NATURAL DISASTERS

ELEVENTH EDITION

Mc Graw Hill Education

PATRICK L. ABBOTT

Natural Disasters

ELEVENTH EDITION

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San Diego State University

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NATURAL DISASTERS, ELEVENTH EDITION

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About the Author

Patrick L. Abbott Patrick Abbott is a native San Diegan. Pat earned his MA and PhD degrees in geology at the University of Texas at Austin. He benefited greatly from the depth and breadth of the faculty in the Department of Geological Sciences at Austin; this was extended by their requirement to take five additional graduate courses outside the department. Developing interests in many topics helped lead to writing this textbook.

Pat's research has concentrated on the Mesozoic and Cenozoic sedimentary rocks of the southwestern United States and northwestern Mexico. Studies have focused on reading the history stored within the rocks—depositional environments, provenance, paleoclimate, palinspastic reconstructions, and high-energy processes.

Pat has long been involved in presenting Earth knowledge to the public, primarily through TV news. He has produced award winning videos for TV broadcast. He was one of the main cast members in the TV series *The Real Gilligan's Island* on TBS, *Serial Killer Earth* on H2 (The History Channel 2), and *So You Think You'd Survive* on The Weather Channel. During part of each year, Pat works as a Smithsonian lecturer visiting all continents and oceans.

Brief Contents

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Preface

Why Study Natural Disasters?

Natural disasters occur every day and affect the lives of millions of people each year. Many students have been affected by earthquakes or tornadoes or hurricanes or floods or landslides or wildfires or other events. They are interested in lectures that explain these processes, and lively discussions commonly ensue.

During decades of teaching courses at San Diego State University, I found that students have an innate curiosity about "death and destruction"; they want to know why natural disasters occur. Initiation of a Natural Disasters course led to skyrocketing enrollments that exceeded 5,000 students per year. Some of these experiences are described in a *Journal of Geoscience Education* article by Pat Abbott and Ernie Zebrowksi [v 46 (1998), pp. 471–75].

Themes and Approach

This textbook focuses on explaining how the normal processes of the Earth concentrate their energies and deal heavy blows to humans and their structures. The following themes are interwoven throughout the book:

- Energy sources underlying disasters
- Plate tectonics
- Climate change
- Earth processes operating in rock, water, and atmosphere
- Significance of geologic time
- Complexities of multiple variables operating simultaneously
- Detailed and interesting case histories

New to This Edition

- Many of the Tables and Figures have been updated and more than 50 new ones have been added.
- Chapter 1: Extensive updating of all disaster and demographic data.
- Chapter 2: New maps of earthquake epicenters and ocean-floor ages. Expanded coverage of plumes versus hot spots.
- Chapter 3: New figures on seismic-wave velocity and amplitude; house building-code updates, 1971 versus 2017.
- Chapter 4: Expanded text on earthquake swarms. New scenario earthquakes for Hayward fault magnitudes and expected deaths.
- Chapter 5: Expanded text on short-term earthquake predictions and alerts (ShakeAlert) and Canada; animal behavior; wastewater-pumping trigger of earthquakes; Virginia earthquake. Update on L'Aquila earthquake trials of scientists.
- Chapter 6: Significant rewriting; opening compares Kilauea versus Fuego; fractional crystallization; melting of basalt rock; external water and explosions; Yellowstone future eruptions.
- Chapter 7: Added pyroclastic eruption of Eyjafjallajokull and jokulhlaup in 2010; viscous magma stored as crystal mush too cool to erupt.
- Chapter 8: Fukushima Daiichi radioactivity clean up five years later; new photo of tsunami chasing tourists out of the ocean.
- Chapter 9: Expanded discussions of convection and conduction; vertical air motions; new line art on wind origin.
- Chapter 10: Updated billion-dollar weather disasters; new figure on 2016 weather fatalities.
- Chapter 11: New sections on U.S. hurricanes 2006-2017, eyewall replacement cycle, Hurricane Harvey and inland flooding; updated tables and Accumulated Cyclone Energy; new figures on hurricane return periods, Atlantic Multi-decadal Variability. Several new figures.
- Chapter 12: Significant new updates and additions: Arctic amplification of global warming; Arctic sea-ice volume 1979-2017; global map of climate tipping points; expanded history of knowledge of carbon-dioxide effect on climate including early computer model; Yellowstone eruption of 631 kya and its effect on climate; expanded discussion of orbital forcing, eccentricity, and tilt effects; Athabasca glacier.
- Chapter 13: New sections on atmospheric rivers, Managed Retreat of buildings from floodplains, Great Mississippi River flood of 1927.

- Chapter 14: Major Reorganization. Added new sections: Fort McMurray, Canada firestorm; fire weather and winds with spotting, pyrocumulus clouds, mega-fires; smoke effects on human health. Added In Greater Depth on origin of fire on Earth as we know it. Deleted some old tables and figures.
- Chapter 15: Added new 4-page section on Landslide Mitigation including 5 new photos. New text analogy of snow avalanche and earthquake-fault movements.
- Chapter 16: Added new sections: sand, a Tragedy of the Commons; submarine canyons and effect on beach sand; tidal waves up Amazon River. Expanded text: coral reefs and coastline protection.
- Chapter 17: Added new sections on coronal mass ejections; new collection sites for micrometeorites. Added In Greater Depth on insights from spacecraft landing on a comet. Expanded dwarf planet coverage. Added images of tektites and Moon impact crater.
- Chapter 18: GREAT NEWS. The chapter on mass extinctions has returned to the print edition of the book.

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I am deeply appreciative of the help given by others to make this book a reality. The photograph collection in the book is immeasurably improved by the aerial photographs generously given by the late John S. Shelton, the greatest geologist photographer of them all. Please see John's classic book *Geology Illustrated.*

The quality of the book was significantly improved by the insights provided by comments from the following reviewers:

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I sincerely appreciate the talents and accomplishments of the McGraw-Hill professionals in Dubuque who took my manuscript and produced it into this book. For the shortcomings that remain in the book, I alone am responsible. I welcome all comments, pro and con, as well as suggested revisions.

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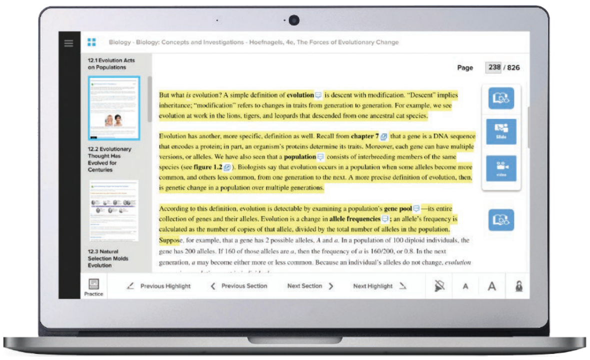

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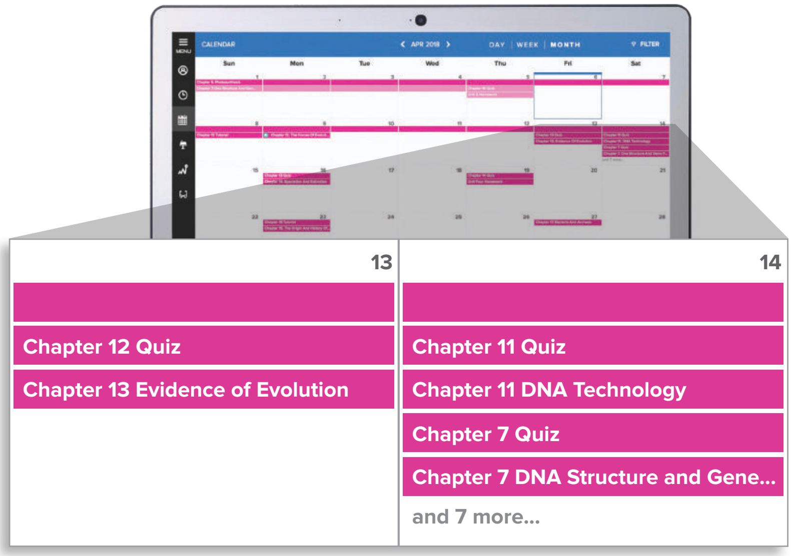

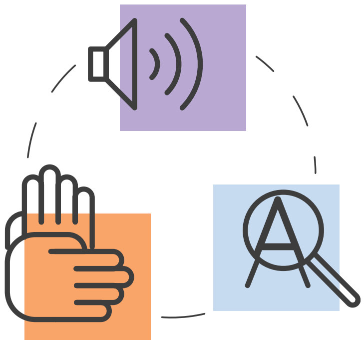

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Prologue: Energy Flows

Earth, the Blue Marble as seen from Apollo 17 in 1972.
Source: NASA

LEARNING OUTCOMES

Earth is a planet with varied flows of energy that can cause problems for humans. After studying the Prologue you should

- know the main flows of energy on Earth.
- comprehend how internal energy creates land.
- understand how external energy destroys land.
- be familiar with the rock cycle.

Disasters occur where and when Earth's natural processes concentrate energy and then release it, killing life and causing destruction. Our interest is especially high when this energy deals heavy blows to humans. As the growth of the world's population accelerates, more and more people find themselves living in close proximity to Earth's most hazardous places. The news media increasingly present us with vivid images and stories of the great losses of human life and destruction of property caused by natural disasters. As the novelist Booth Tarkington remarked: "The history of catastrophe is the history of juxtaposition."*

To understand the natural processes that kill and maim unwary humans, we must know about the energy sources that fuel them. Earth is an active planet with varied flows of energy from: (1) Earth's interior, (2) the Sun, (3) **gravity,** and (4) impacts with **asteroids** and **comets.**

Internal energy flows unceasingly from Earth's interior toward the surface. The interior of the Earth holds a tremendous store of heat accumulated from the initial impacts that formed our planet and from the heat released by the ongoing decay of **radioactive isotopes.** Over short time spans, internal energy is released as eruptions from **volcanoes** and as **seismic waves** from **earthquakes.** Over longer intervals of geologic time, the flow of internal energy has produced our **continents,** oceans, and **atmosphere.** On a planetary scale, this outflow of internal energy causes continents to drift and collide, thus constructing mountain ranges and elevated plateaus.

External energy is delivered by the Sun. About a quarter of the Sun's energy that reaches Earth evaporates and lifts water into the atmosphere. At the same time, the constant pull of gravity helps bring atmospheric moisture down as snow and rain. On short timescales, these processes bring us **hail, lightning, tornadoes, hurricanes,** and floods. Solar energy is also stored in plant tissue to be released later as fire. On a long timescale, the Sun and gravity power the agents of **erosion**—**glaciers,** streams, underground waters, winds, ocean waves, and currents—that wear away the continents and dump their broken pieces and dissolved remains into the seas. Solar radiation is the primary energy source because it evaporates and elevates water, but gravity is the immediate force that drives the agents of erosion.

Gravity is an attractional force between bodies. At equal distances, the greater the mass of a body, the greater its gravitational force. The relatively great mass of the Earth has powerful effects on smaller masses such as ice and rock, causing ice to flow as avalanches and hillsides to fail in landslides and **debris flows.**

An energy source for disasters arrives when visitors from outer space—asteroids and comets—impact Earth. Impacts were abundant early in Earth's history. In recent times, collisions with large bodies have become infrequent. However, asteroids and comets traveling at velocities in excess of 30,000 mph occasionally slam into Earth, and their deep impacts have global effects on life.

The sequence of chapters in this book is based on energy sources, in the following order: Earth's internal energy, external energy supplied by the Sun, gravity, and impacts with space objects.

Earth's internal energy fuels volcanism, as well as providing the energy for earthquakes. Here, lava flows from the Pu'u O'o-Kupaianaha eruption in Hawaii meet the ocean, 18 August 2010.

Source: Michael Poland/USGS

External energy from the Sun fuels tornadoes, as well as hurricanes, floods, and wildfires. Here, a powerful tornado spins down from a supercell thunderstorm and travels along an Oklahoma road.

The pull of gravity brings down hillsides. This earthquake-triggered debris flow destroyed homes and killed 585 people in Santa Tecla, El Salvador on 13 January 2001.

Source: Ed Harp/USGS

High-velocity comets and asteroids can impact the Earth and kill life worldwide. Here the Comet Lovejoy nears Earth's horizon behind airglow in the night sky.

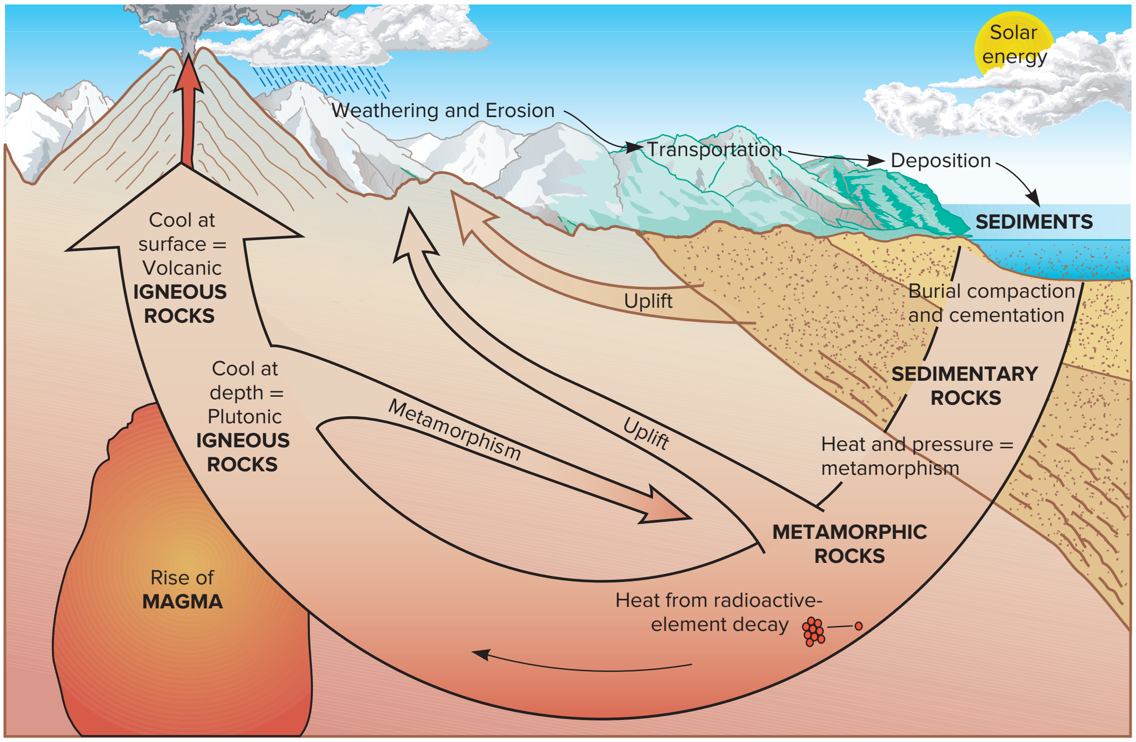
Source: Dan Burbank/NASA

Processes of Construction versus Destruction

Another way to look at energy flow on Earth is by understanding the rock cycle and the construction and destruction of land (continents). Energy flowing up from Earth's interior melts rock that rises as **magma** and then cools and crystallizes to form **igneous rocks;** they are **plutonic rocks** if they solidify at depth or **volcanic rocks** if they cool and harden at the surface. These newly formed rocks help create new land. Igneous-rock formation is part of the internal energy–fed **processes of construction** that create and elevate landmasses.

At the same time, the much greater flow of energy from the Sun, working with gravity, brings water that weathers the igneous rocks exposed at or near the surface and breaks them down into **sediments. Physical weathering** disintegrates rocks into **gravel** and **sand,** while **chemical weathering** decomposes rock into **clay minerals.** The sediments are eroded, transported mostly by water, and then deposited in topographically low areas, ultimately the ocean. These external, energy-fed **processes of destruction** work to erode the lands and dump the debris into the oceans.

These land-building and land-destroying processes result from Earth's energy flows that create, transform, and destroy rocks as part of the rock cycle. Think about the incredible amount of work done by the prodigious flows of energy operating over the great age of Earth. There is a long-term conflict raging between the internal-energy-powered processes of construction, which create and elevate landmasses, and the external-energy-powered processes of destruction, which erode the continents and dump the continental debris into the ocean basins. Visualize this: If the interior of Earth cooled and the flow of internal energy stopped, mountain building and uplift also would stop; then the ongoing solar-powered agents of erosion



The rock cycle. Follow the cycle clockwise beginning in the lower left. Magma cools and solidifies to form igneous rocks. Rocks exposed at Earth's surface break down and decompose into sediments (e.g., gravel, sand, clay), which are transported, deposited, and hardened into sedimentary rock. With increasing burial depth, temperature and pressure increase, causing changes (or metamorphosis) of rocks into metamorphic rocks.

would reduce the continents to sea level in just 45 million years. There would be no more continents, only an ocean-covered planet.

Think about the timescales involved in eliminating the continents. At first reading, 45 million years of erosion may seem like an awfully long time, but the Earth is more than 4.5 billion years old. The great age of Earth indicates that erosion is powerful enough to have leveled the continents about 100 times. This shows the power of the internal processes of construction to keep elevating old continents and adding new landmasses. And woe to human and other life-forms that get too close to these processes of construction and destruction, for this is where natural disasters occur.

Terms to Remember

asteroid 1
atmosphere 1
chemical weathering 3
clay minerals 3
comet 1
continent 1
debris flow 1
earthquake 1
erosion 1
glacier 1
gravel 3
gravity 1
hail 1
hurricane 1
igneous rock 3
lightning 1
magma 3
physical weathering 3
plutonic rocks 3
processes of construction 3
processes of destruction 3
radioactive isotope 1
sand 3
sediment 3
seismic wave 1
tornado 1
volcanic rocks 3
volcano 1

CHAPTER 1

Natural Disasters and the Human Population

"Mankind was destined to live on the edge of perpetual disaster. We are mankind because we survive."

—James A. Michener, 1978, *Chesapeake,* Random House

The world population of humans continues to increase exponentially. Photo of shopping area in New Delhi, India.

LEARNING OUTCOMES

The human population is growing rapidly. Natural disasters are causing great numbers of deaths and economic losses. After studying this chapter you should

- recognize the differences between a natural hazard, a natural disaster, and a great natural disaster.
- be familiar with the processes that cause the deadliest natural disasters.
- understand the relationship between frequency and magnitude of natural disasters.
- know the size of the human population.
- understand the significance of exponential growth.
- recognize the demographic transition of human populations.
- be able to explain the concept of carrying capacity.

OUTLINE

- Great Natural Disasters
- Human Fatalities and Economic Losses in Natural Disasters
- Natural Hazards
- Overview of Human Population
- Future World Population
- Carrying Capacity

In 2016, there were 191 **natural disasters** that claimed 20 or more human lives. They were primarily caused by floods, **earthquakes, hurricanes** (= **cyclones** = **typhoons**), and heat waves; they killed almost 7,000 people. The 14 deadliest events are listed in table 1.1; they occurred in 8 different months and 11 different countries, mostly in Asia. As horrible as the 2016 death total is, it is markedly less than in 2010, when about 286,000 people were killed in two events alone (Haiti earthquake: 230,000; Russian heat wave: 56,000). All these disasters were the result of natural processes operating at high **energy** levels for brief times in restricted areas.

TABLE 1.1

The 14 Deadliest Natural Disasters in 2016

Fatalities	Date	Event	Country
734	28 Sep	Hurricane Matthew	Haiti
673	16 Apr	Earthquake 7.8M	Ecuador
538	29 Aug	Typhoon Lionrock	North Korea
300	13 Apr	Heat wave	India
299	24 Aug	Earthquake 6.2M	Italy
289	30 Jun	Floods	China
289	18 Jul	Floods	China
228	15 Jul	Floods (monsoon)	India
191	15 May	Cyclone Roanu	Sri Lanka
151	1 Aug	Floods (monsoon)	India
141	9 Mar	Floods	Pakistan
137	14 Apr	Earthquake 7.0M	Japan
122	21 Jul	Floods	Nepal
117	6 Feb	Earthquake 6.4M	Taiwan
4,209 Total deaths			

Source: Data from Swiss Reinsurance Company (2017).

Great Natural Disasters

The Japan earthquake and tsunami in 2011, the Haiti earthquake in 2010, and the Myanmar cyclone and China earthquake in 2008 combined to kill almost 500,000 people. They are examples of **great natural disasters:** these events so overwhelm regions that international assistance is needed to rescue and care for people, clean up the destruction, and begin the process of reconstruction. Great natural disasters commonly kill thousands of people, leave hundreds of thousands homeless, and overwhelm the regional economy.

Today, in earthquake-active areas of the world, several hundred million people live in buildings that will collapse during a strong earthquake. An earthquake killing more than 100,000 people could happen any day in Teheran, Iran; in Istanbul, Turkey; or in other large cities. Today, people by the millions are moving to the ocean shores, where they can be hit by tsunami, hurricanes, and floods. We need to learn how to build disaster-resistant communities to lessen the human fatalities and economic losses resulting from natural disasters.

Human Fatalities and Economic Losses in Natural Disasters

The 40 deadliest disasters in the 47-year period from 1970 to 2016 are shown in table 1.2. The most frequent megakillers were earthquakes (23) and hurricanes (10). Notice that 30 of the 40 worst natural disasters occurred in a belt running from China and Bangladesh through India and Iran to Turkey. Nine happened in the Americas but none were in the United States or Canada.

What is the correlation between human population density and the number of natural-disaster deaths? The data of table 1.2 paint a clear picture: densely populated Asia dominates the list of fatalities. The Asian experience offers a sobering view of what may befall the global population of humans if we continue our rapid growth. Where humans are concentrated, disasters can kill many more people during each high-energy event.

THE ROLE OF GOVERNMENT IN NATURAL-DISASTER DEATH TOTALS

As the global population of humans increases, the number of deaths by natural disasters is expected to rise, but the relationship has complexities. Analyses by Gregory van der Vink and students at Princeton University show that between 1964 and 1968, about 1 person in 10,000 was killed by a natural disaster. Between 2000 and 2004, even though the population of humans doubled, the death rate by natural disaster dropped to about 1 person in 100,000. Yet, great natural disasters still result in horrific death totals in some countries. What relationships, in addition to population size, explain the locations of great natural disasters? Their study compared natural-disaster deaths to the levels of democracy and economic development within 133 nations with populations greater than 1 million that

TABLE 1.2

The 40 Deadliest Natural Disasters, 1970–2017

Fatalities	Date/Start	Event	Country
300,000	14 Nov 1970	Hurricane (Bhola)	Bangladesh
255,000	28 Jul 1976	Earthquake (Tangshan)	China
245,000	26 Dec 2004	Earthquake and tsunami	Indonesia, Sri Lanka, India, Thailand
230,000	12 Jan 2010	Earthquake	Haiti
140,000	2 May 2008	Hurricane Nargis	Myanmar
140,000	29 Apr 1991	Hurricane Gorky	Bangladesh
88,000	8 Oct 2005	Earthquake	Pakistan
87,500	12 May 2008	Earthquake (Sichuan)	China
66,000	31 May 1970	Earthquake and debris flow (Nevados Huascaran)	Peru
55,630	15 Jun 2010	Heat wave and fire	Russia
50,000	21 Jun 1990	Earthquake (Gilan)	Iran
35,000	Aug 2003	Heat wave	Europe
27,000	26 Dec 2003	Earthquake (Bam)	Iran
25,000	7 Dec 1988	Earthquake	Armenia
25,000	16 Sep 1978	Earthquake (Tabas)	Iran
23,000	13 Nov 1985	Volcanic eruption and mudflows (Nevado del Ruiz)	Colombia
22,000	4 Feb 1976	Earthquake	Guatemala
20,103	26 Jan 2001	Earthquake (Gujarat)	India
19,184	11 Mar 2011	Earthquake and tsunami	Japan
19,118	17 Aug 1999	Earthquake (Izmit)	Turkey
18,000	15 Dec 1999	Flooding and debris flows	Venezuela
15,000	19 Sep 1985	Earthquake (Mexico City)	Mexico
15,000	1 Sep 1978	Floods (monsoon rains in north)	India
15,000	29 Oct 1999	Hurricane (Orissa)	India
11,000	22 Oct 1998	Hurricane Mitch	Honduras
11,000	25 May 1985	Hurricane	Bangladesh
10,800	31 Oct 1971	Hurricane (Odisha)	India
10,000	20 Nov 1977	Hurricane (Andhra Pradesh)	India
9,500	30 Sep 1993	Earthquake (Marashtra state)	India
8,960	25 Apr 2015	Earthquake	Nepal
8,135	8 Nov 2013	Hurricane Haiyan	Philippines
8,000	16 Aug 1976	Earthquake (Mindanao)	Philippines
6,425	17 Jan 1995	Earthquake (Kobe)	Japan
6,304	5 Nov 1991	Hurricane Thelma (Uring)	Philippines
6,000	Jun 1976	Heat wave	France
5,778	21 May 2006	Earthquake (Bantul)	Indonesia
5,748	14 Jun 2013	Floods	India
5,422	30 Jun 1976	Earthquake (West Irian)	Indonesia
5,374	10 Apr 1972	Earthquake (Fars)	Iran
5,300	28 Dec 1974	Earthquake	Pakistan
2,059,281 Total deaths			

Source: Data from Swiss Reinsurance Company (2017).

experienced five or more natural disasters between 1964 and 2004. Democracy is assessed by the World Bank's Democracy Index, and economic development by gross domestic product (GDP).

The Princeton researchers state that more than 80% of deaths by natural disasters between 1964 and 2004 took place in 15 nations, including China, Bangladesh, and Indonesia. For these 15 countries, 87% are below the median democracy index and 73% are below the median GDP. The correlation between high GDP and low death totals shows exceptions in Iran and Venezuela, two oil-rich nations with significant GDP but low democracy indices. These exceptions suggest a greater importance for democracy than GDP: the stronger the democracy index, the lower the death totals from natural disasters. The mega-killer natural disasters of recent years fit this trend also: Pakistan earthquake in 2005 (88,000 dead), Myanmar cyclone in 2008 (140,000 dead), China earthquake in 2008 (87,500 dead), and Haiti earthquake in 2010 (230,000 dead).

In a thought-provoking paragraph in their conclusion, van der Vink and students state: "Deaths from natural disasters can no longer be dismissed as random acts of nature. They are a direct and inevitable consequence of high-risk land use and the failures of government to adapt or respond to such known risks."

HUMAN RESPONSES TO DISASTER

Decades of social science research help us understand how most human beings react to natural disasters, and the news is good. Our behavior in ordinary times changes following disasters. In day-to-day life, most people are primarily concerned with their own needs and those of their immediate families; other relationships tend to be more superficial. After a natural disaster, many people change from inward-directed concerns to outward-directed actions. After an initial response of shock and disbelief, our emotions of sympathy and empathy tend to dominate. Personal priorities may be set aside and humanitarian and community-oriented actions take over. People reach out to others; they give aid and comfort to strangers; they make great efforts to provide help. Following a natural disaster, people become better connected and cohesive; they experience a heightened and compelling desire to add to the common good.

ECONOMIC LOSSES FROM NATURAL DISASTERS

The deaths and injuries caused by natural disasters grab our attention and squeeze our emotions, but in addition, there are economic losses. The destruction and disabling of buildings, bridges, roads, power-generation plants, and transmission systems for electricity, natural gas, and water, plus all the other built works of our societies, add up to a huge dollar cost. But the economic losses are greater than just damaged structures; industries and businesses are knocked out of operation, causing losses in productivity and wages for employees left without places to work.

In 2016 there were 191 natural disasters that each caused losses greater than $US95 million. The total economic losses were around US$166 billion. The economic losses were 0.24% of global domestic product.

Insured Portion of Economic Losses

The 40 greatest disasters between 1970 and 2017 from the insurance company perspective of dollar losses are listed in table 1.3. Notice that 39 of the 40 most expensive disasters were due to natural processes. The list of most expensive events is dominated by weather events (31 of 40), whereas earthquakes contributed eight. Compare the events on the 40 deadliest disasters list (see table 1.2) with table 1.3.

The locations of the worst dollar-loss disasters for the insurance industry (table 1.3) are different from the worst locations for fatalities (see table 1.2). The highest insurance dollar losses occurred in the United States (23 of 40), Europe (6), and Japan (6). Wealthy countries are better insured and their people live in safer buildings.

The extent of economic and insured losses may take years to become known. For example, the insured losses from the January 1994 Northridge earthquake were listed at $2.8 billion in February 1994, but they grew to $10.4 billion in January 1995 and increased to $15.3 billion in April 1998.

Natural Hazards

Many sites on Earth have not had a natural disaster in recent time, but are hazardous nonetheless. **Natural hazards** may be assessed as the probability of a dangerous event occurring. For example, people migrate and build next to rivers that are likely to flood, on the shoreline of the sea awaiting a powerful storm, and on the slopes of volcanoes that will eventually erupt. Decades, or even centuries, may pass with no great disasters, but the hazard remains.

Sites with natural hazards must be studied and understood. Their risks must be evaluated. Then we can try to prevent natural hazards from causing natural disasters. Remember: *Natural hazards are inevitable, but natural disasters are not.*

In the process of **mitigation,** we make plans and take actions to eliminate or reduce the threat of future death and destruction when natural hazards suddenly become great threats. The mitigating actions taken to protect us may be engineering, physical, social, or political.

Another need for mitigation occurs after great disasters, because people around the world tend to reoccupy the same site after a disastrous event is done. Earthquakes knock cities down, and then the survivors may use the same bricks

TABLE 1.3

The 40 Costliest Insurance Disasters, 1970–2017

Losses in Millions of 2016 US$	Fatalities	Date/Start	Event	Country
80,699	1,836	29 Aug 2005	Hurricane Katrina	USA
37,344	19,184	11 Mar 2011	Earthquake and tsunami	Japan
30,141	237	24 Oct 2012	Hurricane Sandy	USA
27,368	43	24 Aug 1992	Hurricane Andrew	USA
25,456	2,982	11 Sep 2001	Terrorist attack	USA
24,773	61	17 Jan 1994	Earthquake (Northridge)	USA
22,577	136	6 Sep 2008	Hurricane Ike	USA
17,072	181	2 Sep 2004	Hurricane Ivan	USA
16,005	815	27 Jul 2011	Floods (monsoon)	Thailand
16,002	185	22 Feb 2011	Earthquake (Christchurch)	New Zealand
15,447	53	16 Oct 2005	Hurricane Wilma	USA
13,199	34	20 Sep 2005	Hurricane Rita	USA
11,498	123	15 Jul 2012	Drought (corn belt)	USA
10,033	36	11 Aug 2004	Hurricane Charley	USA
9,950	51	27 Sep 1991	Typhoon Mireille	Japan
8,852	71	15 Sep 1989	Hurricane Hugo	USA
8,804	562	27 Feb 2010	Earthquake	Chile
8,577	95	25 Jan 1990	Winter Storm Daria	Europe
8,356	110	25 Dec 1999	Winter Storm Lothar	Europe
7,789	354	22 Apr 2011	Tornadoes (Alabama)	USA
7,522	177	20 May 2011	Tornadoes (Missouri)	USA
7,057	54	18 Jan 2007	Winter Storm Kyrill	Europe
6,546	22	15 Oct 1987	Storm	Europe
6,503	50	26 Aug 2004	Hurricane Frances	USA
6,400	63	17 Oct 1989	Earthquake (Loma Prieta)	USA
6,062	55	22 Aug 2011	Hurricane Irene	USA
5,909	64	26 Feb 1990	Winter Storm Vivian	Europe
5,820	26	22 Sep 1999	Typhoon Bart	Japan
5,548	185	4 Sep 2010	Earthquake (Canterbury)	New Zealand
5,540	600	20 Sep 1998	Hurricane Georges	USA, Caribbean
5,000	137	14 Apr 2016	Earthquake	Japan
4,890	41	5 Jun 2001	Tropical Storm Allison	USA
4,872	3,034	13 Sep 2004	Hurricane Jeanne	USA, Haiti
4,555	45	6 Sep 2004	Typhoon Songda	Japan
4,216	51	2 May 2003	Tornadoes	USA
4,204	25	27 July 2013	Floods	Europe
4,066	78	10 Sep 1999	Hurricane Floyd	USA, Bahamas
4,000	734	6 Oct 2016	Hurricane Matthew	Haiti
3,979	77	4 Oct 1995	Hurricane Opal	USA
3,926	6,425	17 Jan 1995	Earthquake (Kobe)	Japan
$507 Billion	38,907 Total deaths			

Source: Data after Swiss Reinsurance Company (2017).

and stones to rebuild on the same site. Floods and hurricanes inundate towns, but people return to refurbish and again inhabit the same buildings. Volcanic eruptions pour huge volumes of magma and rock debris onto the land, burying cities and killing thousands of people, yet survivors and new arrivals build new towns and cities on top of their buried ancestors. Why do people return to a devastated site and rebuild? What are their thoughts and plans for the future? For a case history of a natural hazard, let's visit Popocatépetl in Mexico.

POPOCATÉPETL VOLCANO, MEXICO

Popocatépetl is a 5,452 m (17,883 ft) high **volcano** that lies between the huge populations of Mexico City (largest city in Mexico) and Puebla (fourth largest city in Mexico) (figure 1.1). The volcano has had numerous small eruptions over thousands of years; thus its Nahuatl name, Popocatépetl, or Popo as it is affectionately called, means smoking mountain. But sometimes Popo blasts forth with huge eruptions that destroy cities and alter the course of civilizations. Around the year 822 CE (common era), Popo's large eruptions buried significant cities. Even its smaller eruptions have affected the course of human affairs. In 1519, Popo was in an eruptive sequence as Hernán Cortéz and about 500 Spanish conquistadors marched westward toward Tenochtitlan, the Aztec capital city. The superstitious Aztec priest-king Montezuma interpreted the eruptions as omens, and they affected his thinking on how to deal with the invasion.

Figure 1.1 Popocatépetl in minor eruption. The cathedral was built by the Spanish on top of the great pyramid at Cholula, an important religious site in a large city that was mostly buried by an eruption around 822 CE.

Popocatépetl has helped change the path of history, but what is the situation now? Today, about 100,000 people live at the base of the volcano; they have been attracted by the rich volcanic soil, lots of sunshine, and fairly reliable rains. Millions more people live in the danger zone extending 40 km (25 mi) away. The Nahuatl people consider Popo to be divine—a living, breathing being. In their ancient religion, God, rain, and volcano are intertwined. Most do not fear the volcano; rather, they believe that God decides events and that with faith, things will work out. Thus, good opportunities for farming, coupled with faith and fatalism, bring people back.

Volcanic activity on Popo resumed on 21 December 1994 with eruptions of ash and gases. The sequence of intermittent eruptions continues today. How do we evaluate this hazard? Is this just one of the common multiyear sequences of small eruptions that gave the volcano its name? Or are these little eruptions the forewarnings of a giant killing eruption that will soon blast forth? We cannot answer these questions for sure. How would you handle the situation? Would you order the evacuation of 100,000 people to protect them, and in so doing, have them abandon their homes, sell their livestock, and leave their independent way of life for an unknown length of time that could be several years? Or would you explain the consequences of an unlikely but possible large eruption and let them decide whether to stay or go? If they decide to stay and then die during a huge volcanic blast, would this be your fault?

It is relatively easy to identify natural hazards, but as the Popocatépetl case history shows, it is not easy to decide how to answer the questions presented by this volcanic hazard. We are faced with the same types of questions again and again, for earthquakes, landslides, tornadoes, hurricanes, floods, and fire.

MAGNITUDE, FREQUENCY, AND RETURN PERIOD

Earth is not a quiet and stable body. Our planet is dynamic, with major flows of energy. Every day, Earth experiences earthquakes, volcanic eruptions, landslides, storms, floods, fires, meteorite impacts, and extinctions. These energy-fueled events are common, but their **magnitudes** vary markedly over space and time.

Natural hazards and disasters are not spaced evenly about Earth. Some areas experience gigantic earthquakes and some areas are hit by powerful hurricanes; some are hit by both, while other areas receive neither.

During a period of several years or even several decades, a given area may experience no natural disasters. But given enough time, powerful, high-energy events will occur in every area. It is the concentrated pulses of energy that concern us here, for they are the cause of natural disasters—but how frequent are the big ones? In general, there is an inverse correlation between the **frequency** and the magnitude of a process. The frequent occurrences are low in magnitude, involving little energy in each event. As the magnitude of an event increases, its frequency of occurrence decreases. For all hazards, small-scale activity is common, but big events are rarer. For example, clouds and rain are common, hurricanes are uncommon; streams overflow frequently, large floods are infrequent.

Another way of understanding how frequently the truly large events occur is to match a given magnitude event with its **return period,** or recurrence interval, which is the number of years between same-sized events. In general, the larger and more energetic the event, the longer the return period.

A U.S. Geological Survey mathematical analysis of natural-disaster fatalities in the United States assesses the likeliness of killer events. Table 1.4 shows the probabilities of 10- and 1,000-fatality events for earthquakes, hurricanes, floods, and tornadoes for 1-, 10-, and 20-year intervals, and estimates the return times for these killer events. On a yearly basis, most low-fatality events are due to floods and tornadoes, and their return times are brief, less than one year. High-fatality events are dominantly hurricanes and earthquakes, and their return times for mega-killer events are much longer than for floods and tornadoes.

Knowing the magnitude, frequency, and return period for a given event in a given area provides useful information, but it does not answer all our questions. There are still the cost-benefit ratios of economics to consider. For example, given an area with a natural hazard that puts forth a dangerous pulse of energy with a return period of about 600 years, how much money should you spend constructing a building that will be used about 50 years before being torn down and replaced? Will your building be affected by a once-in-600-year disastrous event during its 50 years? Should you spend the added money necessary to guarantee that your building will withstand the rare destructive event? Or do economic considerations suggest that your building be constructed to the same standards as similar buildings in nearby nonhazardous areas?

TABLE 1.4

Probability Estimates for 10- and 1,000-Death Natural Disasters in the United States

	Likeliness of a 10-Fatality Event			
	During 1 Year	During 10 Years	During 20 Years	Return Time (in years)
Earthquake	11%	67%	89%	9
Hurricane	39	99	>99	2
Flood	86	>99	>99	0.5
Tornado	96	>99	>99	0.3
	Likeliness of a 1,000-Fatality Event			
	During 1 Year	**During 10 Years**	**During 20 Years**	**Return Time (in years)**
Earthquake	1%	14%	26%	67
Hurricane	6	46	71	16
Flood	0.4	4	8	250
Tornado	0.6	6	11	167

Source: US Geological Survey Fact Sheet (unnumbered).

ROLE OF POPULATION GROWTH

The world experiences significant numbers of great natural disasters and increasing economic losses from these events. The losses of life and dollars are occurring at the same time the global population of humans is increasing (figure 1.2). Population growth places increasing numbers of people in hazardous settings. They live and farm on the slopes of active volcanoes, build homes and industries in the lowlands of river floodplains, and move to hurricane-prone coastlines. How have the numbers of people grown so large? The present situation can best be appreciated by examining the record of population history.

Figure 1.2 The number of people on Earth continues to grow rapidly.

Photo by Pat Abbott

Overview of Human Population

The most difficult part of human history to assess is the beginning, because there are no historic documents and the fossil record is scanty. Fossils of modern humans (*Homo sapiens*) discovered in Ethiopia and South Africa are dated older than 160,000 years. Our species appears to have begun in Africa about 200,000 years ago. The rate of population growth and the number of people alive early in human history were so small that they cannot be plotted accurately on the scale of figure 1.3. The growth from a few thousand people 160,000 years ago to more than 7.5 billion people in 2017 did not occur in a steadily increasing, linear fashion. The growth rate is exponential. Exponential growth seems negligible then suddenly becomes overwhelming.

THE POWER OF AN EXPONENT ON GROWTH

The most stunning aspect of figure 1.3 is the peculiar shape of the human population curve; it is nearly flat for most of human time and then abruptly becomes nearly vertical. The marked upswing in the curve shows the result of **exponential growth** of the human population. Possibly the least appreciated concept of present times is what a growth-rate exponent does to the size of a population over time. Exponential growth moves continuously in ever-increasing increments; it leads to shockingly large numbers in surprisingly short times. Probably our most familiar example of exponential growth occurs when interest is paid on money.

It can be difficult to visualize the results of exponential growth when it is expressed only as a percentage over time, such as the very small growth rate of the human population in 160,000 years or as 7% interest on your money for 50 years. It is easier to think of exponential growth in terms of doubling time—the number of years required for a population to double in size given an annual percentage growth rate. A simple formula, commonly called the rule of 70, allows approximation of doubling times:

$$\text{Doubling time (in years)} = \frac{70}{\%\ \text{growth rate/year}}$$

Learning to visualize annual percentage growth rates in doubling times is useful whether you are growing your money in investments or spending it by paying interest on debts (especially at the high rates found with credit-card debt). Table 1.5 shows how interest rates affect how quickly your money will grow.

THE PAST 10,000 YEARS OF HUMAN HISTORY

The long, nearly flat portion of the population curve in figure 1.3 certainly masks a number of small-scale trends, both upward and downward. The fossil record is not rich enough to plot a detailed record, but surely at times when weather was pleasant and food from plants and animals was abundant, the human population must have risen

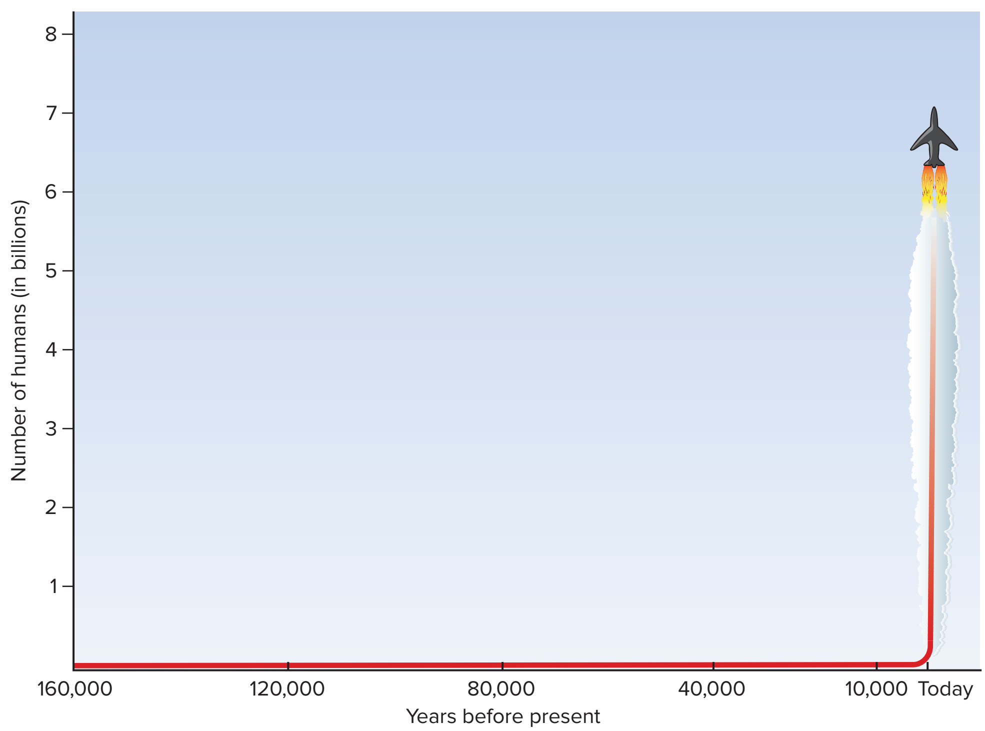


Figure 1.3 Human population growth during the past 160,000 years.

TABLE 1.5

Doubling Times at Some Common Percentage Rates

Growth Rate (% per year)	Doubling Time (years)
0.02	3,500
0.5	140
1	70
1.2	58
2	35
5	14
7	10
10	7
17	4

(figure 1.4). Conversely, when weather was harsh, food was scarce, and diseases were rampant, the human population must have fallen.

The nearly flat population growth curve began to rise about 8,000 years ago, when agriculture became established and numerous species of animals were domesticated. The world population is estimated to have been about 8 million people by 10,000 years ago. After the development of agriculture and the taming of animals removed much of the hardship from human existence, the population growth rate is likely to have increased to 0.036% per year, yielding a net gain of 360 people per million per year. This increased rate of population growth probably caused the human population to reach 200 million people by 2,000 years ago.

As humans continued to improve their ability to modify the environment with better shelter and more reliable food and water supplies, the world population grew at faster rates. From about 1 CE to 1750, world population grew to about 800 million. Growth occurred at an average rate of 0.056% per year, meaning that another 560 people were added per million per year.

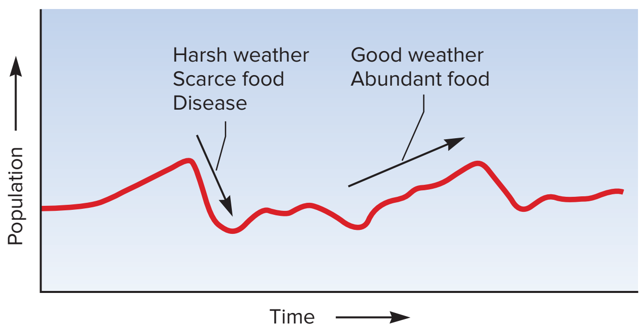


Figure 1.4 Good weather and plentiful food cause upsurges in population; bad weather, disease, and scarce food cause downswings in population.

Throughout the history of the human race, high rates of birth were required to offset high rates of infant mortality and thus maintain a viable-sized human population. The 18th century saw many of the intellectual advances that set the stage for the present phase of cultural change. At long last, the causes of many diseases were being recognized. The health necessities of clean water, sanitation, and nutrition led to the principles of public health being established. Advances in the medical world, including immunization, greatly improved the odds for the survival of individual humans through their reproductive years. No longer were many mothers and great numbers of children dying during childbirth and infancy.

The 18th century saw death rates drop dramatically, but birth rates remained high and population doubling times dropped dramatically; thus population size soared. About 1804, the human population reached 1 billion; by 1922, it had grown to 2 billion; in 1959, it reached 3 billion; by 1974, it was 4 billion; by early 1987, it was 5 billion; in 1999, it reached 6 billion; it passed 7 billion in October 2011 (figure 1.6). Notice the decline in the number of years it takes for a net gain of another 1 billion people on Earth.

Since 1900, more years have been added to average human life spans than ever before. First the increase came by reducing child mortality. Second the number of years in old age increased. Before 1800, no country on Earth had an average human life span at birth that exceeded 40 years. Now the average life span in every country is greater than 40 years.

The 20th-century growth of the human population is unprecedented and breathtaking. The number of humans doubled twice—from about 1.5 billion to 3 billion and again to more than 6 billion. The increased population used 16 times more energy, increased industrial output 40 times, used 7 times more water, caught 35 times more fish, and expanded the cattle population to 1.4 billion. The effect of exponential growth is racing ahead. In his book *Wealth of Nations,* published in 1776, Adam Smith said, "Men, like all other animals, naturally multiply in proportion to the means of their subsistence."

THE HUMAN POPULATION TODAY

At present, the world population is growing at about 1.2% per year for a doubling time of 58 years (table 1.6). The 1.2% gain is a net figure derived by measuring the birth rate (**fertility** rate) and subtracting the death rate (**mortality** rate). Even after subtracting all the human lives lost each year to accidents, diseases, wars, and epidemics such as AIDS, the human population still grows by more than 80 million people per year. Each year, the world population increases by about the total population of Germany.

The net growth of the human population can be grasped by viewing it on short timescales (figure 1.7). There is a net addition of 2.6 people every second, a rate comparable to a full jetliner landing a load of new people every minute. The monthly net growth of people is greater than the population of Massachusetts.

Side Note

Interest Paid on Money: An Example of Exponential Growth

Compare the growth of money in different situations (figure 1.5). If $1,000 is stashed away and another $100 is added to it each year, a linear growth process is in operation. Many of the processes around us can be described as linear, such as the growth of our hair or fingernails.

If, in contrast, another $1,000 is stashed away but this time earns interest at 7% per year and the interest is allowed to accumulate, then an exponential growth-rate condition exists. Not only does the $1,000 earn interest, but the interest from prior years remains to earn its own interest in compound fashion.

Notice that an exponential growth curve has a pronounced upswing, or J shape. A comparison of the linear and exponential curves in figure 1.5 shows that they are fairly similar in their early years, but as time goes on, they become remarkably different. The personal lesson here is to *invest money now.* Smaller amounts of money invested during one's youth will become far more important than larger amounts of money invested later in life. Individuals who are disciplined enough to delay some gratification and invest money while they are young will be wealthy in their later years. Albert Einstein described compound interest, the exponential growth of money, as one of the most powerful forces in the world.

Here is a riddle that illustrates the incredible rate of exponential growth; it shows the significance of doubling times in the later stages of a system. Suppose you own a pond and add a beautiful water lily plant that doubles in size each day. If the lily is allowed to grow unchecked, it will cover the pond in 30 days and choke out all other life-forms. During the first several days, the lily plant seems small, so you decide not to worry about cutting it back until it covers half the pond. On what day will that be?

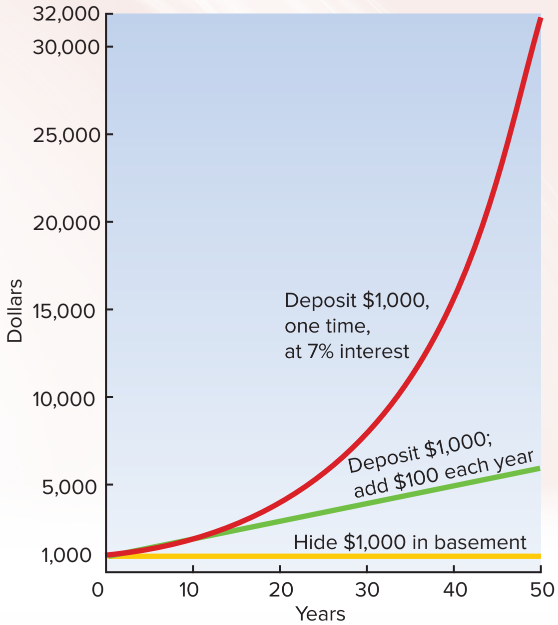


Figure 1.5 Amounts of money versus time. Compound interest (exponential growth) produces truly remarkable sums if given enough time.

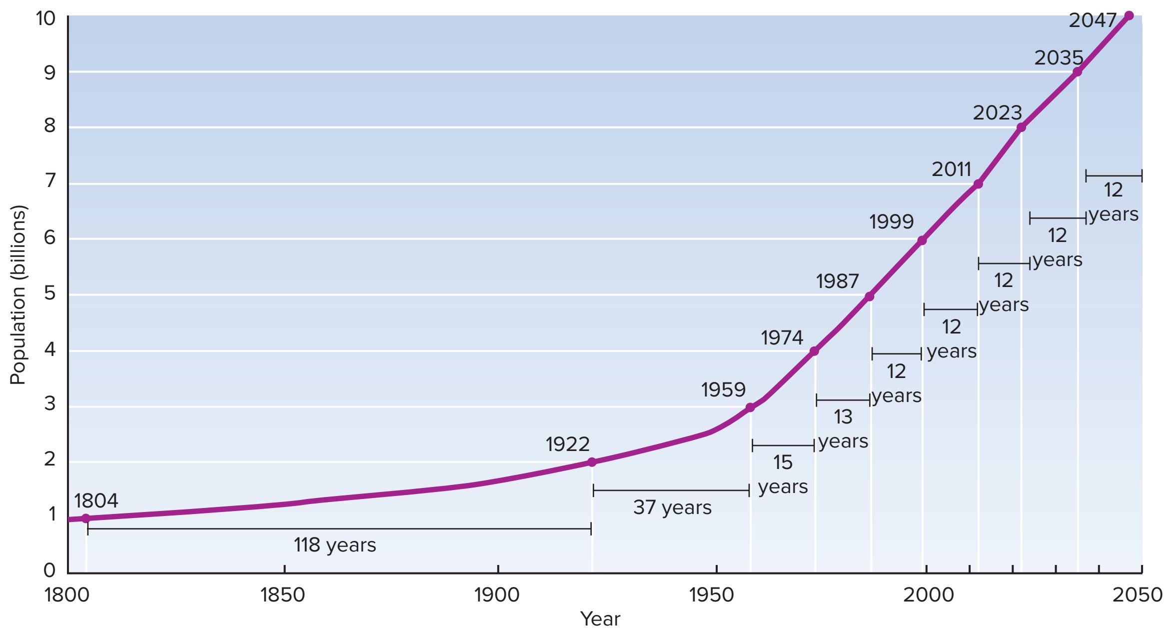


Figure 1.6 Growth of the world population of humans. Notice how the time to add another billion people has decreased. Population grew to 7.5 billion in 2017 but will exceed 10 billion before 2050.

Source: US Census Bureau.

TABLE 1.6

World Population Data, Mid-2017

	Population (millions)	Birth Rate (per 1,000)	Death Rate (per 1,000)	Yearly Growth %	Doubling Time (in years)	Projected Population in 2050 (millions)
World	7,536	20	8	1.2	58	9,846
More-developed countries	1,263	11	10	0.1	700	1,325
Less-developed countries	6,237	21	7	1.4	50	8,520
Least-developed countries*	1,001	33	8	2.4	29	1,952
Africa	1,250	35	9	2.5	28	2,574
Asia	4,494	18	7	1.1	64	5,245
Europe	745	11	11	0	—	736
Northern America	362	12	8	0.5	140	444
Latin America	643	17	6	1.3	54	783
Oceania	42	16	7	1.1	64	63

*Subset of less-developed countries

Source: World Population Data Sheet (2017).

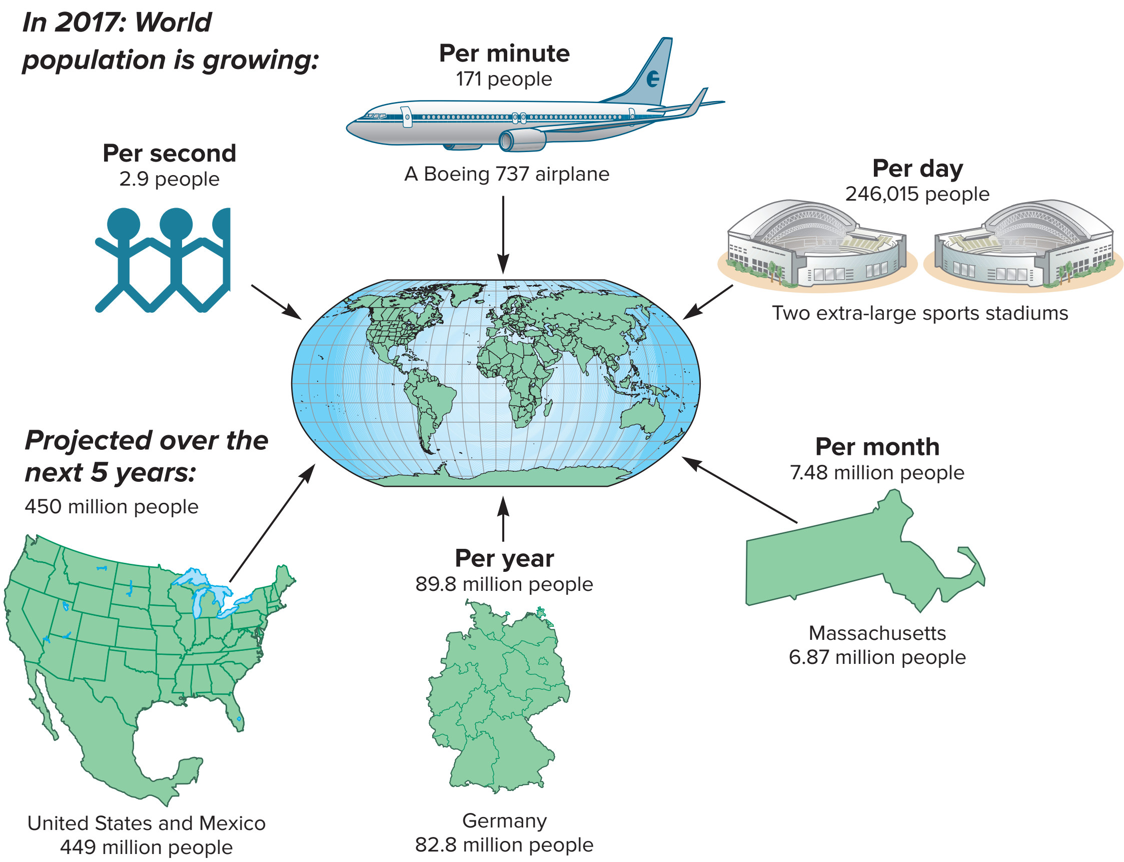


Figure 1.7 Growth of world population over differing lengths of time.

Source: Modified from US Census Bureau.

Future World Population

Today, most of the more-developed countries have gone through **demographic transitions;** they have gone from high death rates and high birth rates to low death rates and low birth rates. But many less-developed countries have low to moderate death rates and high birth rates; will they go through demographic transitions? In demographic transition theory, both mortality and fertility decline from high to low levels because of economic and social development. Yet even without significant economic development, Population Reference Bureau estimates of the rates of world population growth are dropping: from 1.8% in 1990, to 1.6% in 1997, to 1.4% in 2000, and to 1.2% in 2017. What is causing this decrease in fertility? It appears to be due largely to urbanization and increased opportunities for women. At the beginning of the 20th century, less than 5% of people in less-developed countries lived in cities, but by the year 2017, more than half of the people were living in urban areas (table 1.7). This is a change from farmer parents wanting many children to work in the fields and create surplus food, to city parents wanting fewer children to feed, clothe, and educate. Urban women have greater access to education, health care, higher incomes, and family-planning materials. When presented with choices, many women choose to have fewer children and to bear them later. Both of these choices lower the rate of population growth.

In the last 50 years of the 20th century, population grew from about 2.5 billion to over 6 billion, an increase of 3.5 billion people. Even with the recent decreases in fertility rates, the population explosion is not over. A growth rate of 1.2% per year will cause the world population of humans to exceed 10 billion by the year 2050 (see table 1.6), an increase of another 3.5 billion people within 50 years. Population growth is not evenly distributed around the world. In general, wealthy countries have low or even negative rates of population growth. Many poor nations have high rates of population growth (figure 1.8).

An important factor in estimating future growth is the age distribution of the population (table 1.7). Nearly 30% of the population today is less than 15 years old, meaning their prime years for childbearing lie ahead. The century from 1950 to 2050 will see the world population grow from 2.5 billion to more than 10 billion people.

The number of births per woman has a dramatic effect on human population growth. Starting in the year 2000 with a world population in excess of 6 billion people, look at three scenarios for population size in the year 2150 based on births per woman: (1) if women average 1.6 children, world population drops to 3.6 billion; (2) if women average 2 children, population grows to 10.8 billion; (3) if women average 2.6 children, population grows to 27 billion. The difference between a world population of 3.6 billion or 27 billion rests on a difference of only one child per woman.

DEMOGRAPHIC TRANSITION

The demographic transition model is based on the population experiences of economically wealthy countries in the past few centuries. Up through the 17th century, a woman

TABLE 1.7

Data Influencing Future Population, Mid-2017

	Percent of Population of Age		Average Number of Children Born per Woman	Percent Urban (cities >2,000 people)	Percent of Married Women Using Modern Contraception
	<15	65+			
World	26	9	2.5	54	55
More-developed countries	16	18	1.6	78	60
Less-developed countries	28	7	2.6	49	55
Least-developed countries	40	4	4.3	32	32
Africa	41	3	4.6	41	30
Asia	24	8	2.2	49	59
Europe	16	18	1.6	74	56
Northern America	19	15	1.8	81	70
Latin America	26	8	2.1	80	67
Oceania	23	12	2.3	69	53

Source: World Population Data Sheet (2017).

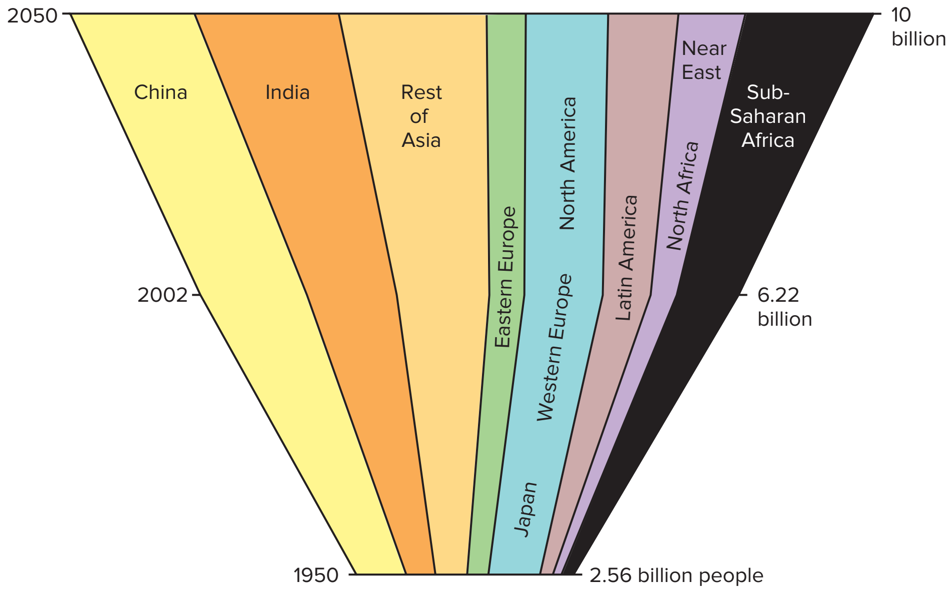


Figure 1.8 World population by region: 1950, 2002, 2050.

Source: US Census Bureau.

had to bear several children to have a few survive to adulthood and replace the prior generation. Births had to be numerous to compensate for the high rates of infant mortality. Beginning in the 18th century, discoveries in public health, medicine, and immunization caused the death rate to drop dramatically. During this time, birth rates stayed high, so overall population grew rapidly. As time passed and people realized that most of their children would survive to adulthood, birth rates dropped and population stabilized at a new and higher level.

The demographic transition takes place in phases:

1. Before the transition: high death rates are offset by high birth rates to maintain a population.
2. During the transition: low death rates coupled with continuing high birth rates cause population to soar.
3. After the transition: low death rates combine with low birth rates to achieve a stable population at a significantly higher level.

Today the transition is taking place at different rates in different countries (figure 1.9). Most of the population growth is occurring in the poorest areas of the poorest countries. Some of the wealthiest countries now have more deaths than births each year.

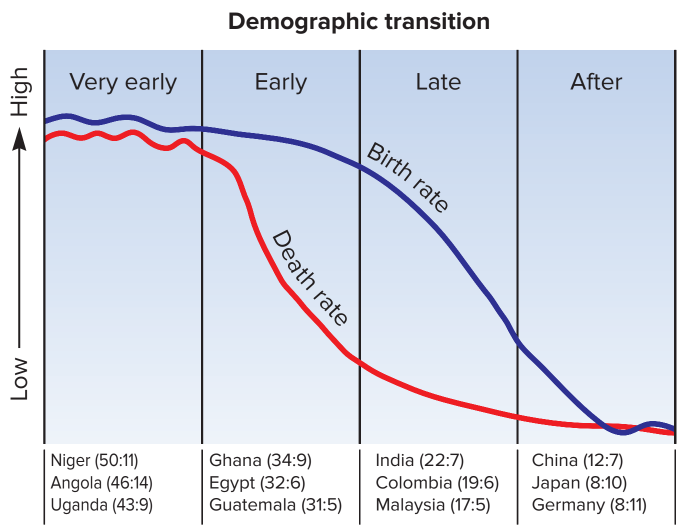


Figure 1.9 Demographic transition. In mid-2014, the shifts in birth rates and death rates vary markedly between countries. Birth and death rates are both expressed in number of people per 1,000 each year. For example, Uganda has 43 births and 9 deaths per 1,000 people each year (43:9).

Data from Population Reference Bureau.

URBANIZATION AND EARTHQUAKE FATALITIES

During the past 500 years, global earthquakes killed about 5 million people. Average numbers of deaths were about 1 million per century, or 100,000 per decade. These simple averages are misleading because they hide the effects of the deadliest earthquakes, such as the 250,000 people killed by the Tangshan, China, event in 1976. The mega-killer earthquakes of the past 500 years occurred in China, Indonesia, Pakistan, Iran, Turkey, Italy, Japan, and Haiti—and they may occur there again.

An analysis of the past 500 years by Roger Bilham shows that, with an average population of about 1.5 billion people, there was one earthquake that killed nearly a million people.

Side Note

A Classic Disaster: Influenza (Flu) Pandemic of 1918

In July 1914, a major war, eventually known as World War I, broke out in Europe. The countries and empires involved contained more than half the people in the world. When the war ceased in November 1918, almost 7 million soldiers had been killed in battle, along with about 1 million civilians.

As bad as 8 million war deaths sounds, a far more deadly natural disaster began during that time: the influenza pandemic of 1918–1919. The flu pandemic killed about 50 million people; this was 3% of the world's population. Estimates of total deaths range up to 100 million people. The influenza migrated around the world in waves. In the United Kingdom, the first wave arrived in the spring of 1918. In the fall of 1918, a longer-lasting, deadlier wave of flu swept the world, followed in 1919 by yet a third wave. Most flu victims were healthy young adults rather than the more typical elderly or juvenile victims of influenza (figure 1.10).

World War I did not cause the flu, but the global movements of millions of troops, weakened by stress and battle, increased the spread and deadly effects of the **virus.** Another 3 million soldiers died, not from World War I battles, but from influenza. In 1918, children skipped rope to this rhyme:

I had a little bird
Its name was Enza
I opened the window
And in-flu-enza.

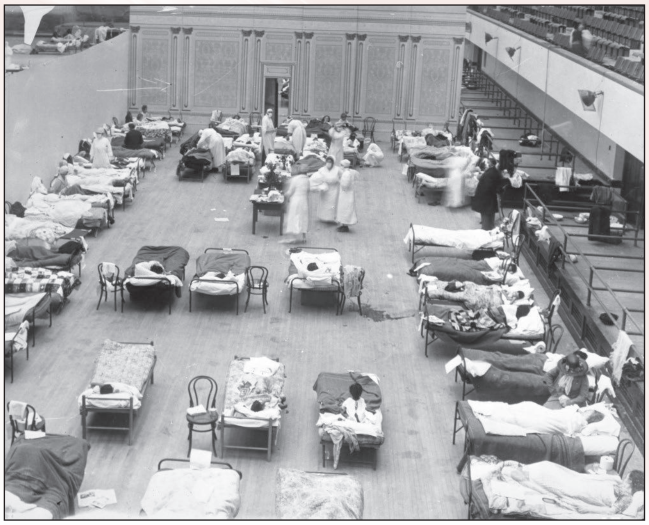


Figure 1.10 A typical scene during the 1918 flu pandemic. The Oakland Municipal Auditorium was used as a temporary hospital, allowing volunteer nurses to tend to the sick.

Source: Photo by Edward A. "Doc" Rogers. From the Joseph R. Knowland collection at the Oakland History Room, Oakland Public Library. Digital copy via Calisphere, University of California.

But with population becoming five times larger at 7.5 billion people in the year 2017, million-death earthquakes may occur five times as frequently, or about one per century. Most of the human population growth, by birth and by migration, is occurring in cities in less-developed countries. Many of these people are living in poorly constructed buildings in mega-cities. Million-death earthquakes are possible in a growing number of mega-cities.

DISEASE PANDEMICS

Throughout recorded history, deadly diseases have swept throughout the world, killing millions of people in **pandemics.** For example, the bacterium *Yersinia pestis,* transmitted to humans by fleas, caused the bubonic plague—the Black Death that killed about 75 million people in Europe in the 14th century.

Viruses have also caused pandemics via smallpox, HIV, polio, **influenza,** and other diseases. For example, in 1918–1919, the influenza virus A (H1N1) spread around the world, killing about 50 million people. With the human population now exceeding 7 billion people, with more than 50% of people now living in cities, and with the rapid movement of people worldwide via jet airplanes, the potential exists for a new pandemic disease.

Viruses

Viruses are life in the simplest form. They are genetic material (DNA or RNA) coated by fat and protein. A **virus** might have only 4 genes, whereas a bacterium might have 4,000 genes, and a human 24,000 genes. Viruses cannot reproduce by themselves; they must invade a host cell and cause the host to reproduce the virus.

Viruses infect many forms of life, including animals, plants, and even bacteria. The same viruses commonly exist in humans, pigs, and birds, and move easily between them. There are an estimated 1 billion pigs and 20 billion chickens in the world. Because humans commonly live and interact with birds and pigs, the transfer of viruses between them is especially likely. Other transfers of viruses to humans include HIV/AIDS from chimpanzees and Ebola from bats. When two different viruses enter a single cell, their genes can form new combinations, creating a new type of virus. On the surface of a virus are molecules shaped into unique configurations that might match a living cell and allow entry, much like a unique key will open a specific lock.

Influenza A Viruses Influenza A viruses cause recurrent **epidemics** and pandemics, as in 1918–1919. Type A viruses examined on the basis of their haemagglutinin (HA) and neuraminidase (NA) molecules are divided into 16 HA subtypes (H1 to H16) and 9 NA subtypes (N1 to N9). In 2005, researchers reported the results of a study of the 1918–1919 influenza virus collected from samples preserved from World War I flu-victim soldiers and from historic individuals buried in Arctic permafrost (frozen soil). The 1918–1919 influenza was type A (H1N1), a subtype with an early history in birds.

Early in 2009, a flu epidemic broke out near La Gloria in the state of Veracruz, Mexico. By 23 April 2009, 23,000 cases had been reported. By 7 May 2009, the flu had spread to become a pandemic, with cases identified in 21 countries on five continents. Laboratory analyses showed that this new virus was type A (H1N1) and was made up of genes from four different flu viruses: from North American pigs (30.6%), Eurasian pigs (17.5%), North American birds (34.4%), and humans (17.5%). People were worried. Could this virus evolve into as big a killer as the one in 1918–1919?

Analysis of H1N1 deaths in 2009 from 214 countries showed 44,100 deaths—a significant total, but far less severe than in 1918. Like the 1918 influenza, though, most of the deaths occurred in young people; 73% of deaths were people 29 years old and younger. The death percentages by age groups include:

- 37% were 10 to 19 years old
- 22% were less than 9 years old
- 14% were 20 to 29 years old

In the reverse of a typical flu year, people 60 years old and older suffered only 3% of the deaths. If one views the 2009 H1N1 figures as deaths only, then it was not as bad a year as had been feared. But if one considers the number of years of life lost by the young victims, then the 2009 pandemic would be more equivalent to 250,000 deaths in a typical flu year.

Carrying Capacity

How many people can Earth support? At this time, the question is unanswerable. Nonetheless, many people worry about dangers resulting from the unprecedented growth of the human population, such as more and greater natural disasters, increased global warming, decreasing supplies of fresh water, depletion of fossil fuels, increased pollution, increased desertification, and the increased rate of extinction of species. Other people see no big problems and point out that humans have already increased the carrying capacity of Earth for us via agriculture, water storage and purification, and advances in public health; they feel that any upcoming problems will be solved just like others have been in the past.

In the natural world, biologists studying **carrying capacity** of the environment for individual species of mammals, birds, frogs, and other animals find that population size is regulated by the resources available. For example, when a resource such as available food increases, a feeding population grows in size. If that food resource decreases due to drought, competition, or other causes, the population dependent on that food dies back and decreases in size.

A fundamental principle of biology is that a population of animals cannot increase forever because they live in a finite ecosystem. Ultimately, population growth is controlled by negative feedbacks such as starvation, predation, and disease.

Ireland in the 1840s

Ireland in the 1840s provides a human example of carrying capacity. The European explorers of the 1500s brought the potato back from South America. The potato is a highly nutritious food. A diet of potatoes, milk (from animals fed potatoes), and greens constitute a nutritionally complete diet. An acre of potatoes could feed an Irish family of six for a year. In Ireland, the potato was the wonder crop that allowed a child-loving population to grow explosively. By 1841, Ireland's population had grown well past 8 million, with nearly half the people surviving wholely or mostly on potatoes. In 1845, heavy spring rains aided growth and spread of a fungal infestation, the potato blight, which caused potatoes to rot during storage. But when the potatoes rotted there was no substitute food. Malnourishment became common. Then the winter of 1846–1847 hit with unusual severity, causing weakened people to suffer even more. The toll was severe: a million people died from disease, and another 1.5 million people emigrated. During their travel to the United States and Canada, 1 in 7 emigrés died.

The carrying capacity of Irish land increased for humans when the potato arrived. Potato plants covered the lands, even extending into bogs and up steep mountain slopes. The human population fed by the increased food supply grew rapidly. But when the potato supply dropped suddenly, so did the human population.

Easter Island (Rapa Nui)

Easter Island (Rapa Nui) is a triangular-shaped, volcanic land with an area of about 165 km^2 (64 mi^2). It lies over 2,000 km (more than 1,200 mi) east of Pitcairn Island and over 3,700 km (more than 2,200 mi) west of Chile (figure 1.11). Easter Island is isolated; it has high temperatures and humidity, poorly drained and marginal soils, no permanent streams, no terrestrial mammals, about 30 native plant species including trees in locally dense growths, and few varieties of fish in the surrounding sea. Year-round water is available only in little lakes within the volcano caldera.

About 1,000 years ago, seafaring Polynesian people arrived on Rapa Nui with 25 to 50 settlers. They were part of the great Polynesian expansion outward from southeast Asia that led them to discover and inhabit islands from Hawaii in the north to New Zealand in the southwest and to

Figure 1.11 Easter Island (Rapa Nui) is an isolated outpost of Polynesian civilization nearly lost in the vast Pacific Ocean.

Figure 1.12 Rapa Nui inhabitants spent much of their energy creating giant statues (moai).

©Adalberto Rios Szalay/Sexto Sol/Getty Images

Rapa Nui in the southeast. The wide-ranging voyagers colonized islands over a Pacific Ocean area more than twice the size of the United States.

The colonizers of Rapa Nui brought chickens and rats, along with several of their food plants. The climate was too severe for most of their plants except the yam. Their resulting diet was based on easily grown chickens and yams, and housing was fashioned using wood from native trees; the people had lots of free time.

The islanders used their free time to develop a complex social system divided into clans that practiced elaborate rituals and ceremonies. Their customs included competition between the clans in shaping and erecting mammoth statues. The statues were carved out of volcanic rock using obsidian (volcanic glass) tools. The statues (moai) were more than 6 m (20 ft) high, weighed about 15 tons apiece, and were erected on ceremonial platforms (ahu) (figure 1.12).

The peak of the civilization occurred about 1550 CE, when the human population had risen to about 7,000; statues numbered more than 600, with half as many more being shaped in the quarries. But from its peak, the civilization declined rapidly and savagely, as first witnessed by the crew of a Dutch ship on Easter Sunday, 5 April 1722. The Europeans found about 2,000 people living in caves in a primitive society engaged in almost constant warfare and practicing cannibalism. What caused this cultural collapse? It appears that human activities so overwhelmed the environment that it was no longer able to support the greatly enlarged human population. The customs of society dissolved in the fight of individuals and clans to survive.

Carving the giant statues had not been particularly difficult, but transporting them was physically and environmentally strenuous. Trees were cut down and placed under statues as rollers. Islanders pushed the heavy statues from the quarry and levered them onto their ceremonial platforms. The competition between clans to create the most statues helped destroy the forests. Without trees, houses could not be built, and people had to move to caves. There was little fuel for cooking or to ward off the chill of colder times. Soil erosion increased and agricultural production dropped. Without trees, there were no canoes, and so islanders caught fewer fish. Without canoes, there was no escape from the remote and isolated island. As food resources declined, the social system collapsed, and the statue-based religion disintegrated. Clans were reduced to warfare and cannibalism in the struggle for food and survival.

Competition between clans was so consuming that they did not consider the health of the environment and thus paid a price: the human population on the island collapsed. Easter Island is one of the most remote inhabited areas on Earth, a tiny island virtually lost in the vast Pacific Ocean. When problems set in faster than the Rapa Nui customs could solve them, there was no place to turn for help, no place to escape. The carrying capacity of the land had been exceeded, and the human population suffered terribly. What lesson does Easter Island have for the whole world? Earth is but a tiny island lost in the vast ocean of the universe (figure 1.13); there is no realistic chance of the human population escaping to another hospitable planet.

The Easter Island example raises interesting philosophical questions. If climate change decreases global food production, causing the human population to exceed Earth's carrying capacity, could human value systems change fast enough to solve the problem? If all the people on Earth had to face the Easter Island situation, how would we fare?

Figure 1.13 Earth is an isolated island nearly lost in the vast "ocean" of the universe.

Photo by Pat Abbott

Summary

Great natural disasters killed almost 500,000 people in four recent events: 2011 Japan earthquake and tsunami, 2010 Haiti earthquake, 2008 hurricane in Myanmar, and earthquake in China. Over time, the two deadliest events are tropical storms (hurricanes) and earthquakes. In 2016, the known economic losses from natural disasters were about US$166 billion. The long-term trend is for economic losses to increase.

Natural hazards exist in areas of obvious danger, such as cities built on the slopes of active volcanoes or on the floodplains of rivers. For these sites, it is only a matter of time before the hazard is realized as a disaster. At any one site, the greater the magnitude of a disaster, the less frequently it occurs. Large disasters have longer return periods.

The curve describing the history of human population growth is flat to gently inclined for 160,000 years, and then it rises rapidly in the last three centuries. In the past, women bore numerous children, but many died, so overall population growth was slow. With the arrival of the scientific-medical revolution and the implementation of the principles of public health, the human population has soared. Birth rates remain high in much of the world, even though death rates have plummeted. The population reached 1 billion in about 1804, 2 billion in 1922, 3 billion in 1959, 4 billion in 1974, 5 billion in 1987, 6 billion in 1999, and it passed 7 billion in 2011.

A steeply rising growth curve is exponential; in terms of population, more people beget ever more people. One way to visualize exponential growth is by using doubling time, the length of time needed for a population to double in size. Doubling times can be approximated by the rule of 70:

$$\text{Doubling time (in years)} = \frac{70}{\text{\% growth rate/year}}$$

At present, after subtracting deaths from births, world population increases 1.2% per year for a doubling time of 58 years.

Much hope is placed in the demographic transition model, which holds that economic wealth, combined with knowing that one's children will survive, leads to dramatic drops in birth rates. This model holds for some more-developed countries. Now some less-developed countries are experiencing drops in birth rates, presumably due to urbanization and more choices for women. Even at lower rates of growth, human population is likely to exceed 10 billion before 2050. The rapid growth in human population sets the stage for mega-death earthquakes and hurricanes.

New flu viruses are commonly created where people live closely with birds and pigs. These new viruses, which have the potential to kill millions of people, can rapidly spread around the world.

Carrying capacity is an estimate of how many individuals of a species the environment can support. How many people can Earth support? The answer is not known, but it is the subject of much debate.

Terms to Remember

carrying capacity 19
CE 10
cyclone 6
demographic transition 16
earthquake 6
energy 6
epidemic 18
exponential growth 12
fertility 13
frequency 11
great natural disaster 6
hurricane 6
influenza 18
magnitude 10
mitigation 8
mortality 13

natural disaster 6
natural hazard 8
pandemic 18
return period 11
typhoon 6
virus 18
volcano 10

Questions for Review

1. What types of natural disasters killed the most people in the past 40 years? Where in the world are deaths from natural disasters the highest? Where in the world are insurance losses from natural disasters the highest?
2. What is a great natural disaster?
3. What is the difference between a natural disaster and a natural hazard? How do economic losses differ from insured losses?
4. For nations, what is the relationship between natural-disaster deaths, gross domestic product, and level of democracy?
5. What is the relationship between the magnitude of a given disaster and its frequency of occurrence?
6. Draw a curve showing the world population of humans in the past 100,000 years. Why has the curve changed shape so dramatically?
7. Explain the concept of exponential growth.
8. What is the size of the world population of humans today? Extrapolating the current growth rate, what will the population be in 100 years? In 200 years? Are these large numbers environmentally realistic?
9. What are the population doubling times given these annual growth rates: Africa, 2.4%; world, 1.2%?
10. For nations, what are demographic transitions?
11. How much time does it take for a flu pandemic to infect people all around the world?
12. What is the relationship between earthquake fatalities and cities?
13. Explain the concept of carrying capacity for a species. What processes might limit the numbers of a species?

Questions for Further Thought

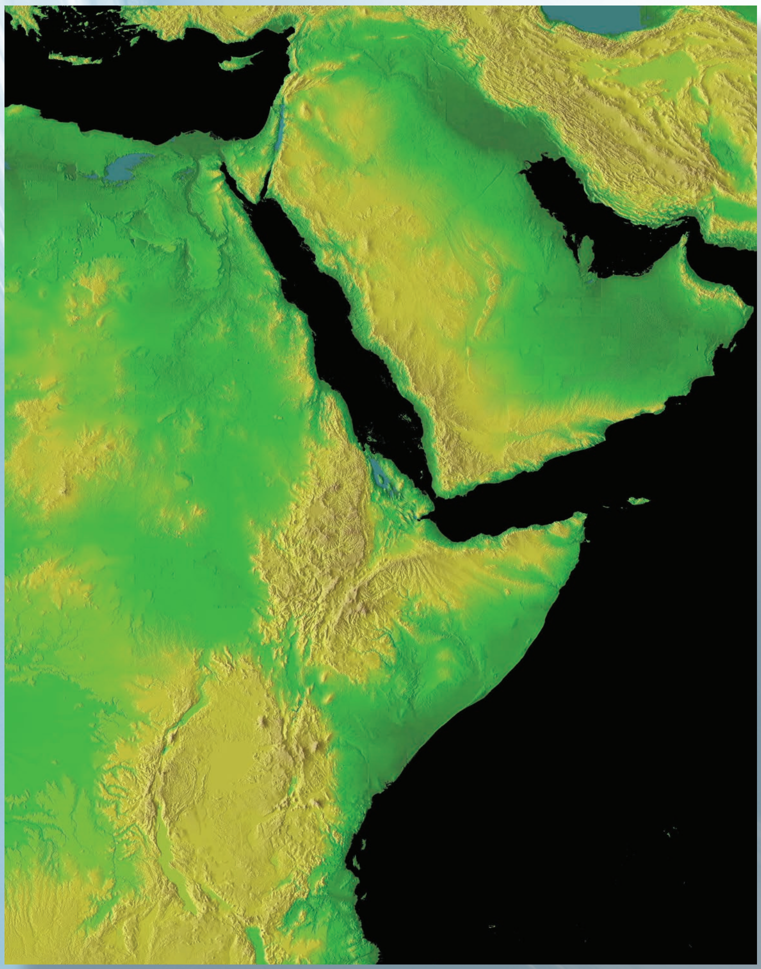
1. Would we call a large earthquake or major volcanic eruption a natural disaster if no humans were killed or buildings destroyed?
2. Which single disaster could kill the most people—a flu pandemic, an earthquake, or a hurricane?
3. Could global building designs be made disaster-proof, thus reducing the large number of fatalities?
4. What is the carrying capacity of Earth for humans—that is, how many humans can Earth support? What factors are most likely to slow human population growth?
5. Compare the rate of change of human populations to the rate of change in religious and cultural institutions. Can religious and cultural institutions change fast enough to deal with world population growth?
6. Evaluate the suggestion that the overpopulation problem on Earth can be solved by colonizing other planets.
7. Is a nation's destiny determined by its demographics?

CHAPTER 2

Internal Energy and Plate Tectonics

Such superficial parts of the globe seemed to me unlikely to happen if the Earth were solid to the centre. I therefore imagined that the internal parts might be a fluid more dense, and of greater specific gravity than any of the solids we are acquainted with; which therefore might swim in or upon that fluid. Thus the surface of the globe would be a shell, capable of being broken and disordered by the violent movements of the fluid on which it rested.

—Benjamin Franklin, 1780



Satellite view of Arabia moving northeast away from Africa.

Source: National Centers for Environmental Information/NOAA

LEARNING OUTCOMES

Internal energy has caused the Earth to differentiate into layers. Throughout the Earth, materials move vertically and horizontally. After studying this chapter you should

- know the layering of the Earth and how it formed.
- be familiar with the sources of energy inside the Earth.
- understand the behavior of materials.
- be able to explain how plate tectonics operates.
- comprehend Earth's magnetic field and the evidence it provides for plate tectonics.
- know the age of the Earth and how it is determined.
- appreciate the thought processes used to understand the Earth.

OUTLINE

- Origin of the Sun and Planets
- Earth History
- The Layered Earth
- Internal Sources of Energy
- Plate Tectonics
- The Grand Unifying Theory
- How We Understand Earth

As described in the Prologue, energy flows upward and outward from the interior of the Earth. At the surface of the Earth we feel this energy where it is released as earthquakes and volcanic eruptions. In order to understand these natural disasters, we need to know what is going on inside the Earth and how plate tectonics operates.

Origin of the Sun and Planets

Impacts of asteroids, comets, and meteorites are not rare and insignificant events in the history of our Solar System; they probably were responsible for its formation. The most widely accepted hypothesis of the origin of the Solar System was stated by the German philosopher Immanuel Kant in 1755. He thought the Solar System had formed by growth of the Sun and planets through collisions of matter within a rotating cloud of gas and dust.

The early stage of growth began within a rotating spherical cloud of gas, ice, dust, and other solid debris (figure 2.1a). Gravity acting upon matter within the cloud attracted particles, bringing them closer together. Small particles stuck together and grew in size, resulting in greater gravitational attraction to nearby particles and thus more collisions. As matter drew inward and the size of the cloud decreased, the speed of rotation increased and the mass began flattening into a disk (figure 2.1b). The greatest accumulation of matter occurred in the center of the disk, building toward today's Sun (figure 2.1c). The two main constituents of the Sun are the lightweight elements hydrogen (H) and helium (He). As the central mass grew larger, its internal temperature increased to about 1,000,000 degrees **centigrade** (°C), or 1,800,000 degrees **Fahrenheit** (°F), and the process of **nuclear fusion** began. In nuclear fusion, the smaller hydrogen atoms combine (fuse) to form helium, with some mass converted to energy. We Earthlings feel this energy as **solar radiation** (sunshine).

The remaining rings of matter in the revolving Solar System formed into large bodies as particles continued colliding and fusing together to create the planets (figure 2.1d). Late-stage impacts between ever-larger objects would have been powerful enough to melt large volumes of rock, with some volatile elements escaping into space. The inner planets (Mercury, Venus, Earth, Mars) formed so close to the Sun that solar radiation drove away most of their volatile gases and easily vaporized liquids, leaving behind rocky planets. The next four planets outward (Jupiter, Saturn, Uranus, Neptune) are giant icy bodies of hydrogen, helium, and other frozen materials from the beginning of the Solar System.

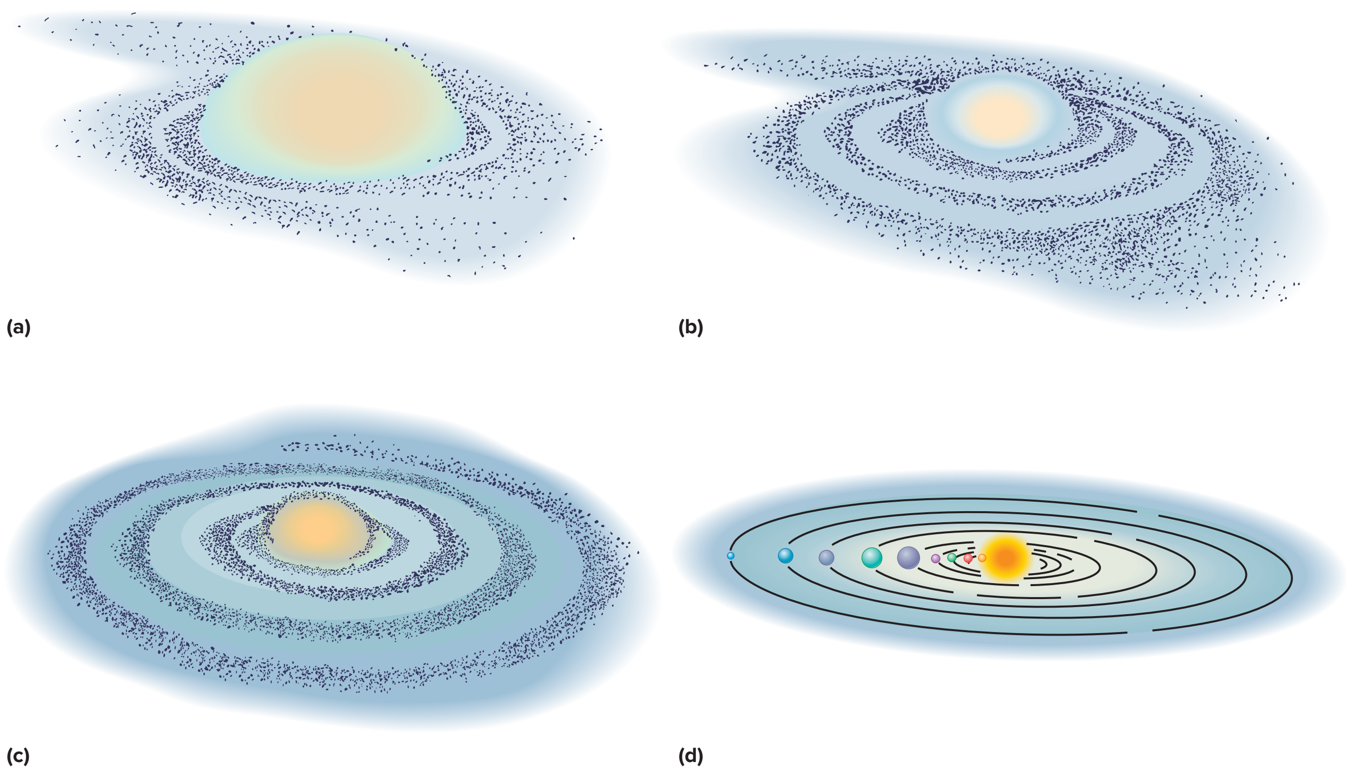


Figure 2.1 Hypothesis of the origin of the Solar System. (a) Initially, a huge, rotating spherical cloud of ice, gas, and other debris forms. (b) The spinning mass contracts into a flattened disk with most of its mass in the center. (c) Planets grow as masses collide and stick together. (d) The ignited Sun is surrounded by planets. Earth is the third planet from the Sun.

IMPACT ORIGIN OF THE MOON

Large impacts can generate enough heat to vaporize and melt rock; they can produce amazing results. For example, the dominant hypothesis on the origin of Earth's Moon involves an early impact of the young Earth with a Mars-size body, a mass about 10 times larger than the Moon. The resultant impact generated a massive cloud of dust and vapor, part of which condensed and accumulated to form the Moon. This theory suggests that the Moon is made mostly from Earth's rocky **mantle.** The theory accounts for the lesser abundance of iron on the Moon (iron on Earth is mostly in the central **core**) and the Moon's near lack of lightweight materials (such as gases and water), which would have been lost to space.

Earth History

To understand the origin and structure of Earth, we must know the flows of energy throughout the history of our planet. Studying early history is difficult because Earth is a dynamic planet; it recycles its rocks and thus removes much of the record of its early history. The older the rocks, the more time and opportunities there have been for their destruction. Nonetheless, the remaining early Earth rocks, along with our growing knowledge of the processes in Earth's interior and in the Solar System, allow us to build an increasingly sophisticated approximation of early Earth history.

Earth appears to have begun as an aggregating mass of particles and gases from a rotating cloud about 4.6 billion years ago. During a 30- to 100-million-year period, bits and pieces of metal-rich particles (similar to iron-rich meteorites), rocks (similar to stony meteorites), and ices (composed of water, carbon dioxide, and other compounds), accumulated to form Earth. As the ball of coalescing particles enlarged, the gravitational force may have pulled more of the metallic pieces toward the center, while some of the lighter-weight materials may have concentrated near the exterior. Nevertheless, Earth in its infancy probably grew from random collisions of debris that formed a more or less homogeneous mixture of materials.

But Earth did not remain homogeneous. The very processes of planet formation (figure 2.2) created tremendous quantities of heat, which fundamentally changed the young planet. The heat that transformed Earth came primarily from (1) impact energy, (2) decay of radioactive isotopes, (3) gravitational energy, and (4) differentiation into layers (figure 2.2).

As the internal temperature of Earth rose beyond 1,000°C (1,800°F), it passed the melting points of iron at various depths below the surface. Iron forms about one-third of Earth's mass, and although it is much denser than ordinary rock, it melts at a much lower temperature. The buildup of heat caused immense masses of iron-rich meteorites to melt. The high-density liquid iron was pulled by gravity toward Earth's center. As these gigantic volumes of liquid iron moved inward to form Earth's core, they released a tremendous amount of gravitational energy that converted to heat and probably raised Earth's internal temperature by another 2,000°C (3,600°F). The release of this massive amount of heat would have produced widespread melting likely to have caused low-density materials to rise and form: (1) a primitive **crust** of low-density rocks at the surface of Earth; (2) large oceans; and (3) a denser atmosphere. The formation of the iron-rich core was a unique event in the history of Earth. The planet was changed from a somewhat homogeneous ball into a density-stratified mass with the denser materials in the center and progressively less-dense materials outward to the atmosphere.

The low-density materials (magmas, waters, and gases), freed by the melting, rose and accumulated on Earth's

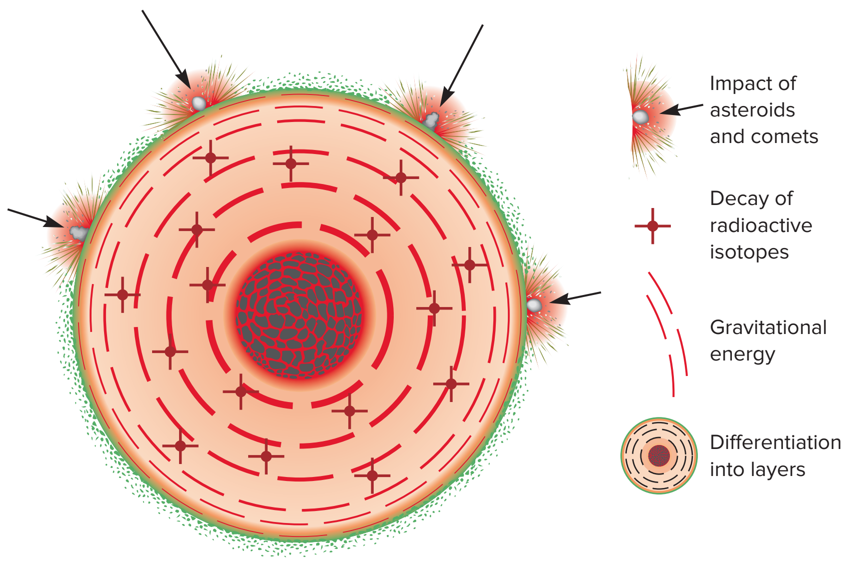


Figure 2.2 Heat-generating processes during the formative years of Earth include (1) impact energy, (2) decay of radioactive isotopes, and (3) gravitational energy. Increasing heat caused Earth to differentiate into layers.

exterior as continents, oceans, and atmosphere. It seems that oceans and small continents existed by 4.4 billion years ago, life probably was present as photosynthetic bacteria 3.5 billion years ago, large continents were present at least 2.5 billion years ago, and the outer layers of Earth were active in the process of plate tectonics by at least 1.5 billion years ago.

The Layered Earth

Earth today is differentiated into layers of varying densities. As we have noted, much of the densest material was pulled toward the center, and some of the least dense substances escaped to the surface (figure 2.3). At the center of Earth is a dense, iron-rich core measuring about 7,000 km (4,350 mi) in diameter. Earth's core is almost exactly the same size as planet Mars. The inner core is a solid mass 2,450 km (1,520 mi) in diameter with temperatures up to 4,300°C (7,770°F). The outer core is mostly **liquid,** and the **viscous** movements of convection currents within it are responsible for generating Earth's magnetic field. The entire iron-rich core is roughly analogous in composition to a melted mass of iron-rich meteorites.

Surrounding the core is a rocky mantle nearly 2,900 km (1,800 mi) thick, with a composition similar to that of stony meteorites. The mantle comprises 83% of Earth's volume and 67% of its mass. The rocks of the mantle can be approximated by melting a stony meteorite in the laboratory; this produces a separation in which an upper froth rich in low-density elements rises above a residue of denser minerals/elements. The low-density material is similar to continental crust that by melting and separation has risen above the uppermost mantle. All the years of heat flow toward Earth's surface have "sweated out" many low-density elements to form a continental crust. Today, the continents make up only 0.1% of Earth's volume. Floating above the rocky layers of Earth are the oceans and the atmosphere.

Earth's layering can be described as based on either (1) different strengths or (2) different densities due to varying chemical and mineral compositions (figure 2.3). Both temperature and pressure increase continuously from Earth's surface to the core, yet their effects on materials are different. Increasing temperature causes rock to expand in volume and become less dense and more capable of flowing under pressure and in response to gravity. Increasing pressure causes rock to decrease in volume and become more dense and more rigid. Visualize tar at Earth's surface. On a cold day, it is solid and brittle, but on a hot day, it can flow as a viscous fluid. Similar sorts of changes in physical behavior mark different layers of Earth. In fact, from a perspective of geological disasters, the crust-mantle boundary is not as important as the boundary between the rigid **lithosphere** (from the Greek word *lithos,* meaning "rock") and the "soft plastic" **asthenosphere** (from the Greek word *asthenes,* meaning "weak") (figure 2.4). The **mesosphere,** the mantle below the asthenosphere (see figure 2.3), is solid; it is a "stiff plastic," but it is not brittle like the lithosphere.

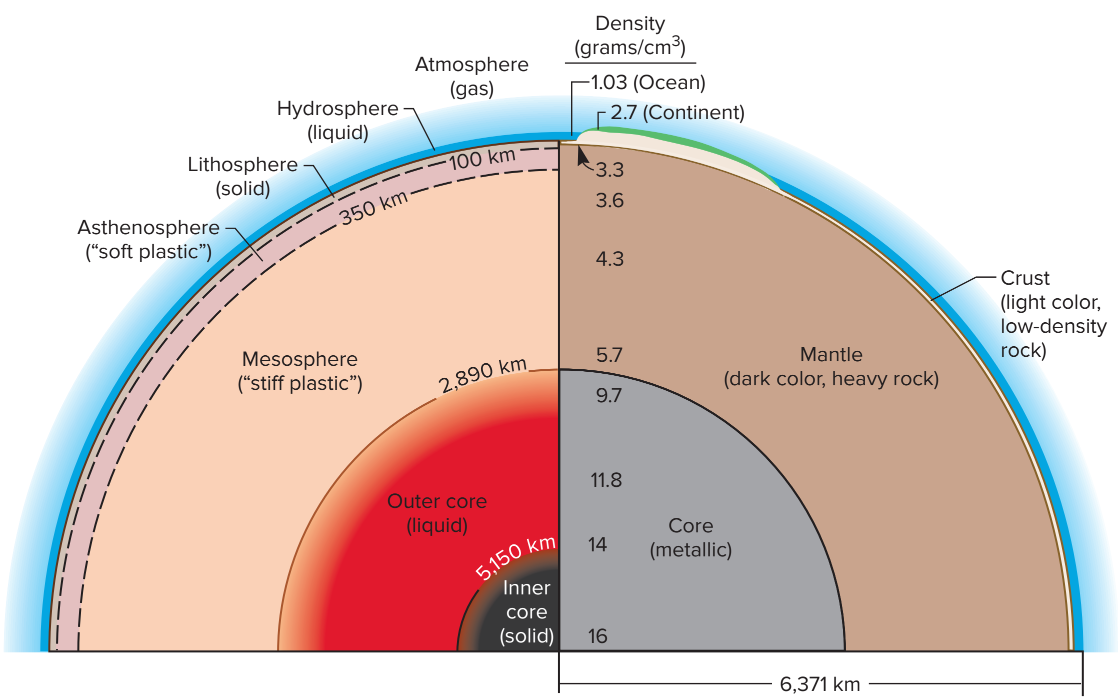


Figure 2.3 Density stratification within Earth—that is, lower-density materials float atop higher-density materials. Pressure and temperature both increase from the surface to the center of Earth. Layers illustrated on the left show the differences in physical properties and strengths. Layers on the right emphasize different mineral and chemical compositions.

Side Note

Mother Earth

The history of the 4.6-billion-year-old Earth has been metaphorically contrasted with the life history of a 46-year-old woman by Nigel Calder in his book *The Restless Earth*. In this metaphor, each of "Mother" Earth's years equals 100 million years of geologic time. The first seven of her years are mostly lost to the biographer. Like human memory, the early rock record on Earth is distorted; it emphasizes the more recent events in both number and clarity. Most of what we know of "Mother" Earth happened in the past six years of her life. Her continents had little life until she was 42. Flowering plants did not appear until her 45th year. Her pet dinosaurs died out eight months ago. In the middle of last week, some ancestors of present apes evolved into human ancestors. Yesterday, modern humans (*Homo sapiens*) evolved and began hunting other animals, and in the last hour, humans discovered agriculture and settled down. Fifteen minutes ago, Moses led his people to safety; five minutes later, Jesus was preaching along the same fault line; and after another minute, Muhammad taught in the same region. In the last minute, the Industrial Revolution began, and the number of humans increased enormously.

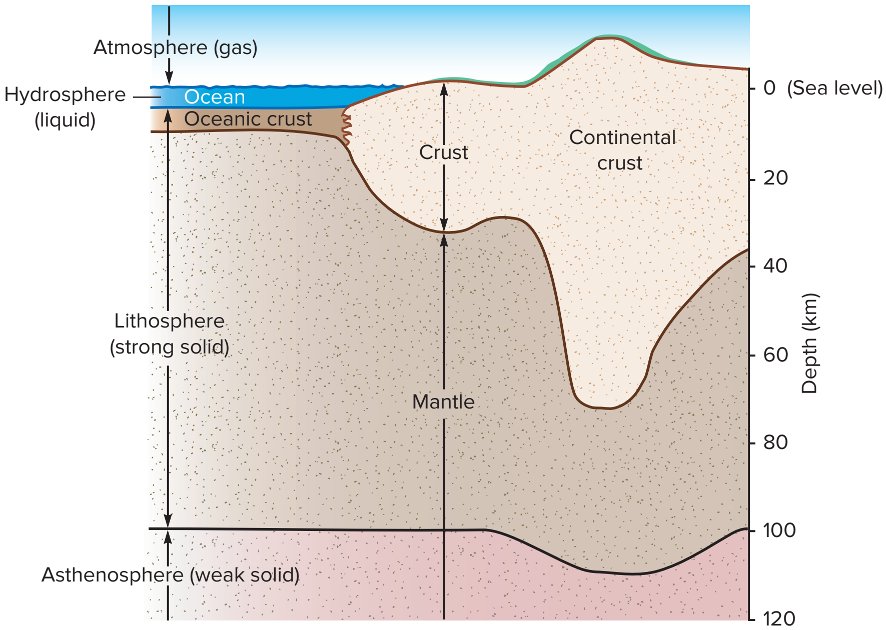


Figure 2.4 Upper layers of Earth may be recognized (1) compositionally, as lower-density crust separated from the underlying higher-density mantle, or (2) on the basis of strength, as rigid lithosphere riding atop "soft plastic" asthenosphere. Notice that the lithosphere includes both the crust and the uppermost mantle.

The differences in strength and mechanical behavior between solid, "plastic," and fluid states are partly responsible for earthquakes and volcanoes.

BEHAVIOR OF MATERIALS

The concepts of gas, liquid, and solid are familiar. Gases and liquids are both **fluids,** but a gas is capable of indefinite expansion, while a liquid is a substance that flows readily and has a definite volume but no definite shape. A solid is firm; it offers resistance to pressure and does not easily change shape. What is not stated but is implicit in these definitions is the effect of time. All of these definitions describe behavior at an instant in time—but how do the substances behave when viewed over a longer timescale? Specifically, some solids yield to long-term pressure such that at any given moment, they are solid, yet internally they are deforming and flowing—that is, behaving as a fluid. A familiar example is the ice in a glacier. When a glacier is hit with a rock hammer, solid chunks of brittle ice break off. Yet, inside the glacier, atoms are changing positions within the ice and dominantly moving to downhill positions of lower

Side Note

Volcanoes and the Origin of the Ocean, Atmosphere, and Life

The **elements** in volcanic gases are predominantly hydrogen (H), oxygen (O), carbon (C), sulfur (S), chlorine (Cl), and nitrogen (N). These gaseous elements combine at Earth's surface to make water (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2) with its rotten egg smell, carbon monoxide (CO), nitrogen (N_2), hydrogen (H_2), hydrochloric acid (HCl), methane (CH_4), and numerous other gases. The dominant volcanic gas is water vapor; it commonly makes up more than 90% of total gases.

The elements of volcanic gases (C, H, O, N, S, Cl) differ from the elements of volcanic rocks: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). The elements of volcanic gases make up the oceans, the atmosphere, and life on Earth, but they are rare in rocks. The 4.5 billion years of heat flow from Earth's interior have "sweated" out many lightweight elements and brought them to the surface via volcanism. Billions of years of volcanism on Earth go a long way toward explaining the origin of the continents, the oceans, the present atmosphere, and the surface concentration of the CHON elements (carbon, hydrogen, oxygen, nitrogen) of which all life on Earth is composed and on which it depends.

stress. At no instant in time does the glacier fit our everyday concept of a liquid, yet over time, the glacier is flowing downhill as an ultra-high-viscosity fluid.

When materials are subjected to sufficient **stress,** or force, they deform or undergo **strain** in different ways (figure 2.5). Stress may produce **elastic** (or recoverable) deformation, as when you pull on a spring. The spring deforms while you pull or stress it, but when you let go, it recovers and returns to its original shape.

If greater stress is applied for a longer time or at higher temperatures, **ductile** (or plastic) deformation may occur, and the change is permanent. You can visualize this with a wad of chewing gum or Silly Putty. If you squeeze them in your hands, they deform. Set them down and they stay in the deformed shape; this is ductile deformation. Another example occurs deep within glaciers where the ice deforms and moves with ductile flow.

If stress is applied rapidly to a material, it may abruptly fracture or break into pieces, called **brittle** deformation. Take a chunk of ice from your refrigerator and drop it or hit it; it will shatter with brittle failure. Notice that the ice in a glacier exhibits both brittle and ductile behavior. Near the surface, there is little pressure on the rigid ice and it abruptly fractures when stressed. Deep within the glacier, where the weight of overlying ice creates a lot of pressure, the ice deforms and moves by ductile flow. The style of ice behavior depends on the amount of pressure confining it.

The type of mechanical behavior illustrated by ice deep within a glacier typifies that of the rock within the Earth's mantle. This rock is **plastic** in the sense used by William James in his 1890 *Principles of Psychology*. He defined *plastic* as "possession of a structure weak enough to yield to an influence, but strong enough not to yield all at once."

When a material such as rock is subjected to the same large amounts of stress on all sides, it compresses. When stresses coming from different directions vary, strain can occur. When the differences in stress are low, strain is elastic and reversible. As stress differences increase, the **yield stress** is reached and permanent strain occurs. Most rocks are brittle at the low temperatures and low pressures at Earth's surface. Most rocks are ductile at the high temperatures and high pressures at depth inside Earth. In the asthenosphere, rock deforms in a "soft plastic" fashion. Most of the deeper mantle rock is solid but not brittle; it behaves as a "stiff plastic"—it deforms.

The top of the asthenosphere comes to the surface at some of the ocean's volcanic mountain chains but lies more than 100 km (about 60 mi) below the surface in other areas. It has gradational upper and lower boundaries and is about 250 km (155 mi) thick. What are the effects of having this "soft plastic" ductile zone so near Earth's exterior? Within the asthenosphere, there is a lot of flowage of rock that helps cause Earth's surface to rise and fall. For example, Earth is commonly described as a sphere, but it is not. Earth may be more properly described as an oblate ellipsoid that is flattened at the poles (nearly 30 km, or 19 mi) and bulged at the equator (nearly 15 km, or 9 mi). Earth is neither solid enough nor even strong enough to spin and maintain a spherical shape. Rather, Earth deforms its shape in response to the spin force. The flattening of Earth during rotation is analogous to the flattening of the early Solar System from a sphere to a disk (see figure 2.1).

ISOSTASY

From a broad perspective, Earth is not a homogeneous, solid ball but rather a series of floating layers where less dense materials successively rest upon layers of more dense materials. The core, with densities up to 16 g/cm^3, supports the mantle, with densities ranging from 5.7 to 3.3 g/cm^3. Atop the denser mantle float the continents, with densities around 2.7 g/cm^3, which in turn support the salty oceans, with densities of about 1.03 g/cm^3, and then the least dense layer of them all—the atmosphere. The concept of floating layers holds true on smaller scales as well. For example, the oceans are made of layered masses of water of differing densities. Very cold, dense Antarctic waters flow along the ocean bottoms and are overlain by cold Arctic water, which

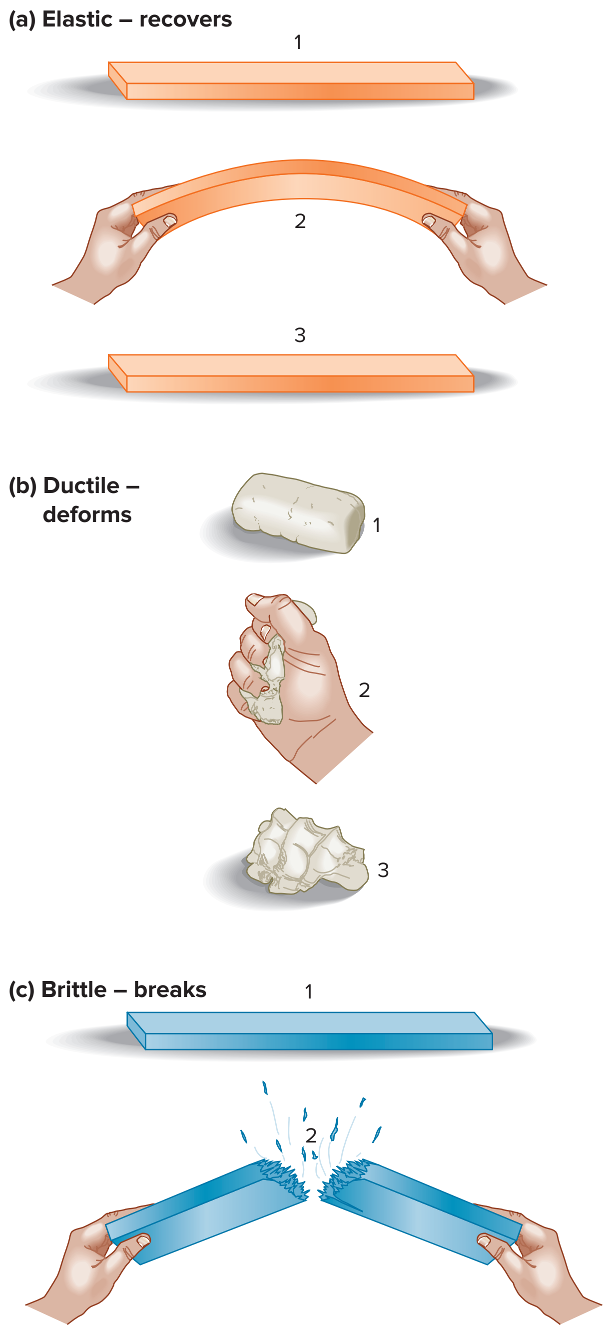


Figure 2.5 Behavior of materials. (a) Elastic: bend a thin board; let it go and the board recovers its original shape. (b) Ductile: squeeze a wad of bubblegum or Silly Putty; let it go and the mass stays in the deformed shape. (c) Brittle: bend a thin board sharply and it breaks.

is overlain by extra-salty waters, which in turn are overlain by warmer, less dense seawater. Earth is composed basically, from core through atmosphere, of density-stratified layers.

The concept of **isostasy** was developed in the 19th century. It applies a principle of **buoyancy** to explain how the low-density continents and mountain ranges literally float on the denser mantle below. Just as an iceberg juts up out of the ocean while most of its floating mass is beneath sea level, so does a floating continent jut upward at the same time it has a thick "root" beneath it (see figure 2.4). Visualize a boat floating in water: Add a load onto the boat and it sinks downward; remove the load and the boat rises upward. So it is with a continent. Add a load onto the land, such as a large glacial ice mass, and the land will sink downward as rock at depth flows outward within the asthenosphere; remove the load (the ice melts), and the land rises or rebounds upward as rock flows inward in the asthenosphere (figure 2.6). An example of this buoyancy effect, or isostatic equilibrium, was defined by carefully surveying the landscape before and after the construction of Hoover Dam across the Colorado River east of Las Vegas, Nevada. On 1 February 1935, the impoundment of Lake Mead began. By 1941, about 24 million **acre feet** of water had been detained, placing a weight of 40,000 million tons over an area of 232 square miles. Although this is an impressive reservoir on a human scale, what effect can you imagine it having on the whole Earth? In fact, during the 15 years from 1935 to 1950, the central region beneath the reservoir sank up to 175 mm (7 in) (figure 2.7). The relatively simple act of impounding water behind the dam triggered an isostatic adjustment as asthenosphere rock flowed away from the pressure of the overlying reservoir, causing the area to subside.

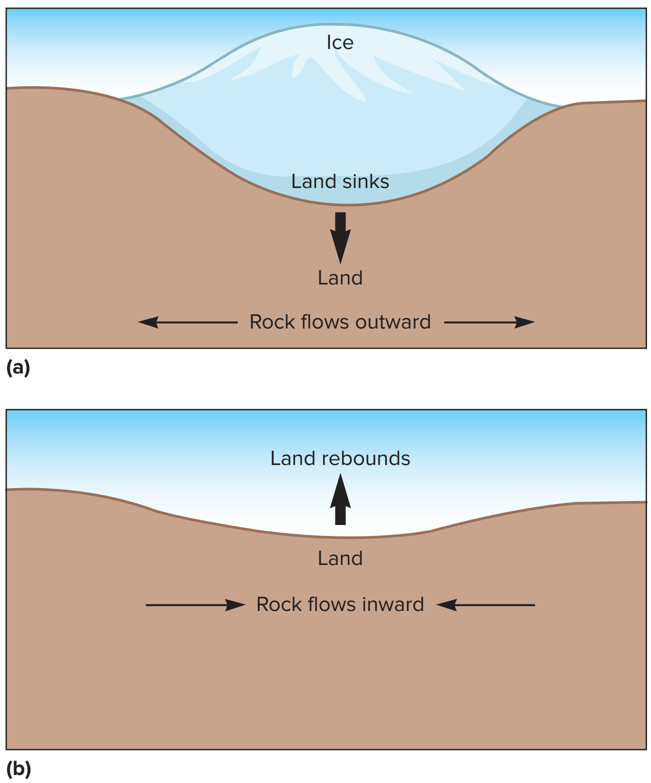


Figure 2.6 Isostatic equilibrium. (a) Land sinks as weight of ice causes rock at depth to flow outward. (b) Land rebounds as ice melts and removes weight, causing rock at depth to flow inward.

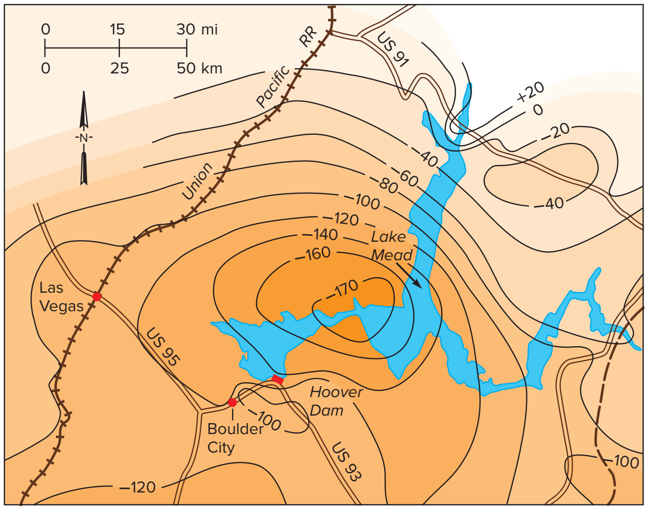


Figure 2.7 Isostatic downwarping caused by the weight of Lake Mead, from 1935 to 1950. Black circular lines (contour lines) define the depressed land surface. In the center is a –170 line where land sank 170 mm (7 in).

Source: Smith, W.O. et al. Comprehensive Survey of Sedimentation in Lake Mead, 1948-49, in *US Geological Survey Professional Paper 295,* 1960.

Just how solid and firm is the surface of the Earth we live on? Larger-scale examples are provided by the great ice sheets of the recent geologic past. The **ice sheet** that buried the Finland-Sweden region was up to 3 km (2 mi) thick less than 20,000 years ago. The land was depressed beneath this great weight. By 10,000 years ago, the ice sheet had retreated and melted, and the water returned to the ocean. The long-depressed landmass, now freed from its heavy load, is rebounding upward via isostatic adjustment. In the past 10,000 years, northeastern coastal Sweden and western Finland have risen about 200 m (650 ft). This upward movement was vividly shown during excavation for a building foundation in Stockholm, Sweden. Workers uncovered a Viking ship that had sunk in the harbor and been buried with mud. The ship had been lifted above sea level, encased in its mud shroud, as the harbor area rose during the ongoing isostatic rebound. Gravity measurements of this region show a negative anomaly, indicating that another 200 m (650 ft) of isostatic uplift is yet to come. The uplift will add to the land of Sweden and Finland and reduce the size of the Gulf of Bothnia between them.

Some of the early uplifting of land after ice-sheet removal occurred in rapid movements that ruptured the ground surface, generating powerful earthquakes. In northern Sweden, there are ground ruptures up to 160 km (100 mi) long with parallel cliffs up to 15 m (50 ft) high. The rocks in the region are ancient and rigid, suggesting that ruptures may go 40 km (25 mi) deep and that they generated truly large earthquakes.

Vertical movements of the rigid lithosphere floating on the flexible asthenosphere are well documented. If we add a load on the surface of Earth, we can measure the downward movement. For example, a 100-meter-thick ice mass will cause the land to sink about 27.5 m (90 ft). Antarctica is buried beneath ice up to 4,470 m (2.8 mi) thick. Thus, Antarctica is depressed up to 1,230 m (4,000 ft), placing most of the continent below sea level. If the ice is removed, Antarctica will slowly rise up and become the fifth largest landmass on Earth. The surface of Earth clearly is in a delicate vertical balance. Do major adjustments and movements also occur horizontally? Yes, there are horizontal movements between lithosphere and asthenosphere, which will bring us into the realm of plate tectonics (described later in this chapter).

Internal Sources of Energy

The flow of energy from Earth's interior to its surface comes mainly from three sources: impact energy, gravitational energy, and the ongoing decay of radioactive isotopes.

IMPACT ENERGY AND GRAVITATIONAL ENERGY

The impact energy of masses colliding with the growing Earth produced heat. Tremendous numbers of large and small asteroids, meteorites, and comets hit the early Earth, their energy of motion being converted to heat on impact.

Gravitational energy was released as Earth pulled into an increasingly dense mass during its first tens of millions of years. The ever-deeper burial of material within the growing mass of Earth caused an increasingly greater gravitational pull that further compacted the interior. This gravitational energy was converted to heat.

The immense amount of heat generated during the formation of Earth did not readily escape because rock conducts heat very slowly. Some of this early heat is still flowing to the surface today.

RADIOACTIVE ISOTOPES

Energy is released from **radioactive isotopes** as they decay. Radioactive isotopes are unstable and must kick out subatomic particles to attain stability. As radioactive isotopes decay, heat is released.

In the beginning of Earth, there were abundant, short-lived radioactive isotopes, such as aluminum-26, that are now effectively extinct, as well as long-lived radioactive isotopes, many of which have now expended much of their energy (table 2.1). Young Earth had a much larger complement of radioactive isotopes and a much greater heat production from them than it does now (figure 2.8). With a declining output of radioactive heat inside the Earth, the flow of energy from Earth's interior is on a slow decline heading toward zero.

TABLE 2.1

Some Radioactive Isotopes in Earth

Parent	Decay Product	Half-Life (billion years)
Aluminum-26	Magnesium-26	0.00072 (720,000 years)
Uranium-235	Lead-207	0.71
Potassium-40	Argon-40	1.3
Uranium-238	Lead-206	4.5
Thorium-232	Lead-208	14
Rubidium-87	Strontium-87	48.8
Samarium-147	Neodymium-143	106

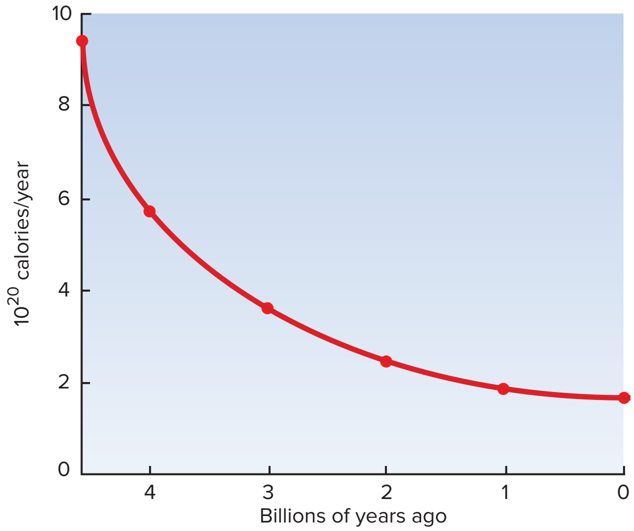


Figure 2.8 The rate of heat production from decay of radioactive atoms has declined throughout the history of Earth.

The radioactive-decay process is measured by the **half-life,** which is the length of time needed for half the present number of atoms of a radioactive isotope (parent) to disintegrate to a decay (daughter) product. As the curve in figure 2.9 shows, during the first half-life, one-half of the atoms of the radioactive isotopes decay. During the second half-life, one-half of the remaining radioactive atoms decay (equivalent to 25% of the original parent atoms). The third half-life witnesses the third halving of radioactive atoms present (12.5% of the original parent atom population), and so forth. Half-lives plotted against time produce a negative exponential curve; this is the opposite direction of a positive exponential curve, such as interest being paid on money in a savings account.

The sum of the internal energy from impacts, gravity, and radioactive isotopes, plus additional energy produced by **tidal friction,** is very large. The greater abundance of radioactive isotopes at Earth's beginning combined with the early gravitational compaction and more frequent meteorite impacts to elevate Earth's internal temperature during its early history. It is noteworthy that this heat buildup reached a maximum early in Earth's history and has declined significantly since then. Nonetheless, the flow of internal heat toward Earth's surface today is still great enough to provide the energy for continents to drift, volcanoes to erupt, and earthquakes to shake.

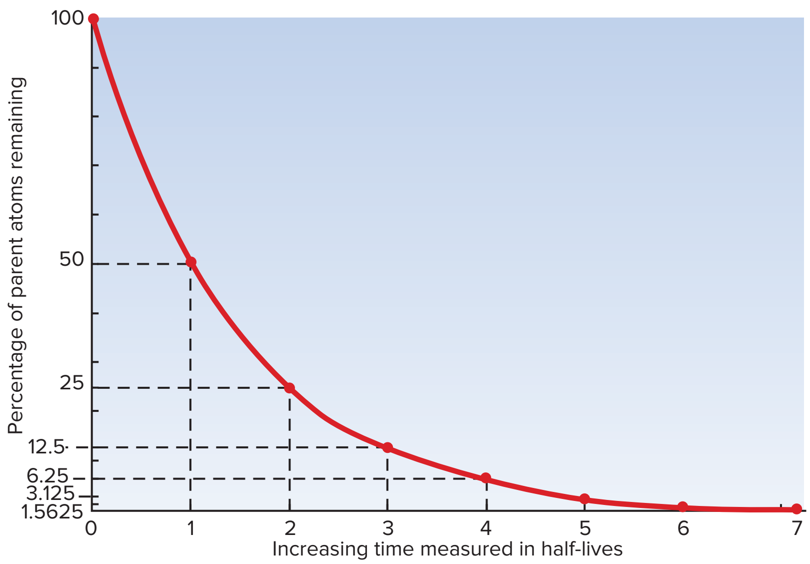


Figure 2.9 Negative exponential curve showing decay of radioactive parent atoms to stable daughter atoms over time. Each half-life witnesses the disintegration of half the remaining radioactive parent atoms.

In Greater Depth

Radioactive Isotopes

Each chemical element has a unique number of positively charged protons that define it. However, the number of neutrons varies, giving rise to different forms of the same element, known as isotopes. Some isotopes are radioactive and release energy during their decay processes. In radioactive decay, unstable parent atoms shed excess subatomic particles, reducing their weight and becoming smaller daughter atoms (figure 2.10). The overly heavy radioactive isotopes slim down to a stable weight by splitting apart, as in emitting alpha particles consisting of two protons and two neutrons (effectively, the nucleus of a helium atom). Beta particles are electrons freed upon a neutron's splitting. Gamma radiation, which is similar to X-rays but with shorter wavelength, is emitted, lowering the energy level of a nucleus. As the rapidly expelled particles are slowed and absorbed by surrounding matter, their energy of motion is transformed into heat.

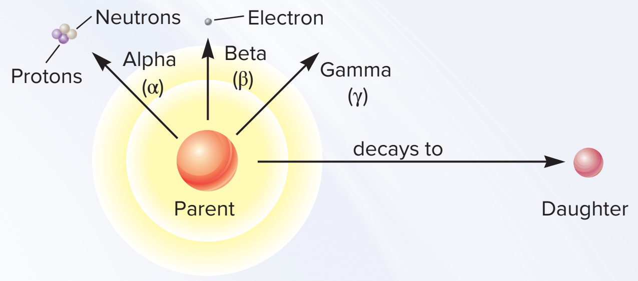


Figure 2.10 A radioactive parent atom decays to a smaller daughter atom by emitting alpha particles (such as the nucleus of a helium atom, i.e., two protons and two neutrons), beta particles (electrons), and gamma radiation (such as X-rays).

DATING THE EVENTS OF HISTORY

The same decaying radioactive isotopes producing heat inside Earth, Moon, and meteorites also may be read as clocks that date events in history. For example, uranium-238 decays to lead-206 through numerous steps involving different isotopes and new elements (figure 2.11). By emitting alpha and beta particles, 32 of the 238 subatomic particles in the U-238 nucleus are lost, leaving the 206 particles of the Pb-206 nucleus. Laboratory measurements of the rate of the decay process have given us the U-238-to-Pb-206 half-life of 4.5 billion years. These facts may be applied to quantifying history by reading the radiometric clocks preserved in some minerals. For example, some **igneous rocks** (crystallized from **magma**) can be crushed, and the very hard mineral zircon (from which zirconium, the diamond substitute in jewelry, is synthesized) separated from it. Zircon crystals contain uranium-238 that was locked into their atomic structure when they crystallized from magma, but they originally contained virtually no lead-206. Thus, the lead-206 present in the crystal must have come from decay of uranium-238.

The collected zircon crystals are crushed into a powder and dissolved with acid under ultraclean conditions. The sample is placed in a mass spectrometer to measure the amounts of parent uranium-238 and daughter lead-206 present. Then, with three known values—(1) the amount of U-238, (2) the amount of Pb-206, and (3) the half-life of 4.5 billion years for the decay process—it is easy to calculate how long the U-238 has been decaying into Pb-206 within the zircon crystal. In other words, the calculation tells us how long ago the zircon crystal formed and consequently the time of formation of the igneous rock.

See the Geologic Timescale in Chapter 18 and Appendix A.

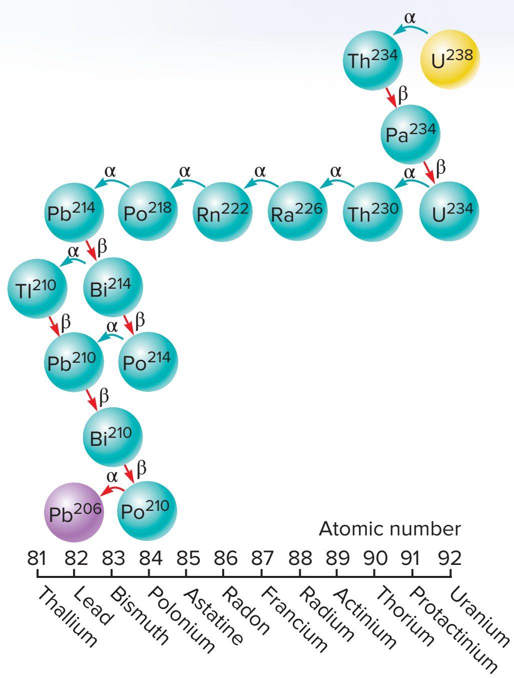


Figure 2.11 Radioactive uranium-238 (U^{238}) decays to stable lead-206 (Pb^{206}) by steps involving many intermediate radioactive atoms. The atomic number is the number of protons (positively charged particles) in the nucleus.

Age of Earth

The oldest Solar System materials are about 4.57 billion (4,570 million) years old. The 4.57-billion-year age has been measured using radioactive isotopes and their decay products collected from meteorites. In 2016, analyses of Moon rocks for hafnium (^{182}HF) indicated that the Moon had formed by 4.51 billion years ago. The oldest ages obtained on Earth materials are 4.4 billion years, measured on sand grains of the mineral zircon collected from within a 3.1-billion-year-old sandstone in western Australia. The oldest Earth rocks found to date are in northwest Canada; they are 4.055 billion years old. These rocks are of crustal composition, implying that they were recycled and formed from even older rocks.

In Greater Depth

Radioactivity Disasters

The term *radioactivity disasters* brings to mind the meltdown of the uranium-rich core of a nuclear-power plant, as happened at Chernobyl in Ukraine, part of the former Soviet Union, on 26 April 1986. This human-caused disaster occurred when the night-shift workers made a series of mistakes that unleashed a power surge so great that the resultant explosions knocked off the 1,000-ton lid atop the nuclear reactor core, blew out the building's side and roof, triggered a partial meltdown of the reactor core's radioactive fuel, and expelled several tons of uranium dioxide fuel and fission products, including cesium-137 and iodine-131, in a 5 km (3 mi) high plume. As many as 185 million **curies** of radioactivity were released. (The worst U.S. incident released 17 curies from the Three Mile Island nuclear-power plant in Pennsylvania in 1979.) After the 1:24 a.m. explosion, people near Chernobyl were at least fortunate that they were indoors and thus somewhat sheltered, there was no rain in the area, and the contaminant plume rose high instead of hugging the ground. The cloud of radioactive contaminants affected people, livestock, and agriculture from Scandinavia to Greece. In the Chernobyl power-plant area, about 50 people died directly. Most of the deaths will come later from cancer and other diseases. The worst contaminant is radioactive iodine-131, which lodges in the thyroid. Cancer of the thyroid is expected to be common in the area; it is estimated that it will shorten the lives of about 8,000 people.

An earthquake may have helped trigger this disaster. The Chernobyl power-plant workers were having difficulties in the early morning hours of 26 April, and then a magnitude 3 earthquake occurred 12 km (7 mi) away. The panicked supervisor thought the shaking meant the power plant was losing control, and he quickly implemented emergency maneuvers, but they jammed the internal works of the reactor, leading to the fateful explosion 22 seconds after the earthquake.

Earthquakes and radioactivity disasters entered the news again on 11 March 2011 when a great magnitude 9 earthquake and resultant tsunami in Japan destroyed several nuclear-power plants. This event is described in Chapter 8 on tsunami.

Chernobyl was a human-caused disaster. What can happen under natural conditions? Today, on Earth and Moon, uranium is present mostly as the heavier U-238 isotope, which has a combined total of 238 protons and neutrons in each uranium atom nucleus. The lighter-weight uranium isotope, U-235, makes up only 0.7202% of all uranium atoms. In nuclear-power plants, the uranium ore fed to nuclear reactors is enriched to 2–4% U-235 to promote more potent reactions. Remember from table 2.1 that U-235 has a half-life of 0.71 billion years, whereas the half-life of U-238 is 4.5 billion years. Because U-235 decays more rapidly, it would have been relatively more abundant in the geologic past. In fact, at some past time, the U-235 natural percentage relative to U-238 would have been like the U-235 percentage added to U-238 and fed as ore to nuclear reactors today.

Have natural nuclear reactors operated in the geologic past? Yes. A well-documented example has been exposed in the Oklo uranium mine near Franceville in southeastern Gabon, a coastal country in equatorial West Africa. At Oklo, 2.1 billion years ago, sands and muds accumulated along with organic carbon from the remains of fossil bacteria. These carbon-bearing **sediments** were enriched in uranium; U-235 was then 3.16% of total uranium. The sand and mud sediments were buried to shallow depths, and at least 800 m^3 (1,050 yd^3) of uranium ore sustained **nuclear fission** reactions that generated temperatures of about 400°C (750°F) regionally and much higher temperatures locally. At Oklo, 17 sites started up as natural nuclear reactors about 1.85 billion years ago; they ran for at least 500,000 years (and maybe as long as 2 million years). Nine of the natural reactors that have been carefully studied are estimated to have produced at least 17,800 megawatt years of energy.

Our understanding of the age of Earth is improving rapidly as new technologies allow measurement of more types of radioactive isotopes. It now seems that Earth has existed as a coherent mass for about 4.54 billion years. Earth must be younger than the 4.57-billion-year-old materials that collided and clumped together to form the planet. The time it took to build Earth is possibly as short as 30 million years. The collision of Earth with the Mars-size body that formed our Moon seems to have occurred between 4.537 and 4.533 billion years ago, suggesting that Earth was already a large, coherent mass at that time. Coming from the other direction, Earth must be older than the 4.4-billion-year-old zircon grains collected from sandstone in Australia. In sum, our planet has existed for about 4.5 billion years.

The work to exactly determine the age and early history of Earth continues today. It is challenging to try and find the oldest minerals and rocks because Earth is such an energetic planet that surface rocks are continually being formed and destroyed. Because of these active Earth processes, truly old materials are rarely preserved; there have been too many events over too many years that destroy rocks.

Plate Tectonics

The grand recycling of the upper few hundred kilometers of Earth is called the **tectonic cycle.** The Greek word *tekton* comes from architecture and means "to build"; it has been adapted by geologists as the term **tectonics,** which describes the building of **topography** and the deformation and movement within Earth's outer layers.

Adding the horizontal components of movements on Earth allows us to understand the tectonic cycle. Ignoring complexities for the moment, the tectonic cycle can be simplified as follows (figure 2.12). First, the asthenosphere rises and melts to form magma that flows upward and cools to form new ocean floor/lithosphere. Second, the new

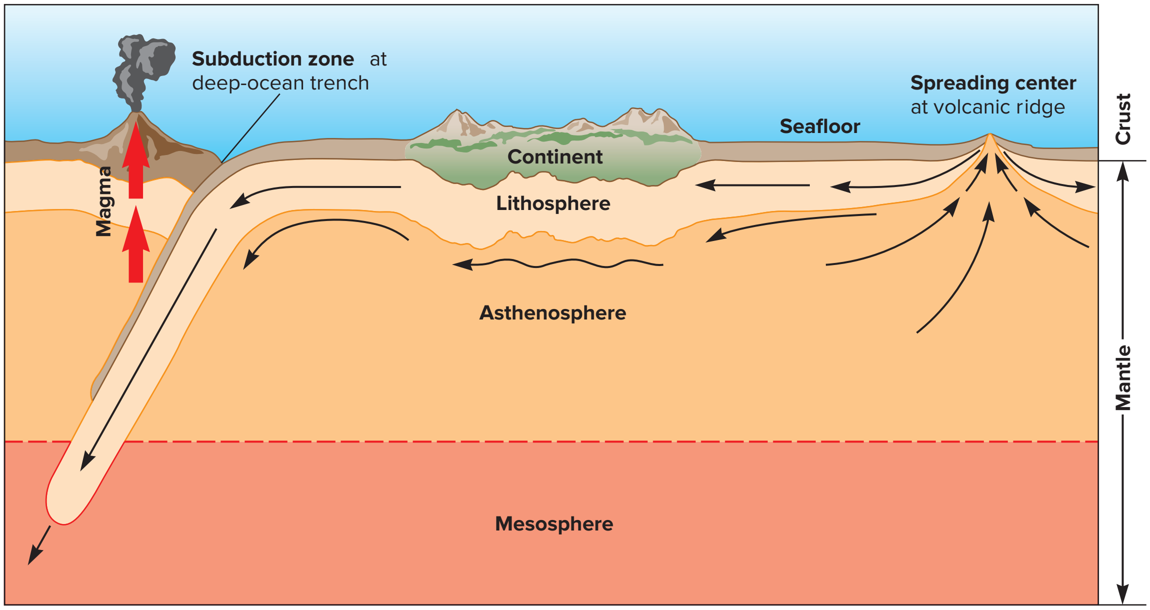


Figure 2.12 Schematic cross-section of the tectonic cycle. Magma rises from the asthenosphere to the surface at the oceanic volcanic ridges where it solidifies and adds to the plate edges. As the igneous rock cools, the plate subsides and gravity pulls the plates from their topographic highs. The plate continues to cool, grows thicker at its base, becomes denser, collides with a less-dense plate, and turns down into the mantle, where it is ultimately reassimilated.

lithosphere slowly moves laterally away from the zones of oceanic crust formation on top of the underlying asthenosphere; this phenomenon is known as **seafloor spreading.** Third, when the leading edge of a moving slab of oceanic lithosphere collides with another slab, the older, colder, denser slab turns downward and is pulled by gravity back into the asthenosphere, a process called **subduction,** while the less-dense, more buoyant slab overrides it. Last, the slab pulled into the mantle is reabsorbed. The time needed to complete this cycle is long, commonly in excess of 250 million years.

If we adopt the perspective of a geologist-astronaut in space and look down upon the tectonic cycle, we see that the lithosphere of Earth is broken into pieces called **plates** (figure 2.13). The study of the movements and interactions of the plates is known as **plate tectonics.** The gigantic pieces of lithosphere (plates) pull apart during seafloor spreading at **divergence zones,** slide past at **transform faults,** or collide at **convergence zones.** These plate-edge interactions are directly responsible for most of the earthquakes, volcanic eruptions, and mountains on Earth.

Another way that plate tectonics can be visualized is by using a hard-boiled egg as a metaphor for Earth. Consider the hard-boiled egg with its brittle shell as the lithosphere, the slippery inner lining of the shell as the asthenosphere, the egg white (albumen) as the rest of the mantle, and the yolk as the core. Before eating a hard-boiled egg, we break its brittle shell into pieces that slip around as we try to pluck them off. This hand-held model of brittle pieces being moved atop a softer layer below is a small-scale analogue to the interactions between Earth's lithosphere and asthenosphere.

DEVELOPMENT OF THE PLATE TECTONICS CONCEPT

Our planet is so large and so old that the combined efforts of many geologists and philosophers over the past few hundred years have been required to amass enough observations to begin understanding how and why Earth changes as it does. The first glimpse of our modern understanding began after the European explorers of the late 1400s and 1500s made maps of the shapes and locations of the known continents and oceans. These early world maps raised intriguing possibilities. For example, in 1620, Francis Bacon of England noted the parallelism of the Atlantic coastlines of South America and Africa and suggested that these continents had once been joined. During the late 1800s, the Austrian geologist Eduard Suess presented abundant evidence in support of **Gondwanaland,** an ancient southern supercontinent composed of a united South America, Africa, Antarctica, Australia, India, and New Zealand, which later split apart. This process of the continents moving, splitting, and recombining is known as **continental drift.** The most famous and outspoken of the early proponents of continental drift was the German meteorologist Alfred Wegener. In his 1915 book, *The Origin of Continents and Oceans,* he collected all available evidence, such as similar rocks, fossils, and geologic structures, on opposite sides of the Atlantic Ocean. Wegener suggested that all the continents had once been united in a