# NATURAL DISASTERS

THIRD EDITION

PATRICK L. ABBOTT

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**PATRICK L. ABBOTT**

*San Diego State University*

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## Why the Book Was Written

In the early 1970s, Bill Ganus and I developed an environmental geology course at San Diego State University. The growing awareness of the environment and the availability of good textbooks made it natural to offer a general education course looking at geological hazards, resource utilization and disposal, and intelligent planning in concert with the environment. The course had moderately successful enrollments, chugging along at 25 to 35 students per semester for over a decade.

In 1987, Tom Rockwell and I were discussing the environmental geology course and speculating on why it never attracted large enrollments. We agreed that the natural disasters portions of the course were the most popular. So, I formally changed the name of the course to "Natural Disasters" but did not change the course description or textbook, or advertise the change in any way. Yet almost instantly, students reading through the fine print of semester course offerings saw the "Natural Disasters" listing and enrollments skyrocketed. Now in the third millennium we offer multiple sections with more than 3,500 classroom seats per academic year and still do not satisfy demand.

San Diego State University students do not have to take Natural Disasters. They can select from over 30 courses among 10 departments with offerings such as Biology of Sex, Evolution, Origin of Life, The Oceans, Dinosaurs, and Confronting AIDS. But more students opt for Natural Disasters than any other course. If your department could benefit from higher enrollments of nonmajor students, I strongly recommend offering a natural disasters course. Earthquakes, hurricanes, tornadoes, and other high-energy processes of our active Earth affect childrens' lives. As students they want to understand why these natural disasters happen. The students' high level of interest can be channeled by the instructor into some significant learning about science.

## About the Book

This book focuses on natural disasters: how the normal processes of the Earth concentrate their energies and deal heavy blows to humans and their structures. It largely ignores the numerous case histories describing human actions and resultant environmental responses; these topics are left to the excellent textbooks on environmental geology. Nor does this book address resource extraction, utilization, and disposal; these subjects are covered by fine textbooks on earth resources, minerals, energy, soils, and water. This book is concerned with how the natural world operates and, in so doing, kills and maims humans and destroys their works.

Throughout the book, certain themes are maintained:

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

The text aims to explain important principles about the Earth and then develop further understanding through numerous case histories. I hope that students will actually enjoy reading most of this book.

The primary organization of the book is based on an energy theme. Chapter 1 examines the energy sources underlying disasters: 1) Earth's internal energy from its formative impacts and continuing radioactive decay, 2) gravity, 3) external energy from the Sun, and 4) impacts with asteroids and comets.

Disasters fueled by Earth's internal energy are addressed in Chapters 2 through 7 and are organized on a plate-tectonics theme. Chapter 2 provides the basic description of plate tectonics and its relationship to earthquakes. Chapter 3 covers the basic principles of earthquake geology and seismology and assumes no prior knowledge. Some better prepared students may wish to merely skim through this chapter. Chapter 4 uses plate tectonics and historic and prehistoric records to explain earthquakes along western North America. Chapter 5 examines the history and potential for earthquakes throughout the rest of North America. The intent is to cover every geographic area and major historic earthquake. Instructors may wish to use only parts of this chapter. Chapter 6 discusses volcanoes and Chapter 7 relates volcanism to plate tectonics. As throughout, case histories are employed to enliven the text.

Disasters powered primarily by gravity are covered in Chapter 8 on mass movements. Many types are discussed and illustrated, from falls to flows and slides to subsidence.

Disasters fueled by the external energy of the Sun are examined in Chapters 9 through 13. Chapter 9 looks at climate change and provides some basis for succeeding chapters. Climate principles governing energy transfer over time scales of millions, thousands, hundreds, and several years are discussed. The time focus shrinks through the chapter, leading to Chapter 10 on severe weather phenomena, such as thunderstorms, lightning, and tornadoes. Chapter 11 examines hurricanes and the coastline. The emphasis on water continues in Chapter 12 on floods and how human activities increase flood damage. Chapter 13 on fire examines the liberation of ancient sunlight captured by photosynthesis and stored in organic material.

Before moving to the fourth energy source (impacts), Chapter 14 examines the great dyings encased in the fossil record. The intent is to document the greatest of all natural disasters and to use multiple variables in analyzing their causes. Specific mass extinctions are examined using causative factors, such as continental unification and separation, climate change, flood-basalt volcanism, sea-level rise and fall, impacts, biologic processes, and the role of humans in the latest mass dying. Chapter 15 examines impact mechanisms in greater detail and includes plans to protect Earth from future impacts.

Chapter 16 looks at population growth, the unprecedented exponential increase in the human population.

There is a lot of material in this book, probably too much to cover in one semester. But the broad range of natural disasters topics allows each instructor to select those chapters that cover their interests and local hazards.

## Acknowledgments

I am deeply appreciative of the help given by others to make this book a reality. Almost all of the figures were drafted or drawn by Rene Wagemakers of San Diego State University. Rene's talent and ready willingness to help are invaluable. The photograph collection in the book is immeasurably improved by the aerial photographs generously given by John S. Shelton, the greatest geologist photographer of them all. More of John's photos have been added in this third edition. The collection of John Shelton photographs in this book is second in number only to his classic book *Geology Illustrated.*

I am indebted to other geologists who provided photographs: Alan Mayo of GeoPhoto Publishing Company on the Winter Park sinkhole and Tucson flooding; Gerald G. Kuhn of San Diego from his space shuttle image collection; Michael W. Hart of San Diego on mass movements; Al Boost of Caltrans on the San Fernando earthquake; Peter Weigand of California State University Northridge, Greg Davis of University of Southern California, and Kerry Sieh of Caltech on the Northridge earthquake; Tim Dawson on the Turkey earthquakes; José Aguirre on the Berkeley fire; and the U.S. Geological Survey Photographic Library.

For the first edition several chapters benefited from helpful reviews by San Diego State University colleagues: Michael J. Walawender on volcanism, J. David Archibald and Richard H. Miller on great dyings, and David L. Kimbrough on impacts.

The quality of the book was significantly improved by the insights provided by comments from the following reviewers: Kevin P. Furlong, *Pennsylvania State University,* Ernest L. Kern, *Southeast Missouri State University,* John Hidore, *University of North Carolina–Greensboro,* Paul K. Grogger, *University of Colorado–Colorado,* Donald J. Stierman, *University of Toledo,* George Hupper, *University of Wisconsin–LaCrosse*

The second edition has been significantly improved following user reviews of the book by Peter Sadler, *University of California,* Dr. Judson Ahern, *University of Oklahoma,* and John Dunbar, *Baylor University.* The expanded coverage of volcanoes was much improved by the advice of Victor E. Camp of San Diego State University.

For the third edition, *all* chapters have been updated and changed. This includes major revisions and significantly increased coverage in Chapter 9 on climate change, Chapter 10 on severe weather including tornadoes, Chapter 11 on hurricanes, and Chapter 12 on floods. In these four chapters in particular, there is much new text, many new photos, and numerous new pieces of line art. The third edition has benefited greatly from the detailed reviews of

Wang-Ping Chen, *University of Illinois at Urbana-Champaign*
Patrick Colgan, *Northeastern University*
Michael Conway, *Arizona Western University*
Michael Forrest, *Rio Hondo Junior College*
David Gonzales, *Fort Lewis College*
Alan Lester, *University of Colorado*
Jon Nourse, *California State Polytechnic University*
Bingming Shen-Tu, *Indiana University*
Philip Suckling, *University of Northern Iowa*

I am grateful for the help of others at San Diego State University: Jacobe Washburn for his original line drawings, Tony Carrasco for invaluable aid on the computer with photos and live drawings, and Marie Grace for forming many of the tables.

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.

*Pat Abbott*
*pabbott@geology.sdsu.edu*

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## CHAPTER 16

# 1

# Energy Sources of Disasters

> Cause and effect, means and ends, seed and fruit, cannot be severed; for the effect already blooms in the cause, the end pre-exists in the means, the fruit in the seed.
>
> —RALPH WALDO EMERSON, 1841, *Compensation*

Disasters occur where and when the Earth's natural processes concentrate **energy** and then release it, killing life and causing destruction. Our interest is especially peaked when this energy deals heavy blows to humans. In 1999, over 105,000 people lost their lives to natural disasters (Table 1.1). Fatalities were due primarily to severe weather and floods and secondarily to earthquakes. The killer events of 1999 were spread around the world.

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

**Table 1.1 The 15 Deadliest Natural Disasters in 1999**

| Fatalities | Date/Start | Event | Country |
|---|---|---|---|
| 50,000 | 15 Dec | Floods and mudflows | Venezuela |
| 19,118 | 17 Aug | Earthquake (Izmit) | Turkey |
| 15,000 | 29 Oct | Hurricane (Orissa) | India |
| 3,400 | 20 Sep | Earthquake (Nantou) | Taiwan |
| 1,300 | 3 Oct | Floods and landslides | Mexico |
| 1,185 | 25 Jan | Earthquake (Quindio) | Colombia |
| 834 | 12 Nov | Earthquake (Duzce) | Turkey |
| 751 | 20 May | Hurricane | Pakistan/India |
| 725 | 16 Jun | Floods (Yangtze River) | China |
| 662 | 25 Oct | Floods | Vietnam |
| 411 | 6 Aug | Floods (West Bengal) | India |
| 307 | 12 Jul | Floods (Andhra Pradesh) | India |
| 275 | 31 Dec | Cold wave | India |
| 265 | 30 Jul | Floods | Philippines |
| 224 | 15 Jul | Heat wave in east | U.S.A. |
| 94,457 Total | | | |

of human life and destruction of property caused by natural disasters. As Booth Tarkington remarked: "The history of catastrophe is the history of juxtaposition."

To understand the natural hazards that kill and maim unwary humans, one must know about the energy sources that fuel Earth processes. Four primary energy sources make the Earth an active body: 1) the Earth's internal heat, 2) the Sun, 3) **gravity,** and 4) the impact of extraterrestrial bodies.

Energy stored inside the Earth flows unceasingly toward the surface. Over short time spans, internal energy is released as eruptions from **volcanoes** and by **earthquakes;** over longer intervals of geologic time, it has caused the formation of **continents,** oceans, and **atmosphere.** On a planetary scale, this outward flow of internal energy causes continents to drift and collide, thus constructing mountain ranges and elevated plateaus. These internally powered forces of continental construction are counteracted by the external energy of the Sun, aided by gravity.

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. Gravity powers the agents of **erosion—glaciers,** streams, underground waters, winds, ocean waves and currents—which wear away the continents and dump their broken pieces and dissolved remains into the seas. Thus, solar radiation is the most important external energy source because it evaporates and elevates water, but gravity is the immediate force that drives the agents of erosion.

Another energy source for disasters arrives when visitors from outer space—**asteroids** and **comets**—impact the Earth. Although collisions with large bodies are infrequent, their effects on life can be global.

A long-term conflict rages between the internally powered **forces of construction** that create and elevate landmasses at the same time that externally powered **forces of destruction** erode the continents and dump the continental debris into the ocean basins. If all mountain building and uplift stopped, the combined power of the agents of erosion would be enough to reduce the continents to sea level in just 45 million years. At first reading, this may seem like an awfully long time, but the Earth is 4.57 billion years old. The great age of the Earth indicates that erosion is powerful enough to have leveled the continents about 100 times. This shows the power of the internal forces of construction to keep elevating old continents and adding new landmasses. And woe be it to humans and other life forms that get too close to these forces of construction and destruction, for this is where disasters occur.

## Origin of the Sun and Planets

To understand the origin and character of Earth's internal energy, one must know the early history of our planet. The 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 the Earth's interior and in the Solar System, allow us to build an increasingly sophisticated approximation of early Earth history.

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 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 about 4.6 billion years ago within a rotating spherical cloud of gas, ice, dust and other solid debris (Figure 1.1a and b). 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 1.1c). The greatest accumulation of matter occurred in the center of the disk, building toward today's Sun (Figure 1.1 d and e). 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 1.1f). 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.

## Internal Sources of Energy

Earth appears to have begun as an aggregating mass of particles and gases from a rotating cloud some 4.57 billion years ago. During a 50- to 100-million-year period, bits and pieces of metal-rich particles (similar to iron-rich **meteorites**), rocks (similar to stony meteorites), and ices (of water, carbon dioxide, and other compounds) accumulated to form the 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, the Earth in its infancy probably grew from

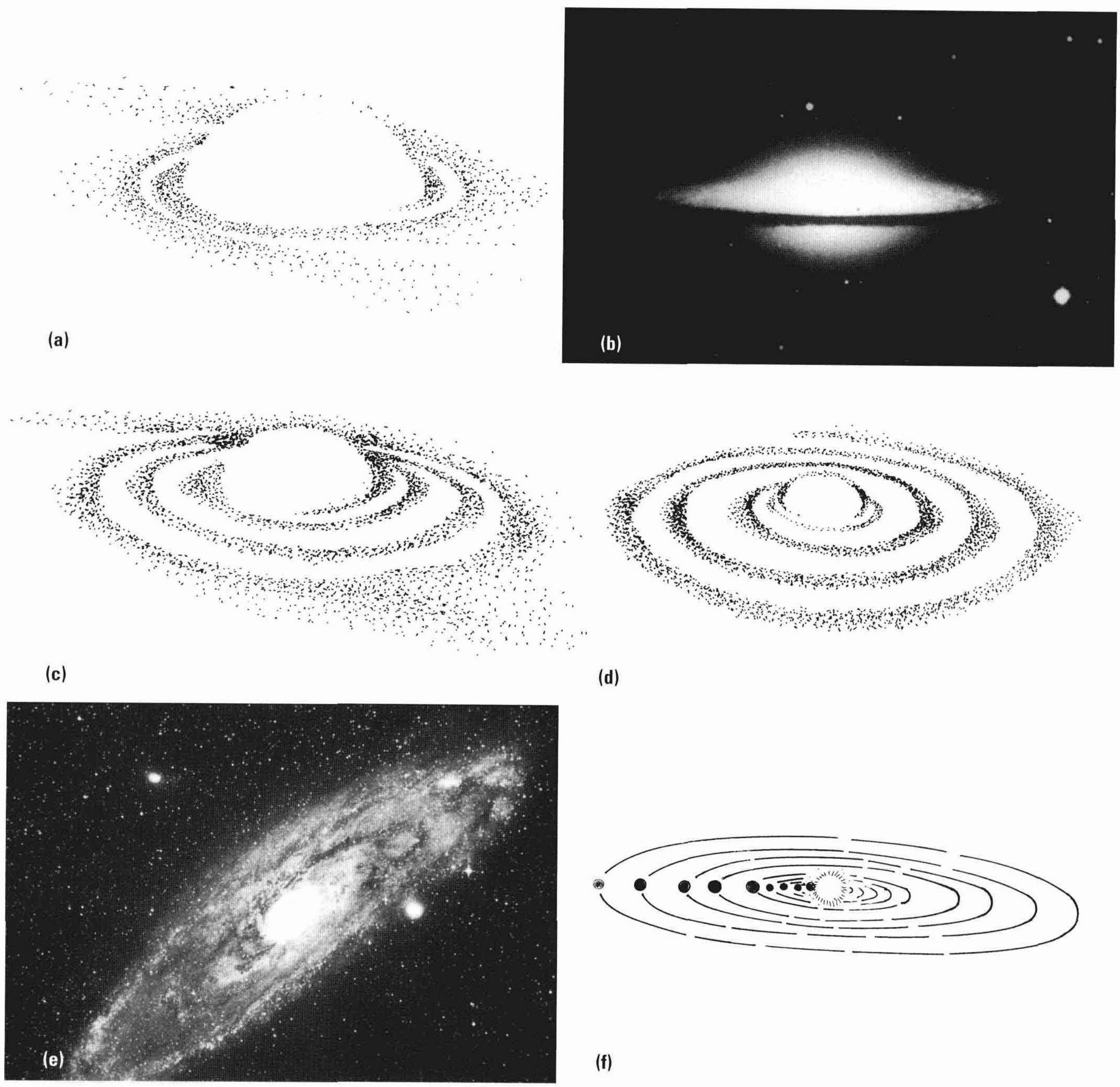


**Figure 1.1** Hypothesis of the origin of the Solar System. **(a and b)** Initially, a huge, rotating spherical cloud of ice, gas, and other debris forms. **(c)** Spinning mass contracts into a flattened disk with most mass in the center. **(d and e)** Planets grow as masses collide and stick together. **(f)** Ignited Sun is surrounded by planets. Earth is the third planet from the Sun.

random collisions of debris to form a more or less homogeneous mixture of materials.

But the Earth did not remain homogeneous. The very processes of planet formation (Figure 1.2) created tremendous quantities of **heat,** which fundamentally changed the young planet from a somewhat homogeneous ball into a density-stratified mass with the heavier materials in the center and progressively lighter materials outward to the atmosphere. The heat that transformed the Earth came primarily from: 1) impact energy, 2) gravitational energy, and 3) decay of **radioactive** elements.

## Impact Energy

The impact energy of particles colliding with the growing Earth produced heat. Tremendous numbers of large and

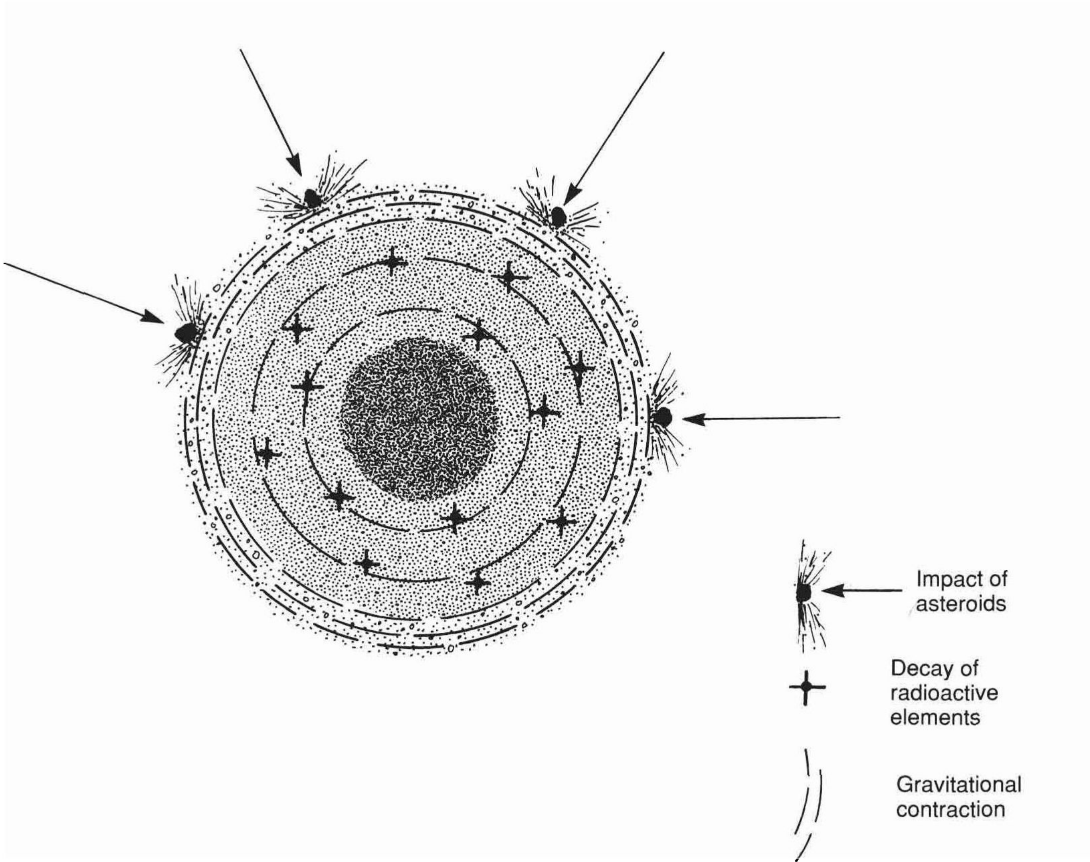


**Figure 1.2** Heat-generating processes during the formative years of the Earth include: 1) impact of asteroids, 2) decay of radioactive elements, and 3) gravitational contraction.

small asteroids, meteorites, and comets hit the early Earth, with their energy of motion converted to heat on impact. Large impacts can generate enough heat to vaporize and melt rock. 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. The resultant impact generated a massive vapor cloud, part of which condensed to form the Moon. This theory suggests the Moon is mostly made from the Earth's rocky **mantle.** The theory accounts for the lesser abundance of iron on the Moon (iron on the Earth is mostly in the central **core**) and the Moon's near absence of lightweight materials (such as gases and water), which would have been lost to space.

## Gravitational Energy

Gravitational energy was released as the Earth pulled into an increasingly dense mass during its first 50 to 100 million years. The ever-deeper burial of material within the growing mass of the Earth caused an increasingly greater gravitational pull that further compacted the interior. This gravitational energy was converted to heat that did not readily escape because heat conducts very slowly through rock. As the internal temperature of the Earth rose beyond 1,000° centigrade (C) or 1,800° Fahrenheit (F), it passed the melting points of iron at various depths below the surface. Iron forms about one-third of the 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 the Earth's center. As these gigantic volumes of liquid iron moved inward to form the Earth's core, they released a tremendous amount of gravitational energy that converted to heat and probably raised the Earth's internal temperature by another 2,000° C. 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 the Earth; 2) large oceans; and 3) a heavier atmosphere. The formation of the iron-rich core was a unique event in the history of the Earth.

## Energy from Radioactive Elements

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

In the beginning of the Earth, there were abundant, short-lived radioactive elements, such as aluminum-26, that are now effectively extinct, as well as long-lived radioactive elements, many of which have now expended much of their

**Table 1.2 Some Radioactive Elements in the 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 | 47 |
| Samarium-147 | Neodymium-147 | 106 |

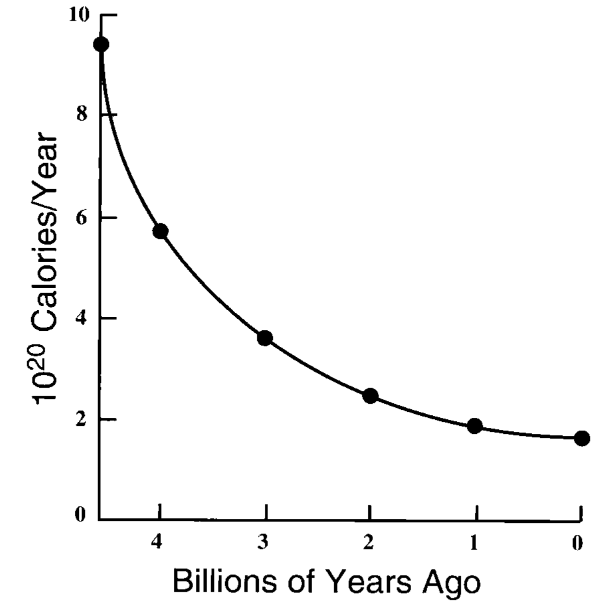


**Figure 1.3** Rate of heat production from decay of radioactive atoms has declined throughout the history of the Earth.

energy (Table 1.2). The young Earth had a much larger complement of radioactive elements and a much greater heat production from them than it does now (Figure 1.3). With a declining output of radioactive heat inside the Earth, the flow of energy from the Earth's interior is on a slow decline curve heading toward zero.

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 element (parent) to disintegrate to a decay (daughter) product. As the curve in Figure 1.4 shows, during the first half-life, one-half of the radioactive atoms decay. During the second half-life, one-half of the remaining radioactive atoms decay (equivalent to 25 percent of original parent atoms). The third half-life witnesses the third halving of radioactive atoms present (12.5 percent of the original parent atom population), and so forth. Half-lives plotted against time produce a negative exponential curve (Figure


**Figure 1.4** 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 parent atoms.

## Radioactive Elements

Energy is released from radioactive elements in the process of **nuclear fission** when unstable, radioactive parent atoms shed excess subatomic particles, reducing their weight and becoming smaller daughter atoms (Figure 1.5). The nuclei of radioactive atoms are unstable and contain too many subatomic particles, both positively charged protons and neutral neutrons. The overly heavy radioactive atoms slim down to a stable weight by emitting: 1) alpha particles, consisting of two protons and two neutrons (effectively, the nucleus of a helium atom); 2) beta particles, which are electrons freed upon a neutron's splitting; and 3) gamma radiation, which is similar to X rays but with shorter wavelength. As the rapidly expelled particles are slowed and absorbed by surrounding matter, their energy of motion is transformed into heat.

### Dating the Events of Earth History

The same decaying radioactive elements producing heat inside the Earth also may be read as clocks that date events in Earth history. For example, uranium-238 decays to lead-206 through numerous steps involving different isotopes and new elements (Figure 1.6). 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 Earth 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 no lead-206. Thus, all 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.

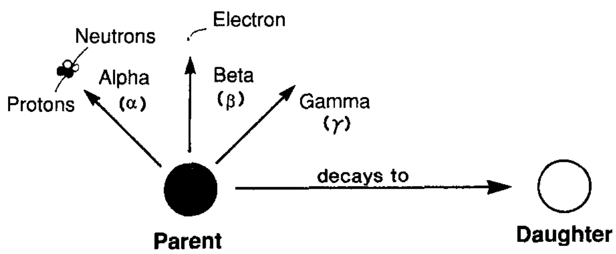


**Figure 1.5** A radioactive parent atom decays to a smaller daughter atom by emitting alpha particles (such as the nucleus of a helium atom, i.e., two protons and two neutrons), beta particles (electrons), and gamma radiation (such as X rays).

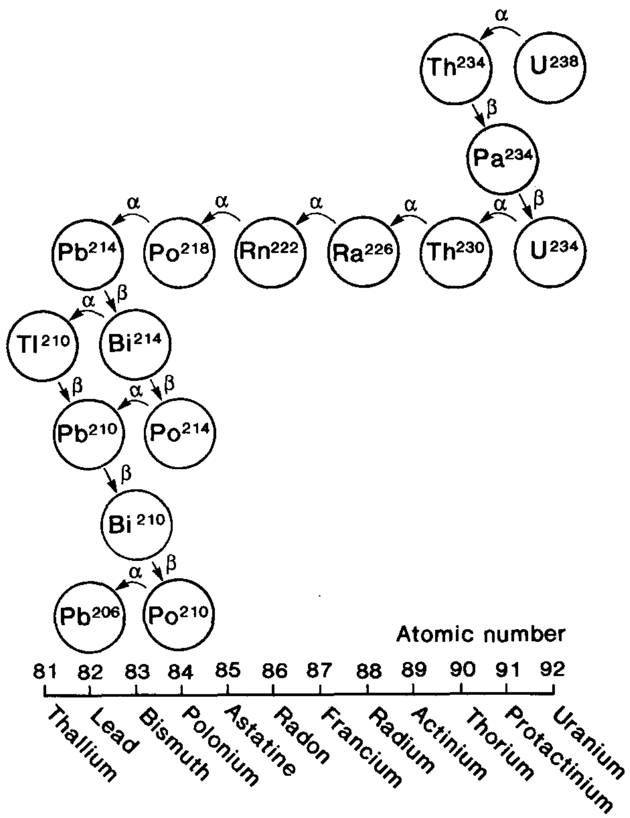


**Figure 1.6** Radioactive uranium-238 ($U^{238}$) decays to stable lead-206 ($Pb^{206}$) by steps through many intermediate radioactive atoms. The atomic number is the number of protons (positively charged particles) in the nucleus.

1.4); this is the reverse 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 elements, plus additional energy produced by tidal friction, is very large. The greater abundance of radioactive elements at the Earth's beginning plus the early gravitational crowding and more frequent meteorite impacts combined to elevate the Earth's internal temperature during its early history. It is noteworthy that this heat buildup inside the Earth reached a maximum early in the Earth's history

## Radioactivity Disasters

"Radioactivity disasters"—the term brings to mind the meltdown of the uranium-rich core of a nuclear power plant, such as happened at Chernobyl in the Ukraine 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, such as cesium-137 and iodine-131, in a 5-km-(3-mi)-high plume. As much as 185 million **curies** of dangerous radioactive atoms were released. (The worst U.S. incident released 17 curies from the Three Mile Island nuclear power plant in Pennsylvania during 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. At the Chernobyl power plant, 31 workers were killed. But most deaths came later from cancer and other diseases. At the end of 1999, there were 165,000 deaths attributed to this nuclear accident by Swiss insurance companies. And many more will die in upcoming years.

An earthquake may have helped trigger this disaster. It is widely reported in Europe that the Chernobyl power-plant workers were having difficulties in the early morning hours of 26 April when 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 made emergency maneuvers, but they jammed the internal works of the reactor leading to the fateful explosion 22 seconds after the earthquake. Can the Chernobyl meltdown be considered an earthquake disaster?

But Chernobyl was a human-caused disaster. What can happen under natural conditions? Today, on Earth and the 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 percent of all uranium atoms. In nuclear power plants, the uranium ore fed to nuclear reactors is enriched to 2 to 4 percent U-235 to promote more potent reactions. Remember from Table 1.2 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 percent of total uranium. The sand and mud sediments were buried to shallow depths, and at least 800 $m^3$ of uranium ore sustained nuclear fission reactions that generated temperatures of about 400°C regionally with much higher local temperatures. 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.

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and has declined significantly since then. Nonetheless, the flow of internal heat toward the Earth's surface today is still great enough to provide the energy for continents to drift, volcanoes to erupt, and earthquakes to shake.

# Age of the Earth

The Earth is inferred to be about 4.57 billion years old; this is 4,570 million years—time for many changes to occur. The 4.57 billion-year age has been measured using radioactive elements and their decay products collected from Moon rocks and meteorites. The oldest Earth rocks found to date are 4.055 billion years old in northwest Canada and 3.9 billion years old in Greenland. These rocks are of crustal composition, implying that they were recycled and formed from even older rocks. (The oldest ages obtained on Earth materials are 4.28 billion years, measured on zircon sand grains from a 3.1 billion-year-old sandstone in western Australia.)

How can we infer that the Earth is 4.57 billion years old if the oldest known Earth rocks are slightly less than 4 billion years old and the oldest known minerals are 4.2 billion years old? 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. We look instead to the oldest rocks on the Moon, which is no longer geologically active, and to the meteorites that arrive from the refrigerator of space, noting that they have consistent ages of about 4.57 billion years. Then, from the hypothesis of a common origin for the Earth, Moon, meteorites, and the rest of our Solar System, the 4.57 billion-year age measured on Moon rocks and meteorites is used as the age for all. Thus, we can conclude