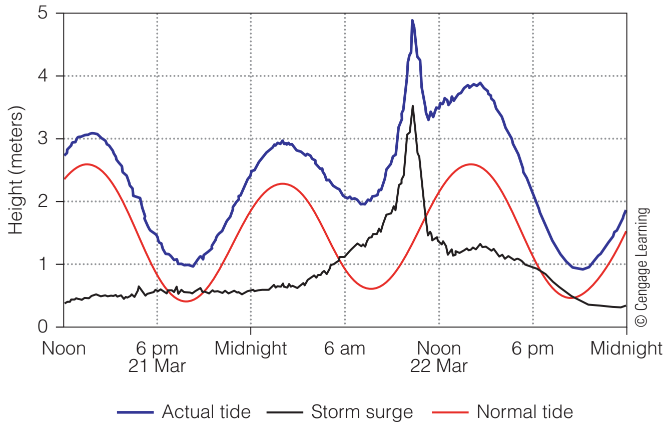


FIGURE 1-9 Amplification of Overlapping Effects

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.

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. "Soft" solutions for hazardous areas include zoning to prevent building in certain regions and strict building codes, which minimize damage and are much less expensive in the long run. "Hard" alternatives, including levees on rivers and riprap along coasts, are expensive, often short-term, and create other problems. Throughout 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 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.

Should landowners be permitted to do whatever they wish with their property? Property rights advocates often say yes. If a governmental entity permits building on land within its jurisdiction, should the taxpayers in the district shoulder the responsibility if there is a disaster? Should the government inform a buyer that a property is in a hazardous location and what the hazards are? Should a landowner be prevented from developing a piece of property that might be subjected to a disaster? If so, has the government effectively taken the landowner's anticipated value without compensation, a taking characterized in the courts as **reverse condemnation?**

FIGURE 1-10 Risky Development

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.

What about personal responsibility? As adults we like to think that we are responsible for our actions. That assumes, of course, that we know what we are doing and understand the consequences of our actions. If we build in the forest, surrounded by brush and trees, who should be responsible for fighting a forest fire (**FIGURE 1-11**)? Who should pay if we suffer loss? If we decide to build our home close to a stream, do we really understand enough about the natural behavior of streams to safely and responsibly do that? If the government were to restrict us from building on our own property, would they be infringing on our rights? If a future major flood wipes out our investment or causes severe damage to a downstream neighbor who sues us because of our construction, then what? Are we then likely to blame the government for permitting us to build there in the first place? If we demand personal rights, we need to be responsible for the consequences of our actions.

If you buy a property you later decide is at risk of a hazard, what responsibility do you have to a potential buyer? In many aspects of society, property sellers are held responsible if they are aware of some aspect of a property that is dangerous or damaged. Home owners commonly blame—and often sue—others for damages to property they have purchased. However, perhaps they should have remembered the old adage, "Buyer beware."

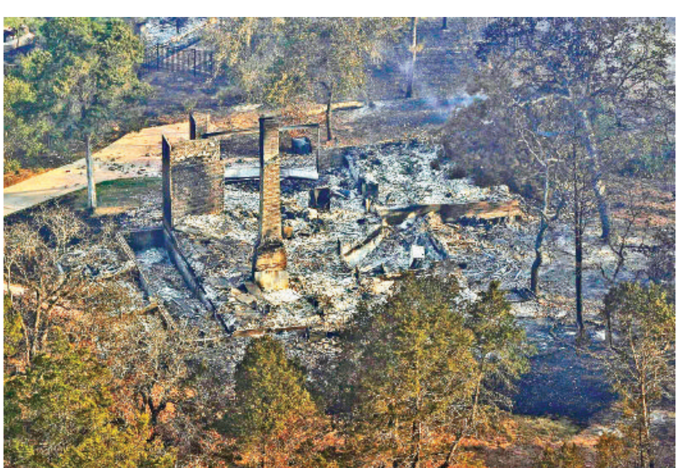
Insurance

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, and therefore the level of risk. 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 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 damages from such hazards. In those states, nonprofit 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.



Texas Parks and Wildlife

FIGURE 1-11 Who Should Pay?

Remains of a home surrounded by brush and trees that was destroyed by the Bastrop fire in Texas, 2011.

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].

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. Banks and others that make loans or provide insurance on property need to therefore be aware of natural processes and risks to their investments.

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 consider potential hazards, inventories of the hazards, direct damages, induced damages, direct economic and social losses, and indirect losses. To address the hazards and potential damages, they need to understand the hazards and processes that drive them.

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 it 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 often 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. Where the risk of earthquakes is high, the government places emphasis on preparing the public through drills and education programs (**FIGURE 1-12**).

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

Jessica Robertson, USGS

FIGURE 1-12 Earthquake Drill

The Great ShakeOut Earthquake Drill, October 16, 2014. Middle school students in Reston, Virginia, participate.

resistance. People losing their homes to a landslide are 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.

Different Ground Rules for the Poor

In countries where poverty is widespread, the forces that drive many people's behavior are different than those in prosperous countries. Food and shelter dictate where they live. In Guatemala and Nicaragua, giant corporate farms now control most of the fertile valley bottoms, leaving peasants little choice but to work for them in the fields at minimal wages and to provide their own shelter on the steep landslide-prone hillsides. Their choice of steep hillsides as a place to live is a hazardous one, but they have little choice to survive. Compounding the problem is that fertility rates and population growth in desperately poor countries are among the highest in the world, so more people are forced to live in less suitable areas.

The disaster differences between poor and more affluent countries were accentuated in early 2010 by the earthquakes in Haiti and Chile. The magnitude 7.0 Haiti earthquake, which struck near the capital city of Port-au-Prince, killed more than 159,000 people and left 1.3 million homeless, whereas the magnitude 8.8 earthquake in Chile killed about 800. Although the Chile earthquake was about 500 times stronger at its epicenter, it caused far fewer fatalities. The greatest difference was that Haiti has no building codes, and even if it did, most people have no money to follow them. The annual per capita income for Haiti is only $834*, so most people live on only about $2 per day. Most are uneducated and cannot even read or write. Chile, however, is the wealthiest country in Latin America with an annual per capita income of $14,520*. Being along one of the world's most active subduction zones, Chile is very familiar with earthquakes; its building codes, upgraded after the 1960 earthquake (the world's largest), are among the strongest in the world.

The 2015 magnitude 7.8 earthquake in Nepal provided a severe reminder of the hazards of a small, poor country living in the collision zone of two major tectonic plates. The ancient Indian plate's ongoing collision with the Asian plate crumples the country to raise the Himalayas, the highest mountain range in the world.

Walls of most buildings in the country were constructed from loose stone or bricks with little or no mortar. Heavy poured concrete floors of two- to four-story buildings were supported on thin concrete posts with little or no reinforcing. Shaking from that strong earthquake on such heavy, weak, and rigid structures collapsed many like a tall stack of kid's blocks. Large aftershocks brought down many buildings weakened by the main shocks. More than 9000 people died, most crushed under tons of masonry (**FIGURE 1-13**).

The example of Hurricane Katrina, in New Orleans in 2005, provides additional understanding of the effects of a catastrophic event on poor people, even in an affluent country (**FIGURE 1-14**). Despite clear prediction of a dangerous storm approaching, many residents had no means to leave the city and nowhere to go even if they could have left. Ten days after the storm, an estimated 10,000 people still refused to leave their homes in flooded and seriously contaminated

Photo by Dr. Rebecca Bendick and Ellen Knappe, University of Montana

FIGURE 1-13 Earthquake Aftermath

Buildings in Kathmandu and most other cities in Nepal collapsed into piles of bricks and stone, providing occupants little chance of survival.

*World Bank, 2014.

FIGURE 1-14 Failed to Evacuate

Survivors of Hurricane Katrina wait on a roof for rescue. Why did they not evacuate when warned? Lack of transportation? Previous false alarms?

areas. The predominantly poor people from the eastern part of the city, who were unable to evacuate before the storm's arrival, made up most of the flood survivors who crowded into the Superdome and the Convention Center during the storm. Before Katrina, 23% of New Orleans residents lived below the poverty line. Many survived from day to day, had no savings or working cars, and lived in rented homes or apartments. Less than half of New Orleans residents had flood insurance.

A major problem for many families—especially the poor—was separation of family members during evacuation and the storm. For example, a mother or father evacuated with children but left behind an elderly parent who couldn't be moved. In some cases, parents were separated from their children during evacuation, or one parent left to help a relative, friend, or neighbor and was unable to return. Because their home was no longer a point of reference, communication became difficult or impossible.

In the case of Hurricane Katrina, evacuees' medical problems were compounded by the storm. Patients could not find their doctors and doctors could not find their patients. Patients on prescription medications or undergoing specialized treatments often could not remember the names of their medicines or the details of their treatments. Years of medical records were lost.

For such poor societies, the reduction of vulnerability to natural hazards does not depend much on strengthening the zoning restrictions against living in dangerous areas or improving warning systems, though education can help. More so, it depends on cultural, economic, and political factors. Because more affluent individuals and corporations control many of those factors, the poor are left to fend for themselves.

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.

Overall, as a society, we seem to be following trends recognized by Jared Diamond in his book *Guns, Germs, and Steel: The Fates of Human Societies* (1999). Diamond recounts the collapse of ancient civilizations that failed to anticipate a problem, failed to recognize an existing problem, or neglected to fix the problem until it was too late. For gradual problems, many even denied that there was a problem. In some cases, they denied that they themselves were the cause of the problem and therefore could not see a solution. Does this sound like today? Throughout this book, we address natural hazards that affect us, some sudden and unexpected (for example, earthquakes, some landslides); some repeated but which we address with temporary short-term fixes (floods, hurricanes), and some slow and insidious that we deny exist or that we contribute to (climate change).

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, but then they often regress because of local pressure from groups of affected residents or from groups wanting to develop an affected site. 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.

Where are specific natural hazards most widespread? Where can we live to avoid them? As **FIGURE 1-15** shows, there is no easy answer: There are earthquakes along the West Coast, especially in California; wildfires throughout the western states, especially in southern California; tornadoes in the Midwest and farther east; hurricanes and floods along the Gulf Coast and central Atlantic coast; flash floods in southern California; sinkholes in Florida; and landslides and floods happen throughout the country, including in the Great Plains. These hazards can be found almost anywhere, although they may vary in severity. Volcanoes are active in the Pacific Northwest, and tsunamis can affect almost any coast. How do we stop the rise of global warming and learn to live with its worsening effects? You may believe you will not be impacted by a major hazard, but you may well be wrong. The following chapters help you decide what natural hazards are most likely to affect you wherever you live—and how to avoid them.

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.

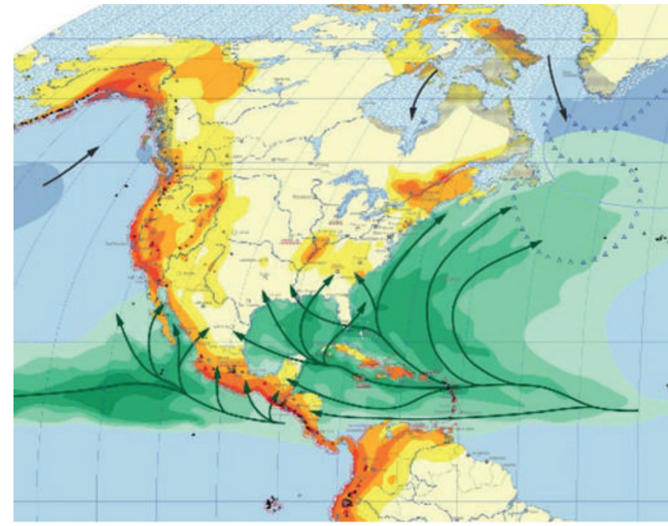


FIGURE 1-15 Living with Tropical Storms

Tropical storms (green) sweep north along the East Coast and up through the Gulf of Mexico, bringing sometimes severe weather to the central and eastern United States (no map color). Earthquakes (yellow to red) concentrate near the West Coast and Intermountain West.

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 1-3**.
- 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 1-4**.
- Climate change and global warming potentially increase the severity of weather-related hazards.

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 in a feedback effect.
- 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.
- In poor societies, the reduction of vulnerability to natural hazards does not depend on zoning restrictions or improving warning systems but on cultural, economic, and political factors.

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. 9
land-use planning, p. 8
magnitude, p. 5
mitigation, p. 8
natural disaster, p. 3
natural hazard, p. 3
precursor event, p. 7
recurrence interval, p. 5
risk, p. 9
reverse condemnation p. 8

Questions for Review

1. What are some of the reasons people live in areas prone to natural disasters?
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 natural hazards in the United States?
6. What are the main reasons for the ever-increasing costs of catastrophic natural 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 a prediction and a 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 100 years and the stream flooded last year, what is the probability of the stream flooding again this year?
13. What are the two main factors insurance companies use to determines the cost of an insurance policy for a natural hazard?
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, describe 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?
5. What are the main natural hazards in the region where you currently live or where you grew up?
6. If I sell a house that is later damaged by landsliding, who is responsible, that is, what are the main considerations?
7. When the federal government provides funds to protect people's homes from floods or wildfires, individual home owners benefit at the expense of taxpayers. What are the two main types of alternatives to eliminate taxpayer expense for natural hazard losses?
8. What is meant by the expression "Those who ignore the past are condemned to repeat it"? Provide an example related to natural hazards.
9. When we note that people need to take responsibility for their own actions when living in a hazardous environment, what is different about the behavior of poor people living in underdeveloped countries?

The Himalayas of Nepal mark the collision zone between the Eurasian tectonic plate and the northward-moving plate containing India.

Donald Hyndman

2 Plate Tectonics and Physical Hazards

The Big Picture

Why is the Pacific coast of North America so rugged and mountainous, with steep slopes prone to landslides, whereas the Atlantic coast is relatively flat with gently sloping beaches? Why are most active volcanoes and large earthquakes concentrated near the edge of the Pacific? Why are most tsunamis in the Pacific Ocean rather than the Atlantic? Why do the continents on the edges of the Atlantic Ocean look like they would fit if you were to push them together? The answers to all of these questions and many others lie in the theory known as plate tectonics.

We now know that giant blocks of the upper layers of Earth move around, grind sideways, collide, or sink into the hot interior of the planet where they cause melting of rocks and formation of volcanoes. Those collisions between tectonic plates squeeze up high mountain ranges, even as landslides and rivers erode them away. To understand these processes and associated hazards, we need to understand the forces that drive them. Natural hazards of all kinds are ultimately driven by mountains, oceans, coasts, and the weather and climate that they control.

Earth Structure

At the center of Earth is its **core**, surrounded by the thick **mantle** and covered by the much thinner **crust** (**FIGURE 2-1**). 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 called 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 842°F) 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.

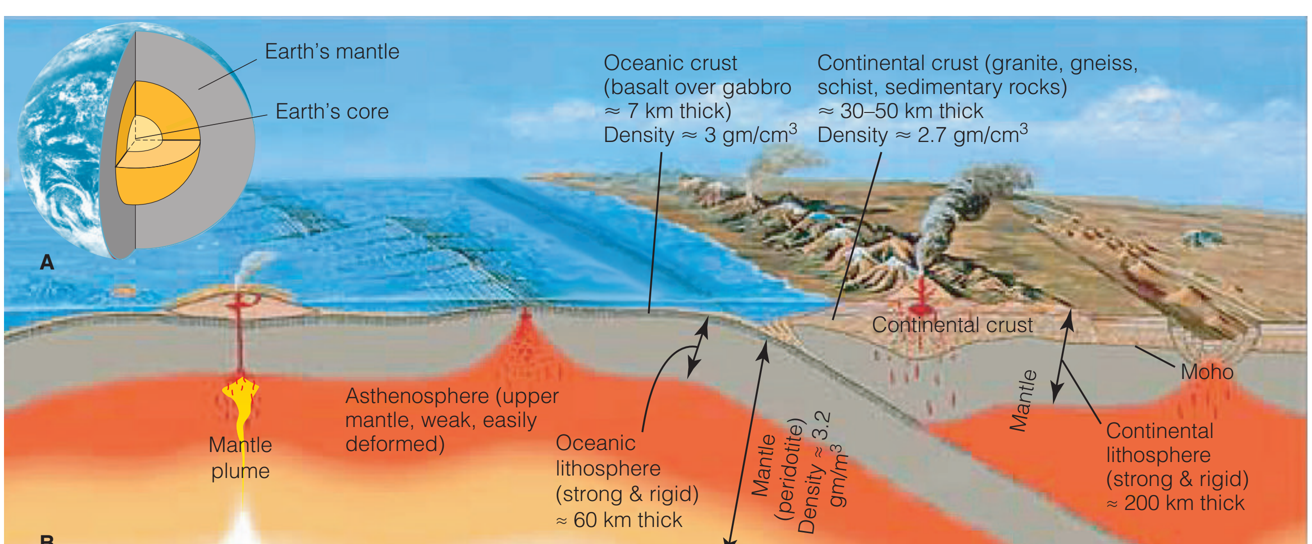


FIGURE 2-1 Earth Structure

A (whole-Earth inset). 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 (main diagram). 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*.

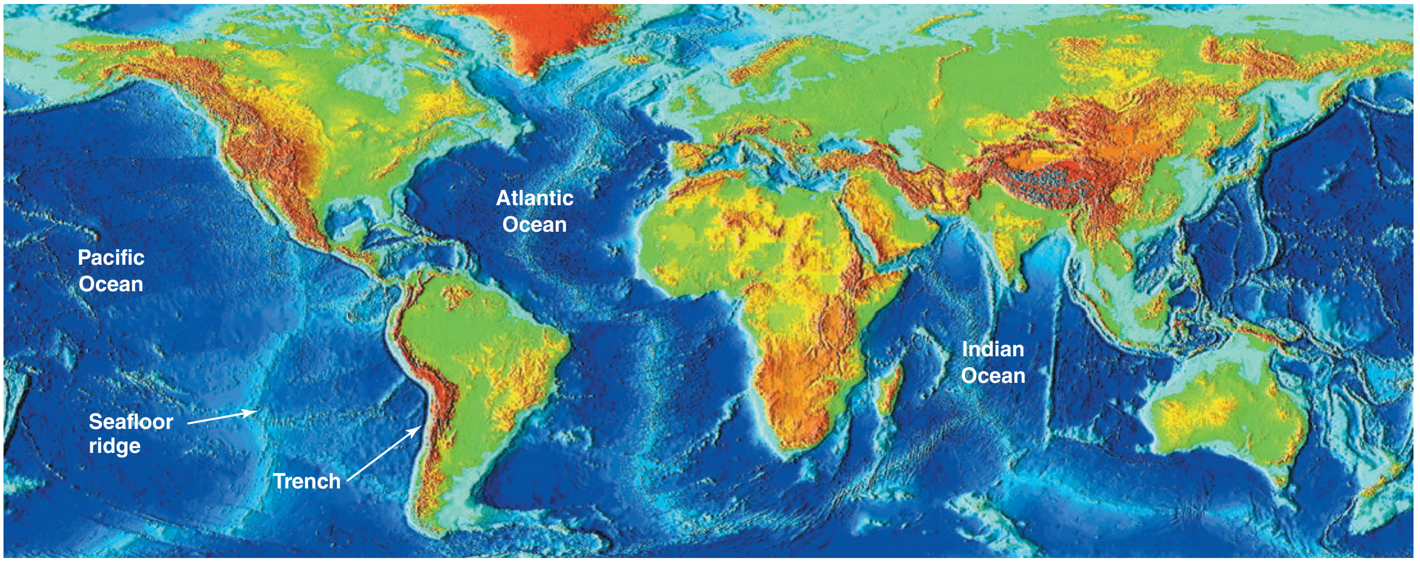


FIGURE 2-2 Mountain Ranges

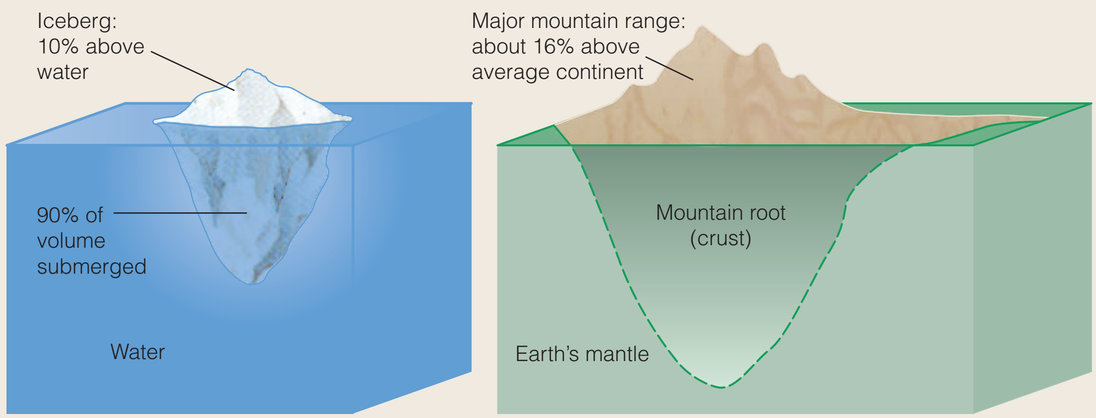
This shaded relief map shows the continents standing high. Mountain ranges in red tones concentrate at some continental margins. Dark blue areas are the deep ocean floor. Light blue seafloor ridges in oceans are mountain ranges on the ocean floor. Dark blue trenches are deep subsea valleys.

As the ice melted, these areas gradually rose back toward their original heights.

About 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 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

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.

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 that makes up the mountains 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 this one, 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. Most plates consist of a combination of continent and ocean areas. About half of the South American Plate lies under the Atlantic Ocean and half is 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 rates up to 8 cm (3.2 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.

Some plates separate, others collide, and still others slide under, over, or past one another (**FIGURES 2-3** and **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

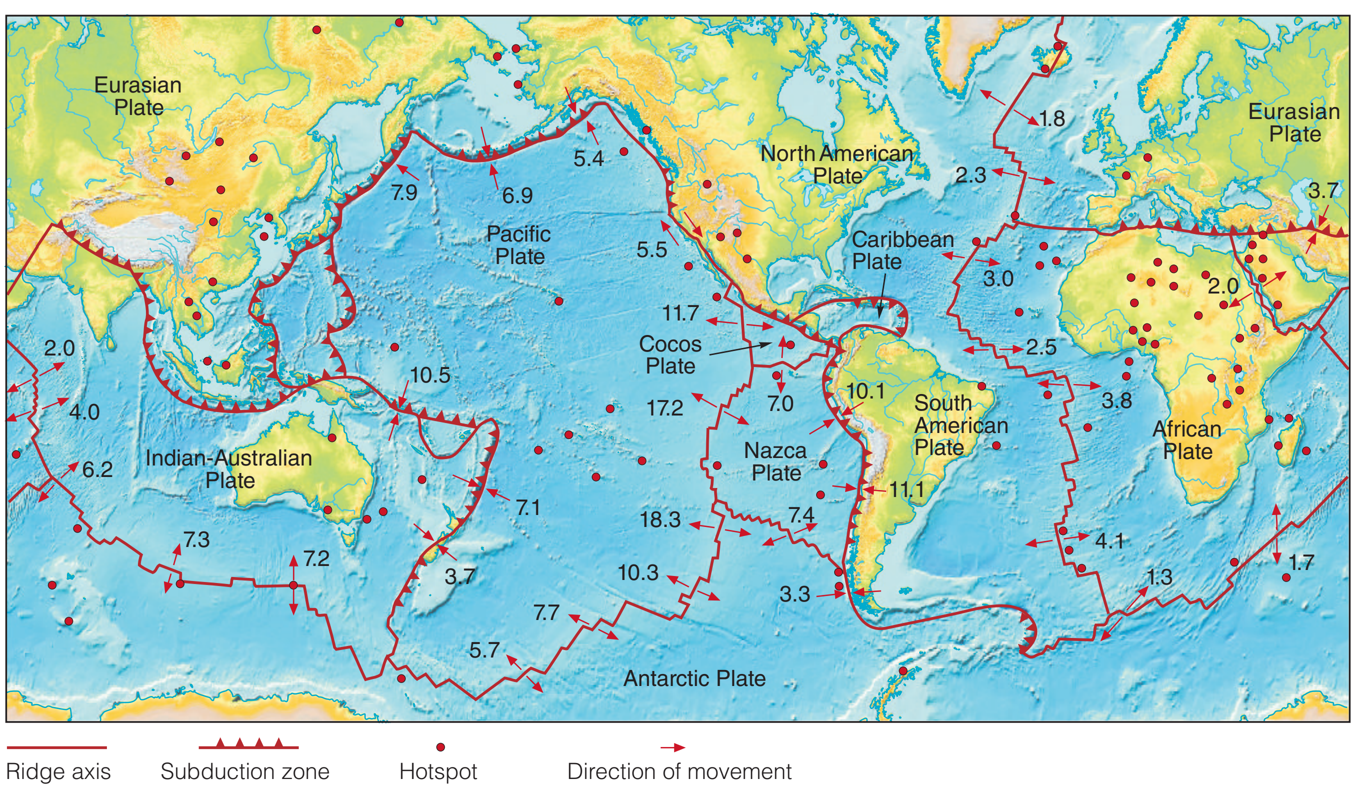


FIGURE 2-3 Lithospheric Plates

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.

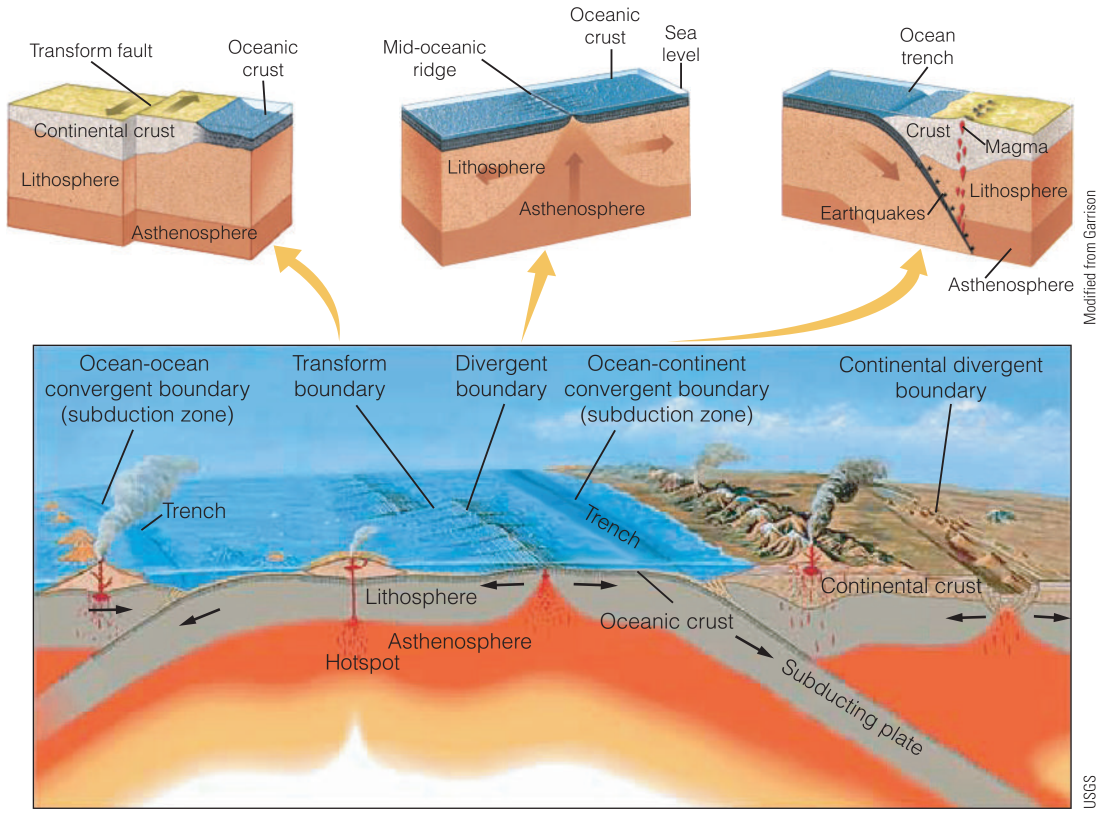


FIGURE 2-4 Plate Boundaries

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

down, or be *subducted*, into the asthenosphere, forming a **subduction zone**. When two continental plates collide (**collision zone**), 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 drift 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 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.

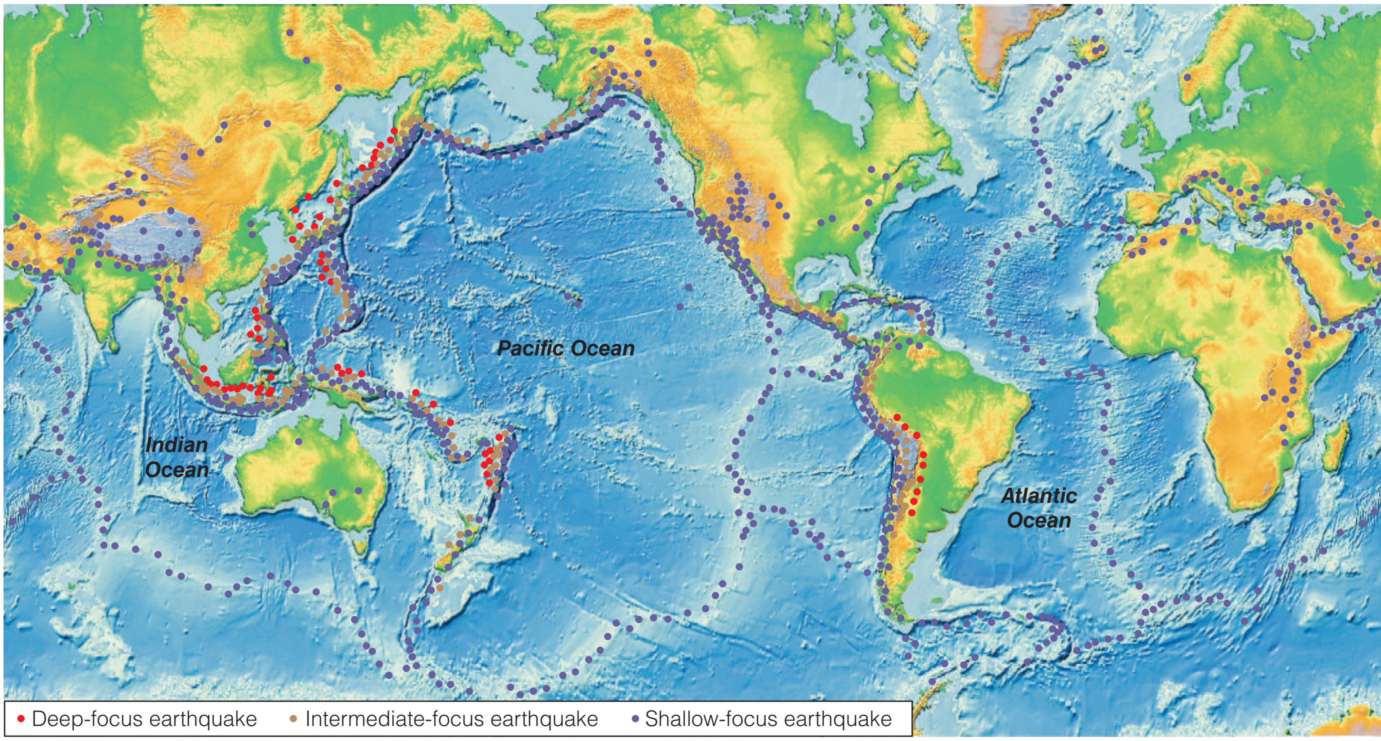


FIGURE 2-5 Earthquakes at Plate Boundaries

Most earthquakes are concentrated along boundaries between major tectonic plates, especially subduction zones and transform faults, with fewer along spreading ridges. The depth at which the earthquake occurred is called the focus, and is shown in different colors.

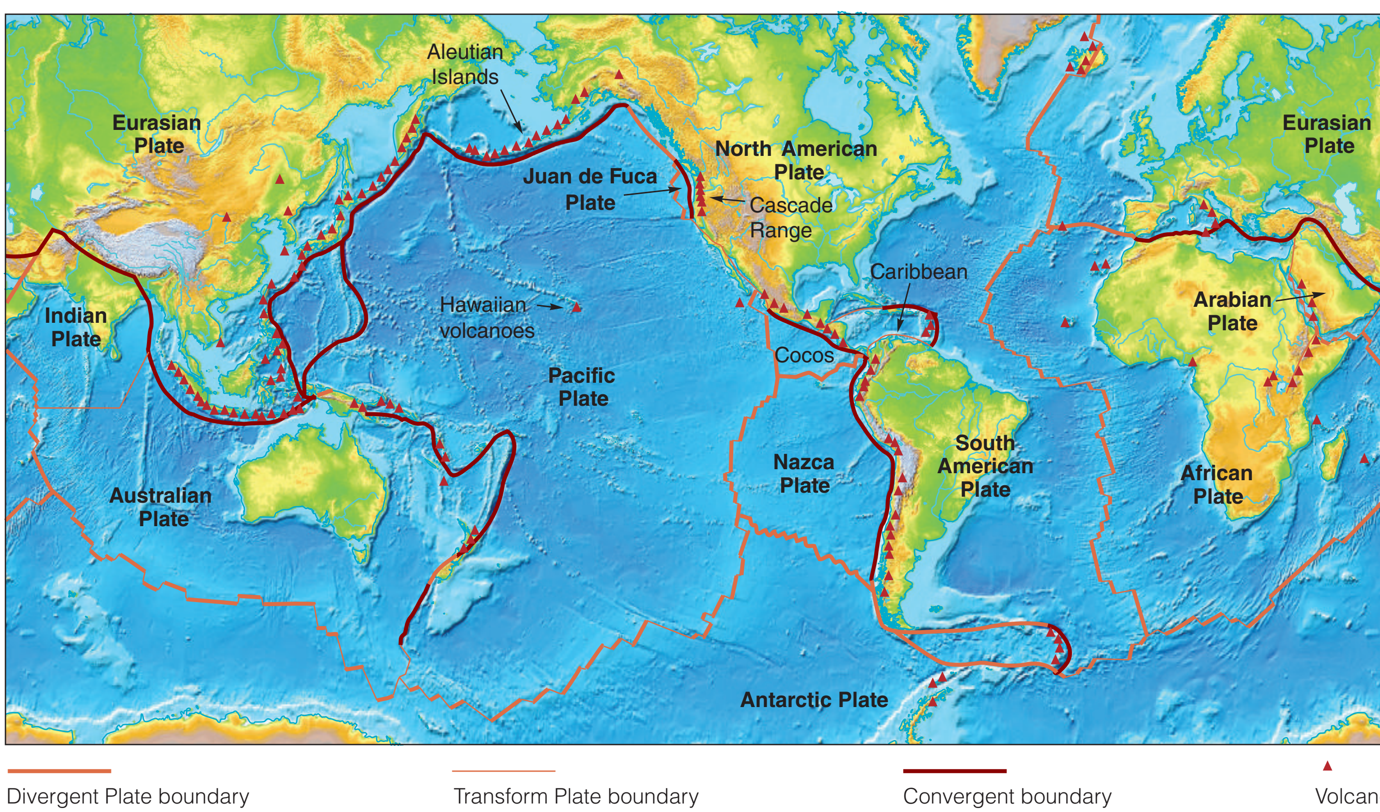
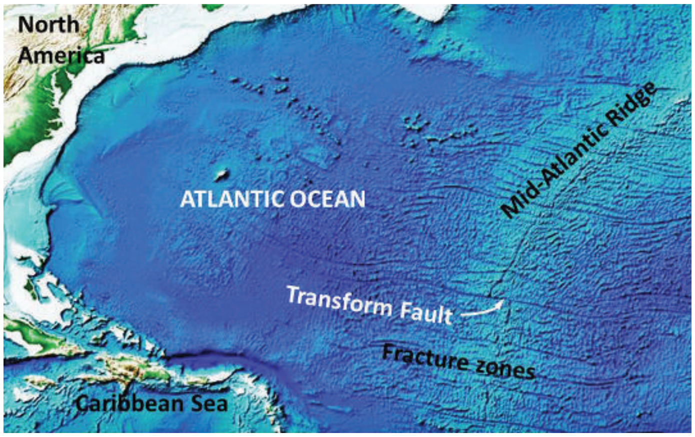


FIGURE 2-6 Volcanoes Near Plate Boundaries

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.



NGDC-NOAA

FIGURE 2-7 Mid-Oceanic Ridge

The spreading Mid-Atlantic Ridge, fracture zones, and transform faults are dramatically exhibited in this topography of the ocean floor. Fracture zones across the ridge are parallel to the spreading-movement direction but not necessarily perpendicular to the ridge. Transform faults are offsets (e.g., of ridge crests) along fracture zones.

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.

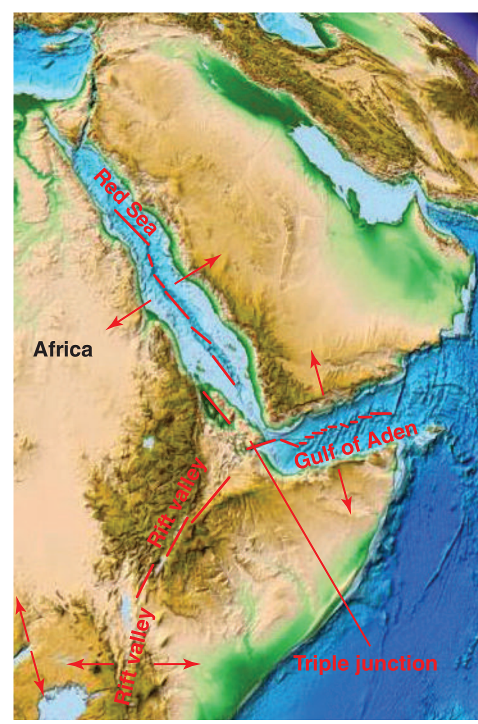
These spreading centers are the source of the basalt lava flows that cover the entire ocean floor, roughly two-thirds of Earth's surface, to an average depth of several kilometers. The molten basalt magma rises to the surface, where it comes in contact with water. It then rapidly cools to form pillow-shaped 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.

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 central 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 at any time. 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 early stage of a future ocean. Continental rifts, such as the Rio Grande Rift of New Mexico and the Basin and 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. 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



NOAA basemap

FIGURE 2-8 Beginning of an Ocean

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 along more rapidly spreading rifts.

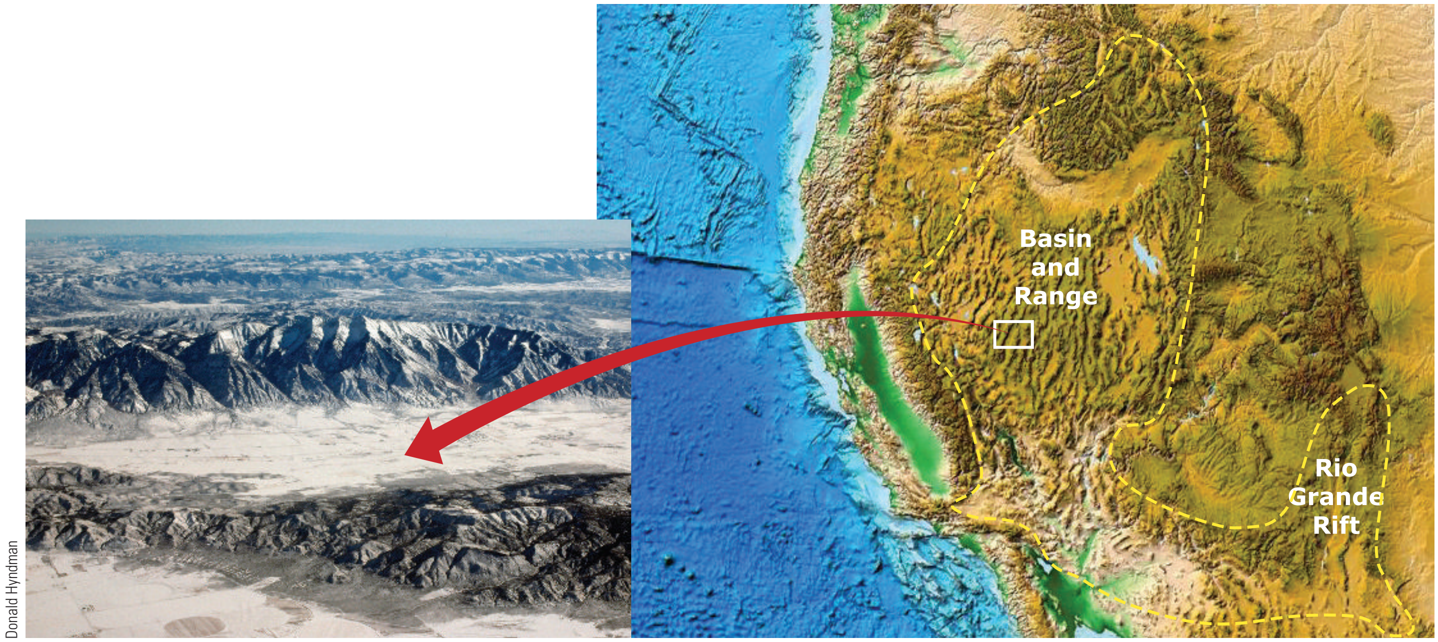


FIGURE 2-9 Continental Spreading

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 between 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 near the east side of Great Salt Lake, Utah. An eastern branch includes the Rio Grande Rift of central New Mexico.

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 Table 6-1). 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 volcanoes. 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.

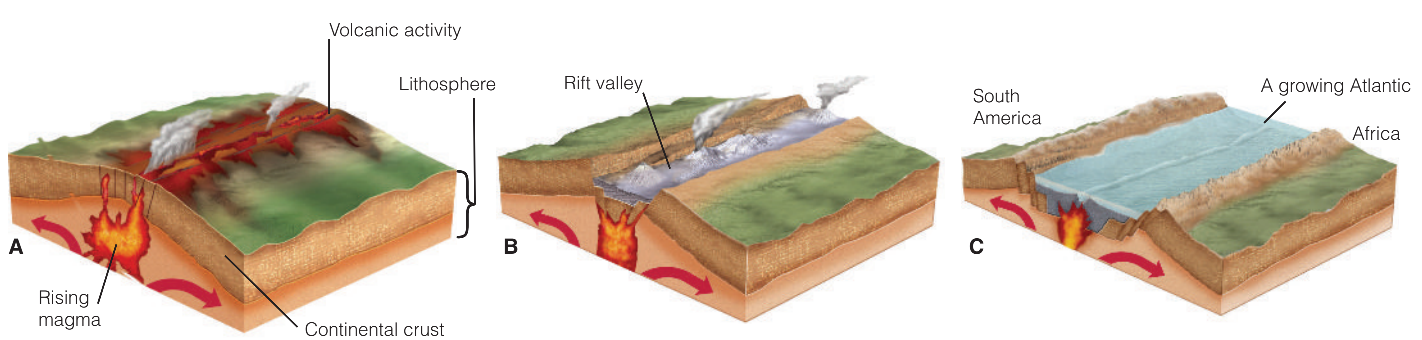


FIGURE 2-10 Evolution of a Spreading Ridge

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. A, B, and C show progressive stages in opening of the ocean, beginning with swelling of the hot lithosphere. This spreading eventually results in an ocean basin, as shown in C.

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.

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 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.

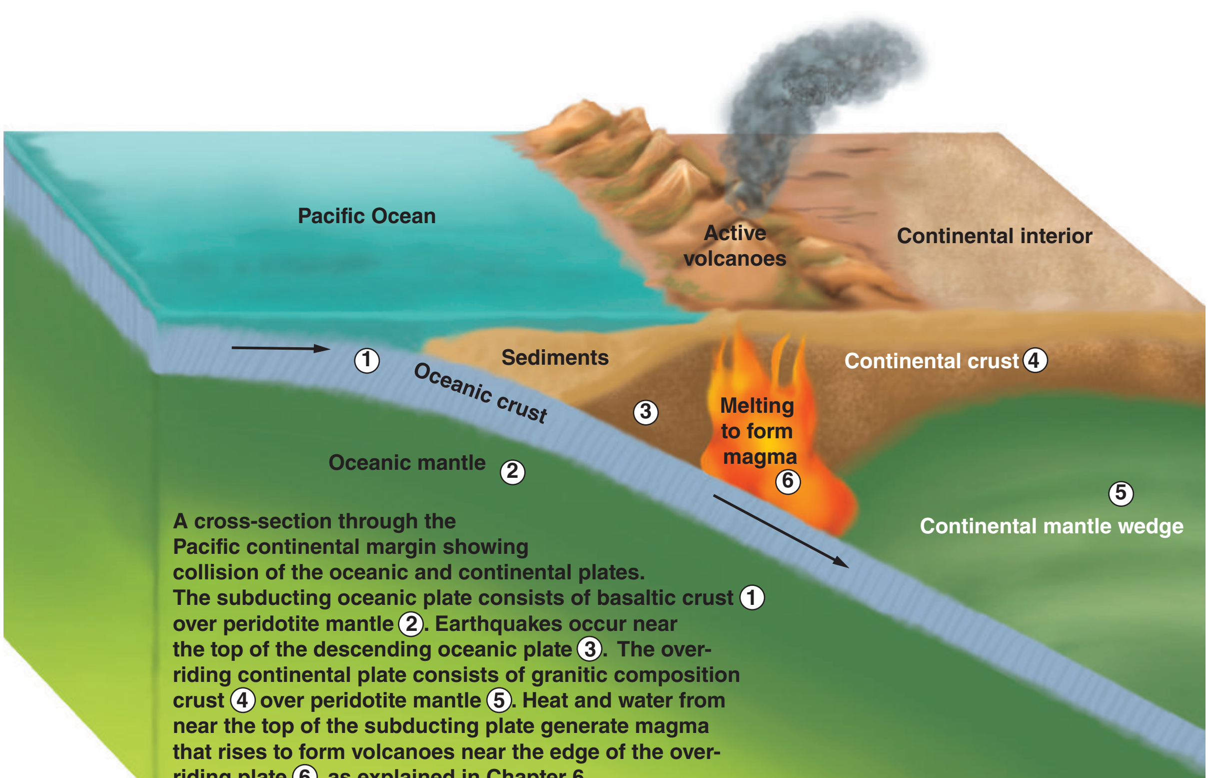
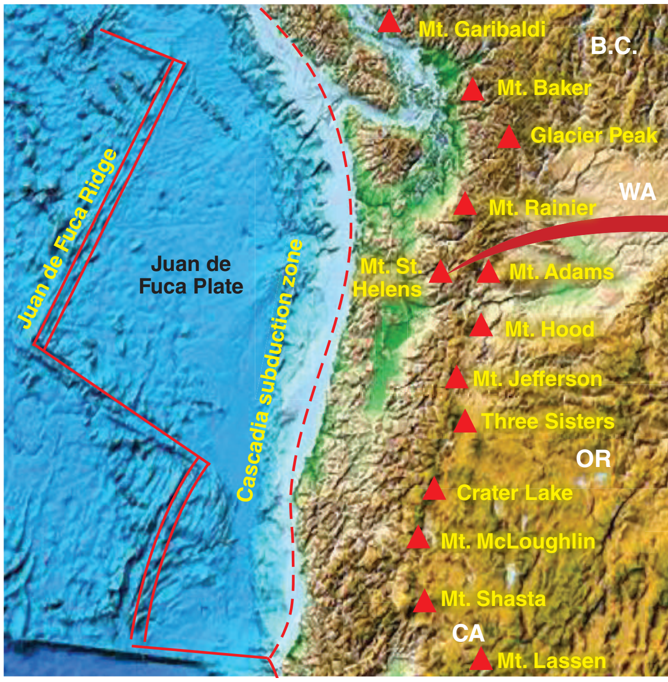


FIGURE 2-11 **Subduction Zone Processes**



NOAA basemap

John Pallister, USGS

FIGURE 2-12 Volcanoes Near Subduction Zones

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, to the north) are two of the picturesque active volcanoes that lie inland from the Cascadia subduction zone.

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 such as the 2011 earthquake in Japan. 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 such as in the 2015 earthquake in Nepal. 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 away from them. The section of the fault between the offset ends of the spreading ridge has significant relative movement (**FIGURE 2-14A**). 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 2-14B**) is a well-known continental example. 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.

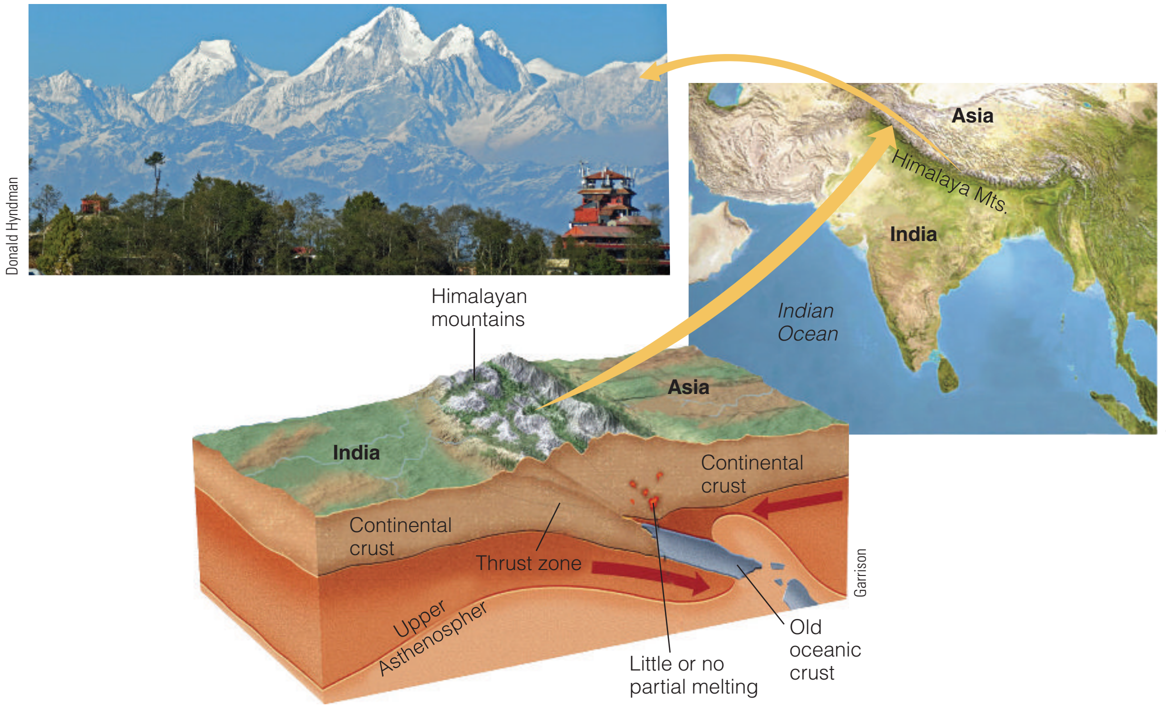


FIGURE 2-13 **Continental Collision Zones**

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.

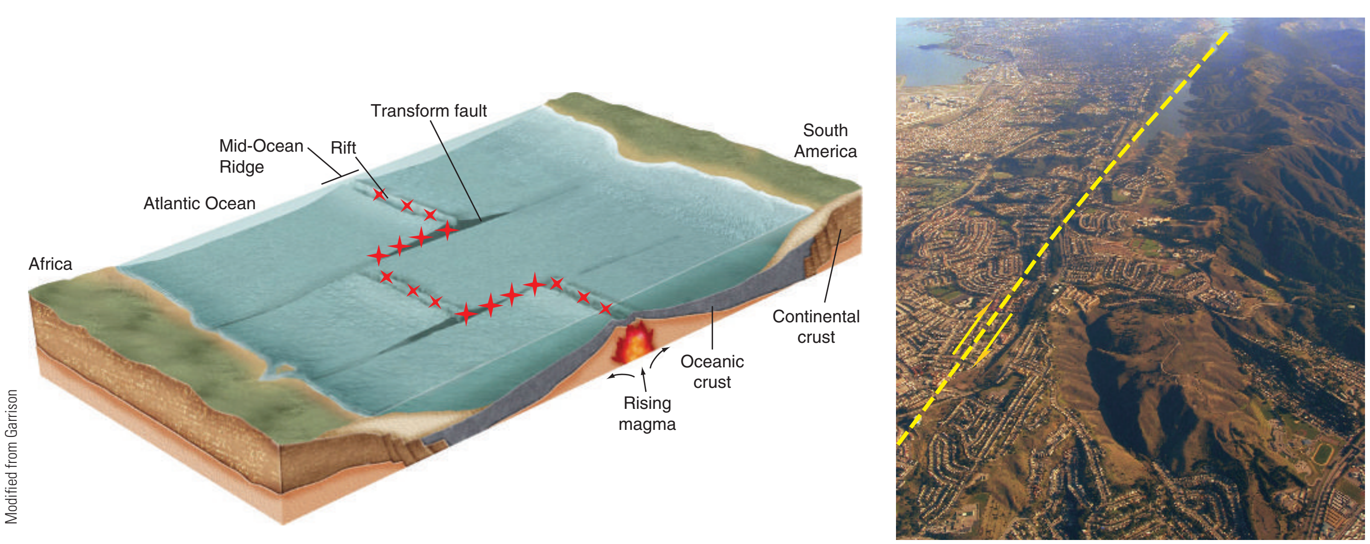


FIGURE 2-14 **Transform Fault**

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.

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 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

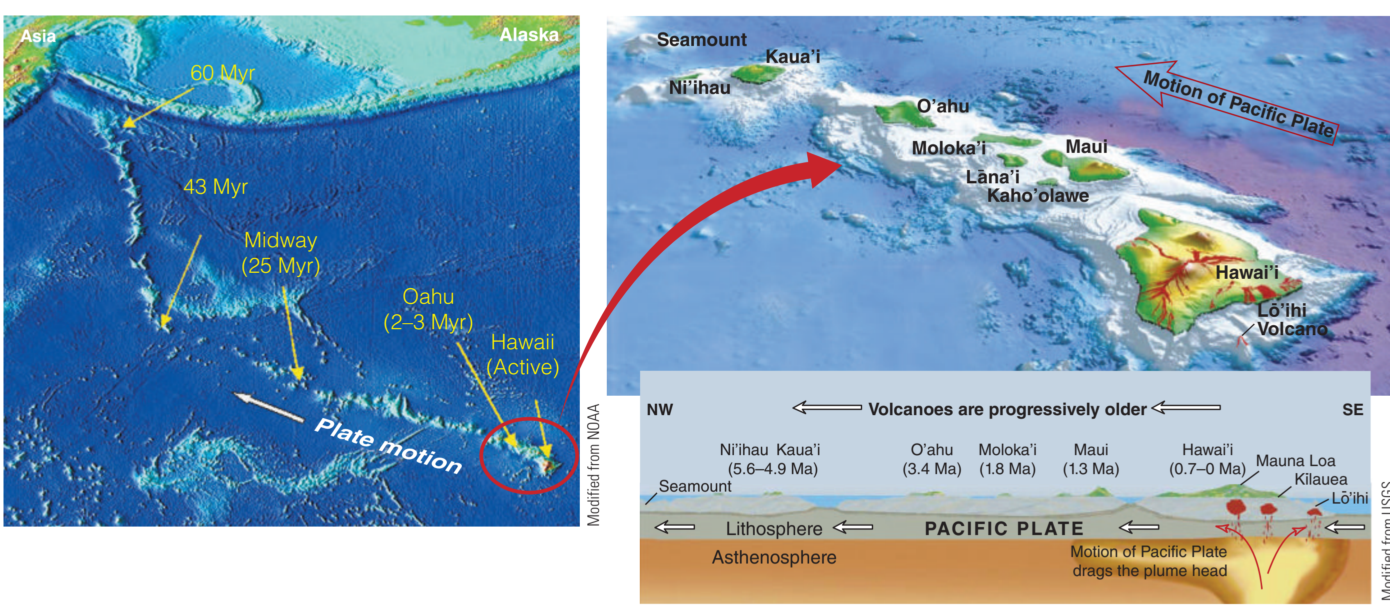
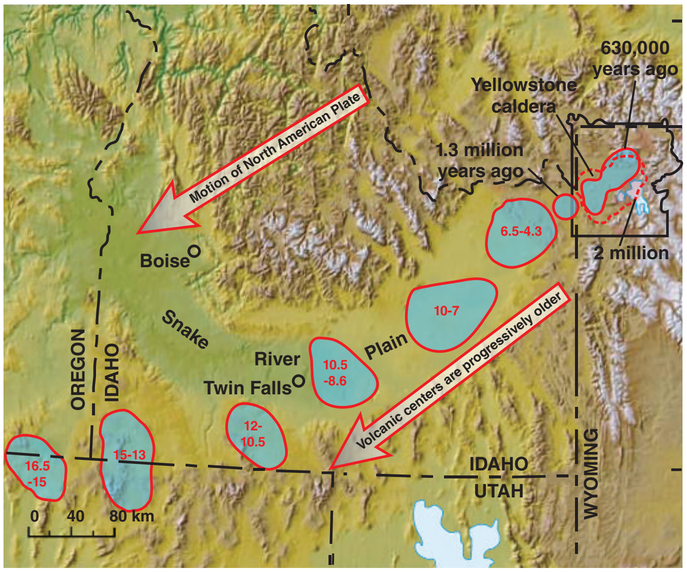


FIGURE 2-15 Oceanic Hotspots

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 the Earth for millions of years. 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.



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

FIGURE 2-16 Continental Hotspots

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.

containing the hotspot is not itself moving. Comparison of different hotspots suggests that this is generally valid compared with migration of the tectonic plates, but many researchers suggest that it is not absolutely so.

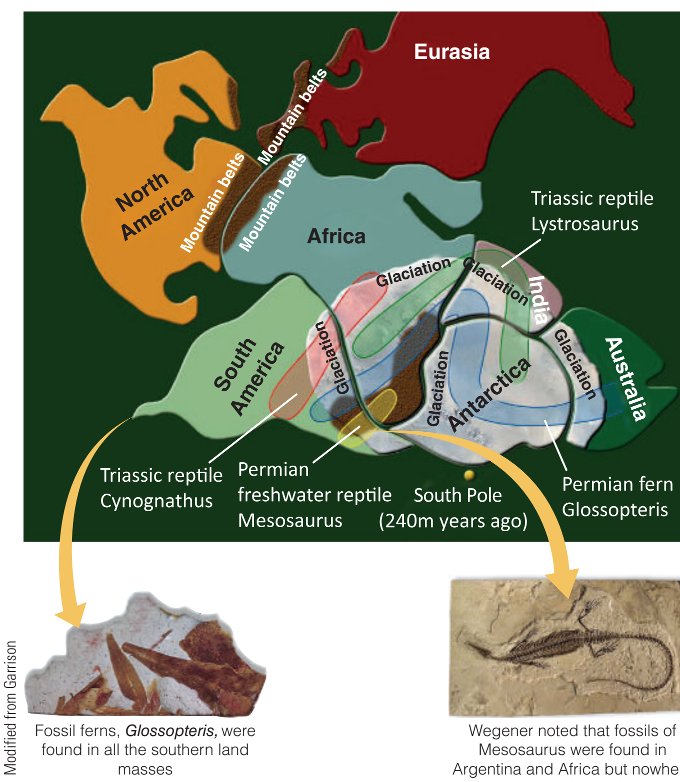
The Snake River Plain of southern Idaho is probably the best example of a continental hotspot track. Along this track is a series of extinct *resurgent calderas*, depressions where the erupting giant volcano collapsed. Those volcanoes began to erupt some 14 million years ago. They track generally east 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 that remain 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?

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 2-17**). 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. 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



Modified from Garrison

The U. of Edinburgh (2009)

FIGURE 2-17 Continents Once Fit Together

Before continental drift a few hundred million years ago, the continents were clustered together as giant supercontinent Pangaea. The Atlantic Ocean had not yet opened. The continents match almost perfectly at the continental shelves, which are part of the continents. Some distinctive fossils and mountain ranges lie in belts across the Atlantic and Indian oceans.

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,

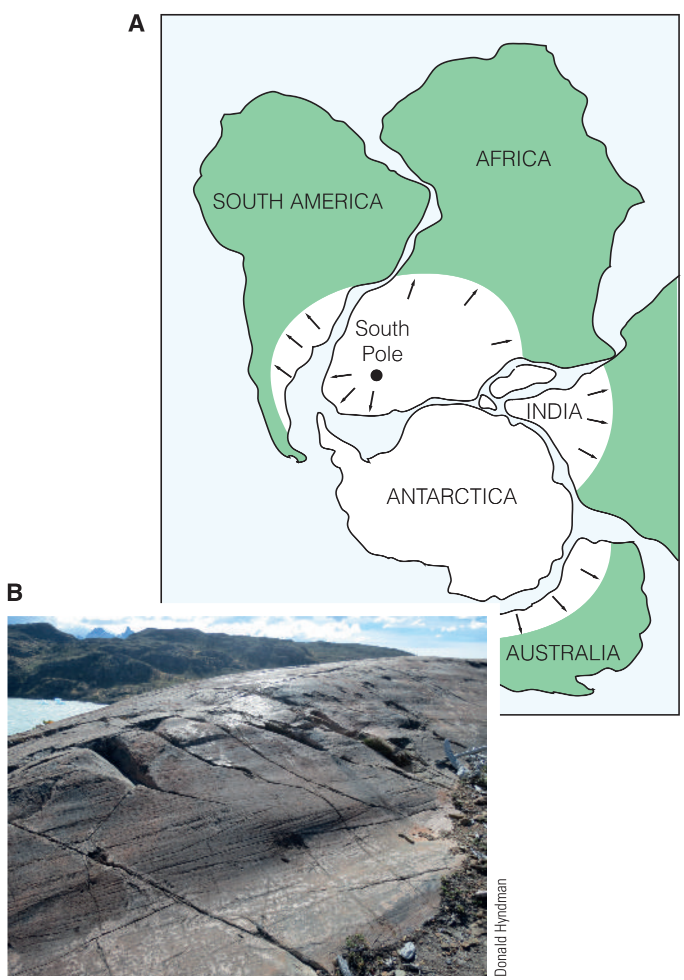


FIGURE 2-18 Glaciation in Warm Areas

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 in Torres del Paine, Chile, part of the largest remaining ice field in South America.

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.

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. Oceanographers from Woods Hole Oceanographic Institution 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. 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 2-19**). 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

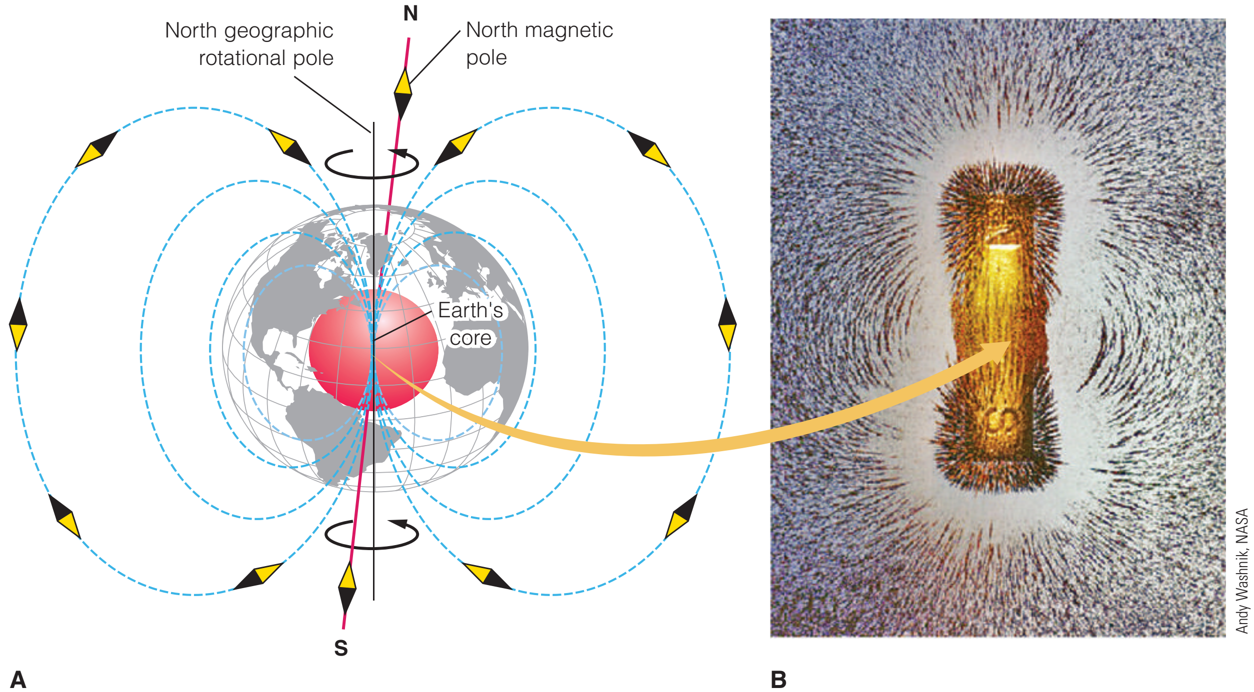


FIGURE 2-19 **Earth's Magnetic Field**

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".

parallel to the mid-oceanic ridge (**FIGURE 2-20**). 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 Institutions 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 2-21**).

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 2-22**).

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

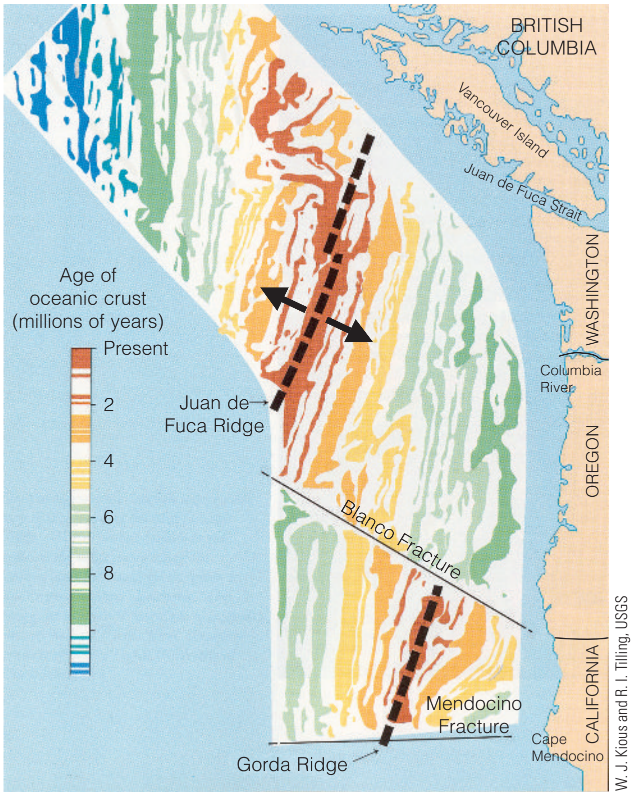


FIGURE 2-20 **Magnetic Record of Ocean-Floor Spreading**

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.

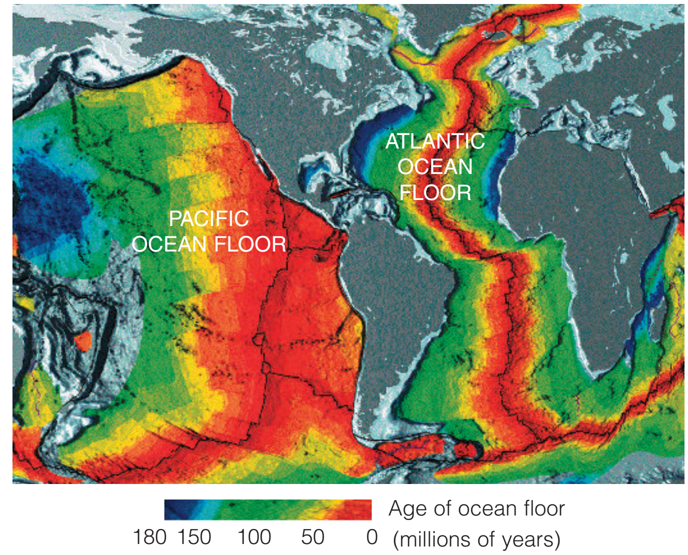


FIGURE 2-21 **Ages of Ocean Floor**

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.

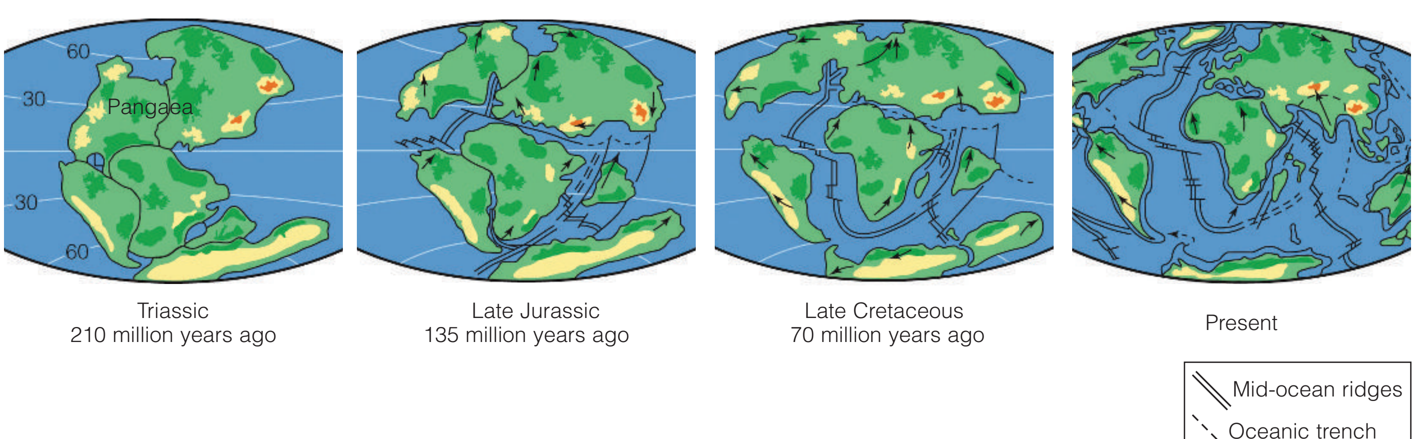


FIGURE 2-22 **Continents Spread Apart**

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** to **2-22**.
- The scientific method involves developing tentative hypotheses that are tested by new observations and experiments, which can lead to confirmation or rejection of the hypothesis.
- When hypotheses are confirmed by multiple sources of data over a long time, they become a theory—a widely accepted scientific fact.

Key Terms

- asthenosphere, p. 17
- collision zone, p. 20
- continental drift, p. 29
- convergent boundary, p. 19
- core, p. 17
- crust, p. 17
- divergent boundary, p. 19
- hotspot volcano, p. 27
- hypothesis, p. 28
- isostacy, p. 17
- lithosphere, p. 17
- lithospheric plate, p. 19
- magnetic field, p. 29
- mantle, p. 17
- mid-oceanic ridge, p. 20
- Pangaea, p. 28
- plate tectonics, p. 19
- rift zone, p. 22
- scientific method, p. 30
- seafloor spreading, p. 20
- spreading center, p. 22
- subduction zone, p. 20
- theory, p. 28
- transform boundary, p. 20
- trench, p. 20

Questions for Review

1. Describe differences between Earth's crust, lithosphere, asthenosphere, and mantle.
2. What does oceanic lithosphere consist of and how thick is it?
3. What are the main types of lithospheric plate boundaries described in terms of relative motions? Provide a real example of each (by name or location).
4. Why does oceanic lithosphere almost always sink beneath continental lithosphere at convergent zones?
5. Along which type(s) of lithospheric plate boundary are large earthquakes common? Why?
6. Along which type(s) of lithospheric plate boundary are large volcanoes most common? Provide an example.
7. What direction is the Pacific Plate currently moving, based on FIGURE 2-15? How fast is this plate moving?
8. Before people understood plate tectonics, what evidence led some scientists to believe in continental drift?
9. If the coastlines across the Atlantic Ocean are spreading apart, why isn't the Atlantic Ocean deepest in its center?
10. What evidence confirmed seafloor spreading?
11. Why are high volcanoes such as the Cascades found on the continents and in a row parallel to the continental margin?
12. Explain how the modern theory of plate tectonics developed in the context of the scientific method.
13. How does the height of a mountain range compare with the thickness of the crust or lithosphere below the mountain? Relate this to the percentage of an iceberg above the water line.

Critical Thinking Questions

1. Explain the role of Earth material densities with respect to Earth's features such as mountains and mid-oceanic ridges. For example, why is the top of basaltic crust below sea level while the surface of granitic crust is generally above sea level?
2. The Basin and Range region of Nevada and Utah is a continental spreading zone. Because it is pulling apart, why isn't its elevation low, rather than as high as it is? Why isn't it an ocean?
3. The scientific community initially rejected Wegener's hypothesis of continental drift and remained skeptical for decades. Does skepticism help or hinder scientific progress?
4. In common usage, *hypothesis* often indicates a guess or hunch, whereas a scientific *theory* is based in evidence tested over a long time and is considered to be scientific fact. What other scientific issues have caused broad debate in social and political culture? Are they well-supported scientific theories or just hypotheses?

AP Images/Eric Risberg

A cellar worker at Kieu Hoang Winery in Napa tallies damage after the earthquake.

3 Earthquakes and Their Causes

Public Ignorant of Bay Area Earthquake Risk

In 2005, residents in California's wine country, some 110 km north of San Francisco, remarked to us that "we only get a few small quakes here, nothing to worry about." The individuals we talked to lacked critical information about the region's earthquake risk. Although the San Andreas Fault is approximately 40 km (25 mi) to the west, Napa and Sonoma Valleys are dissected by two active faults, which together have higher risk of large earthquakes than the main San Andreas Fault in the region. At 3:20 a.m. on August 24, 2014, Napa was rocked by a magnitude 6 earthquake. Although the loss of life was low, the economic damages were significant, including loss of wine from many of the producers in the area who did not adequately secure their barrels and bottles (**Case in Point:** Recent San Francisco Bay Earthquakes, 1989 and 2014, Chapter 4, p. 85).

Faults and Earthquakes

To understand why earthquakes happen, remember that the plates of Earth's crust move, new crust forms, and old crust sinks into subduction zones. These movements give rise to earthquakes, which form along **faults**, or ruptures, in Earth's crust. Faults are simply fractures in the crust along which rocks on one side of the break move past those on the other. Faults are measured according to the amount of displacement along the fractures. Over several million years, for example, the rocks west of the San Andreas Fault of California have moved at least 450 km north of where they started. Thousands of other faults have moved much less than 1 km in the same period.

Some faults produce earthquakes when they move; others produce almost none. Some faults have not moved for such a long time that we consider them inactive; others are clearly still active and potentially capable of causing earthquakes. Earthquakes are common in the mountainous western parts of North America, where the rocks are deformed into complex patterns of faults and folds. Active faults are rare in regions such as the American Midwest and central Canada, where the continental crust has been stable for hundreds of millions of years. Such stable regions contain many faults that geologists have yet to recognize. Some of these first announce their presence when they cause an earthquake; others are marked by the line of a recent break near the base of a mountainside called a *fault scarp*.

Types of Faults

Faults can be classified according to the way the rocks on either side of the fault move in relation to each other (**FIGURE 3-1**). **Normal faults** move on a steeply inclined surface. Rocks above the fault surface slip down and over the rocks beneath the fault. Normal faults move when Earth's crust pulls apart, during crustal extension. **Reverse faults** move rocks on the upper side of a fault up and over those below. **Thrust faults** are similar to reverse faults, but the fault surface is more gently inclined. When thrust faults don't break the surface, they are called **blind thrusts**. Blind thrusts are dangerous because they often remain unknown until they cause an earthquake (**Case in Point:** A Major Earthquake on a Blind Thrust Fault—Northridge Earthquake, California, 1994). Reverse and thrust faults move when Earth's crust is pushed together, during crustal compression. **Strike-slip faults** move horizontally as rocks on one side of a fault slip laterally past those on the other side. If rocks on the far side of a fault move to the right, it is a right-lateral fault. If they moved to the left, it would be a left-lateral fault.

The orientations of rock layers and faults are described in terms of *strike* and *dip*. *Strike* is the compass orientation of a horizontal line on a rock surface. *Dip* is the inclination angle (perpendicular to the strike direction) down from horizontal to the rock surface (**FIGURE 3-2**).

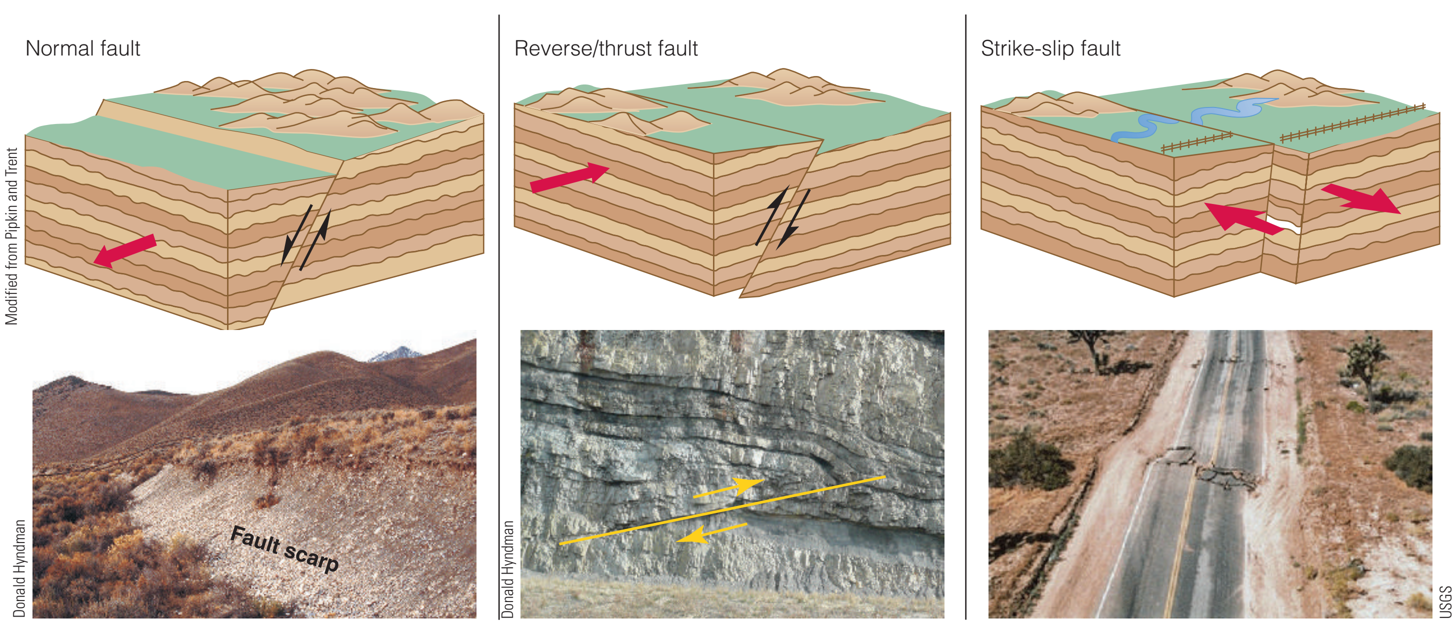


FIGURE 3-1 Types of Fault Movement

A. A normal fault near Challis, Idaho, moved in the 1983 earthquake. The rock mass above the fault slipped downward relative to the mass below.

B. A small thrust fault (reverse fault movement, where one slab of rock moves up and over another, see arrows) east of Vail, Colorado.

C. A strike-slip (lateral slip) fault offset the road after the Landers earthquake in California.

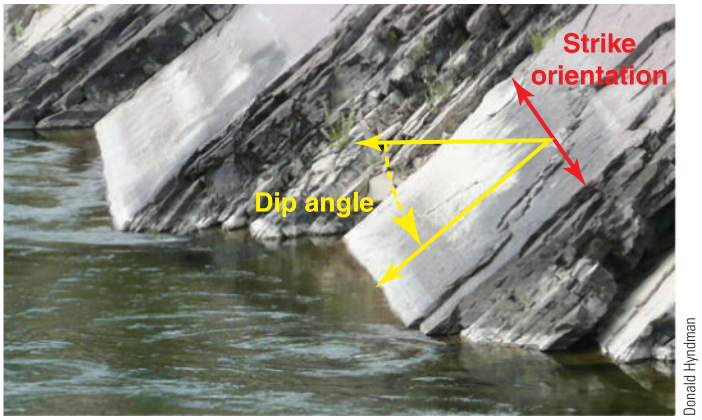


FIGURE 3-2 Strike and Dip

In this example, the strike orientation is about 30º west of north (if north is parallel to the edge of the photo). The dip is 45º down from a horizontal plane to the surface of the rock layer.

Causes of Earthquakes

At the time of the great San Francisco earthquake of 1906, the cause of earthquakes was a complete mystery. The governor of California at the time appointed a commission to ascertain the cause of earthquakes. The director of this commission, Andrew C. Lawson, was a distinguished geologist and one of the most colorful personalities in the history of California. Lawson and his students at the University of California (UC)–Berkeley had already recognized the San Andreas Fault and mapped large parts of it, but until the 1906 event they had no idea that it could cause earthquakes. During their investigation, members of the commission found numerous places where roads, fences, and other structures had broken during the 1906 earthquake just where they crossed the San Andreas Fault. In every case, the side west of the fault had moved north as much as 7 m (23 ft). That led to the theory of how fault movement causes earthquakes.

The earthquake commission hypothesized that as Earth's crust moved, the rocks on opposite sides of the fault had bent, or *deformed*, instead of slipping, over many years. As the rocks on opposite sides of the fault bent, they accumulated energy. When the stuck segment of the fault finally slipped, the bent rocks straightened with a sudden snap, releasing energy in the form of an earthquake (**FIGURE 3-3**). Imagine pulling a bow taut, bending it out of its normal shape, and then releasing it. It would snap back to its original shape with a sudden release of energy capable of sending an arrow flying. This explanation for earthquakes, called the **elastic rebound theory**, has since been confirmed by rigorous testing.

We now know enough about the behavior of rocks in response to stress to explain why faults either stick or slip. We think of rocks as brittle solids, but rocks are elastic, like a spring, and can bend when a force is applied. We use the term **stress** to refer to the forces imposed on a rock and **strain** to refer to the change in shape of the rock in response to the imposed stress. The larger the stress applied, the greater the strain.

Rocks deform in broadly consistent ways in response to stress. Typical rocks will deform *elastically* under low stress, which means that they revert to their former shape when the applied force is relieved. At higher stress, these rocks will deform *plastically*, which means they permanently change shape or flow when forces are applied. Deformation experiments show that most rocks near Earth's surface, where they are cold and not under much pressure from overlying rocks, deform elastically when affected by small forces. Under other conditions, such as deep in Earth where they are hot and under high pressure imposed by the overlying load of rocks, it is much more likely that rocks will deform plastically.

Rocks can bend, but they also break if stretched too far. In response to smaller stresses, rocks may merely bend, while in response to large stresses, they fracture or break. As stress levels increase, rocks ultimately succumb to *brittle failure*, causing fault slippage during an earthquake (**FIGURE 3-4**). Under these conditions, a fault may

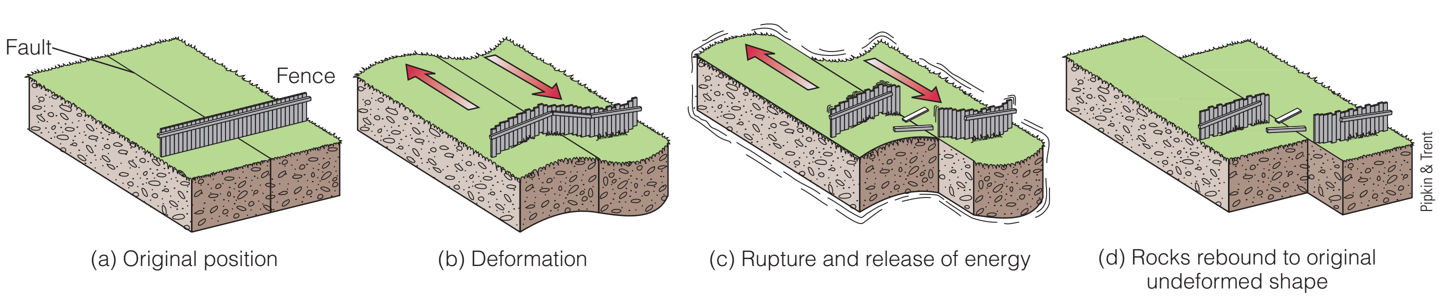


FIGURE 3-3 Elastic Rebound Theory

Rocks near a fault (a) are slowly deformed elastically (b) until the fault breaks during an earthquake (c), when the rocks on each side slip past each other, relieving the stress. After the earthquake the rocks regain their original, undeformed shape, but in a new position (d).

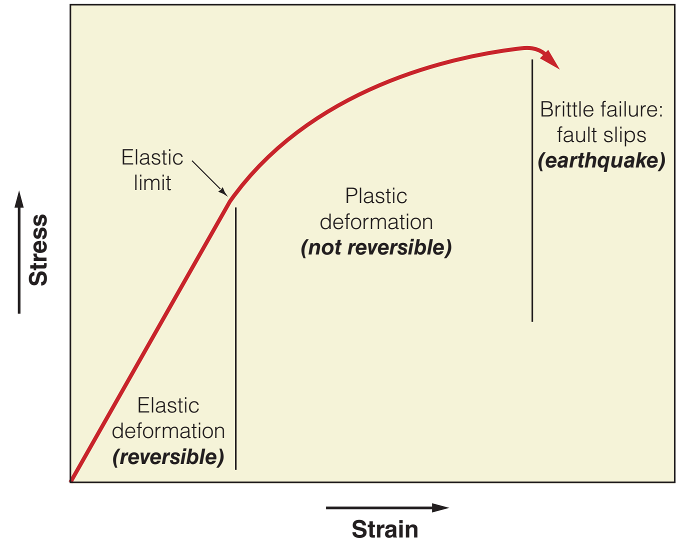


FIGURE 3-4 Stress and Strain

With increasing stress, a rock deforms elastically, then plastically, before ultimately failing or breaking in an earthquake. A completely brittle rock fails at its elastic limit.

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FIGURE 3-5 Slickensides

Scratches on a fault surface in the French Alps (horizontal in this photo) indicate movement orientation.

begin to fail, with smaller slips, called **foreshocks**, preceding the main earthquake. It then continues to adjust with smaller slips called **aftershocks** after the event. In a few cases aftershocks can be large and devastating. About 7 weeks after the magnitude 7.8, 2015 earthquake in Nepal that killed almost 9000 people, a magnitude 7.3 aftershock killed an additional 218.

When brittle failure occurs, rocks break in a predictable direction. Deformation of a rock by compression generally results in slippage diagonal to the direction of compression (**By the Numbers 3-1:** Compression and Rock Shear). In Figure 3-1A, for example, Earth's gravity is pulling straight down, but the rock breaks along a dipping fault. Along a fault, differential plate motions apply stresses continuously. Because those plate motions do not stop, elastic deformation progresses to plastic deformation within meters to kilometers of the fault, and the fault finally ruptures in an earthquake. When stress on a section of a fault releases as slippage during a large earthquake, some of that stress is often transferred to increasing stress on a part of the fault beyond the slip zone or to adjacent faults. That makes those adjacent areas more prone to slip than they were before.

The orientation of movement along a fault can often be determined from surface scratches—*slickensides*—imposed by sliding of one surface of the fault against the other (**FIGURE 3-5**).

The size of an earthquake is related to the amount of movement on a fault. The displacement, or **offset**, is the distance of movement across the fault, and the **surface rupture length** is the total length of the break (**FIGURE 3-6**). The largest earthquake expected for a particular fault generally depends on the *total fault length*, or the longest segment of the fault that typically ruptures.

This relationship between fault-segment length and earthquake size puts a theoretical limit on the size of an earthquake at a given fault. A short fault only a few kilometers long can have many small earthquakes but

By the Numbers 3-1

Compression and Rock Shear

Experimental study of compression of a cylinder of rock from the top and bottom breaks the rock on diagonal shear planes. Shear is generally on one plane only, as shown by the red line. The maximum principal stress is σ_1.