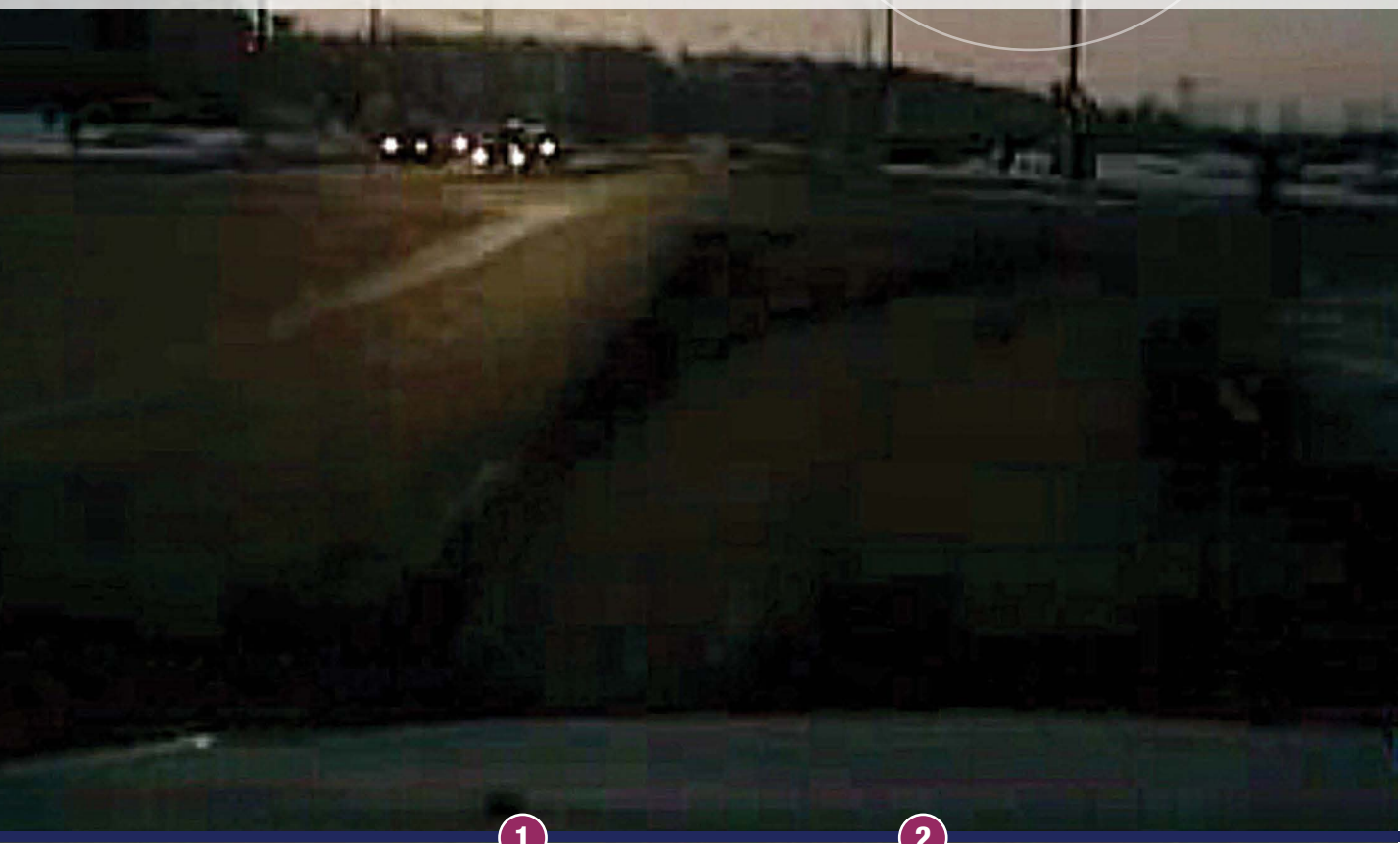
No one knew the object was coming. Over 7,000 buildings in six cities across the region were damaged

14



APPLYING the 5 fundamental concepts Chelyabinsk Meteor, February 2013

1

Science helps us predict hazards.

The potential hazard from extraterrestrial impact is well known; NASA scientists and meteor astrophysicists from around the world currently track more than 10,000 objects in our solar system that could potentially impact Earth in the future, like the one that passed by the same day as the 2013 Chelyabinsk meteor.

2

Knowing hazard risks can help people make decisions.

Earth is bombarded by thousands of tiny extraterrestrial objects every day, but the effect of these impacts is negligible, so the risk is low. In contrast, a large extraterrestrial impact would be globally catastrophic, but the probability of such an impact is extremely low and so is the risk.

Impacts and Extinctions

Chelyabinsk Meteor, February 2013

Imagine driving to work early one morning, and observing through your car window a small streak of light moving across the sky that explodes in a flash more brilliant than the sun. On February 15, 2013, this scenario was recorded on countless car-mounted security cameras all over northwestern Russia, when a small asteroid traveling about 20 times faster than a speeding bullet entered Earth's atmosphere and exploded (chapter-opener photograph). People living in Chelyabinsk (Figure 14.1), the city closest to the impact, could feel the intense heat from the fireball, as well as the shock wave from the explosion. Because the object entered Earth's atmosphere at a low angle and at incredible velocity, the meteor did not impact the Earth directly but rather exploded in the stratosphere about 23 km (~15 mi.) above the surface, releasing energy equivalent to 20 to 30 World War II–era nuclear explosions.[1] Such impacts are known as airbursts. The Chelyabinsk meteor is the largest known asteroid to have entered Earth's atmosphere since a much larger airburst in 1908, which also occurred in Siberia near the town of Tunguska (Figure 14.1).

< 2013 CHELYABINSK METEOR, RUSSIA
A car-mounted camera captures the Chelyabinsk meteor exploding into in a fireball in the morning sky over Russia on February 15, 2013. *(AP Images)*

LEARNING Objectives

Earth has been bombarded by objects from space since its birth. Such impacts have been linked to the extinction of many species, including the large dinosaurs. The risk of impact from asteroids, comets, and meteoroids continues today. The hazard from extraterrestrial impact is very different from other hazards we have discussed in this book and for which we have the ability to mitigate damages. We do have the technology to identify large, 1.5 km (1 mi.) or greater, extraterrestrial objects that could impact Earth several decades or longer in the future. However, with present technology, we cannot minimize this hazard.

After reading this chapter, you should be able to:

LO:1 Differentiate between asteroids, meteoroids, and comets.

LO:2 Describe the physical processes associated with airbursts and impact craters.

LO:3 Suggest the possible causes of mass extinction and provide examples.

LO:4 Evaluate the evidence for the impact hypothesis that produced the mass extinction at the end of the Cretaceous Period.

LO:5 List the physical, chemical, and biological consequences of an impact from a large asteroid or comet.

LO:6 Analyze the risk of impact or airburst of extraterrestrial objects and suggest how that risk might be minimized.

3

Linkages exist between natural hazards.

Extraterrestrial impact is directly linked to many other hazards, which may vary depending on the size of the impact and whether the impact occurs in the ocean or on land.

4

Humans can turn disastrous events into catastrophes.

Humans have no control over the occurrence of extraterrestrial impact, but a large airburst or direct impact of a Chelyabinsk-sized meteor in a heavily populated area would be catastrophic.

5

Consequences of hazards can be minimized.

Consequences of an extraterrestrial impact can be understood, but our ability to minimize the effects depends on the magnitude of the event and our ability to predict when and where a damaging impact might occur. The two extraterrestrial events of February 15, 2013, illustrate both the potential and the shortcomings of our prediction capabilities.



FIGURE 14.1 Meteor Impact Locations
Locations of the Chelyabinsk event of 2013 and the Tunguska event of 1908, both in Russia (light brown).

Before the atmospheric entry and explosion, no one knew that the object was coming. Coincidentally, meteor astrophysicists from around the world at that time were, literally, looking the other way because they were tracking a much larger and completely unrelated asteroid (2012 DA14) that was to make a close fly-by of Earth just sixteen hours later. The Chelyabinsk meteor damaged more than 7,000 buildings in six cities across the region and injured about 1,500 people seriously enough to require medical treatment, mostly due to flying glass from windows broken by the shock wave. Following the explosion, people were confused and frightened about what was happening, and mobile phone networks were soon overloaded with calls. Office buildings in Chelyabinsk were evacuated, and schools were closed with parents rushing to pick up their children. In all, about 100,000 homes sustained broken windows, requiring immediate attention along with maintaining the region's central heating systems at a time of year when subzero temperatures are the norm.

14.1 Earth's Place in Space

Preston Cloud, a famous geologist, wrote in 1978:

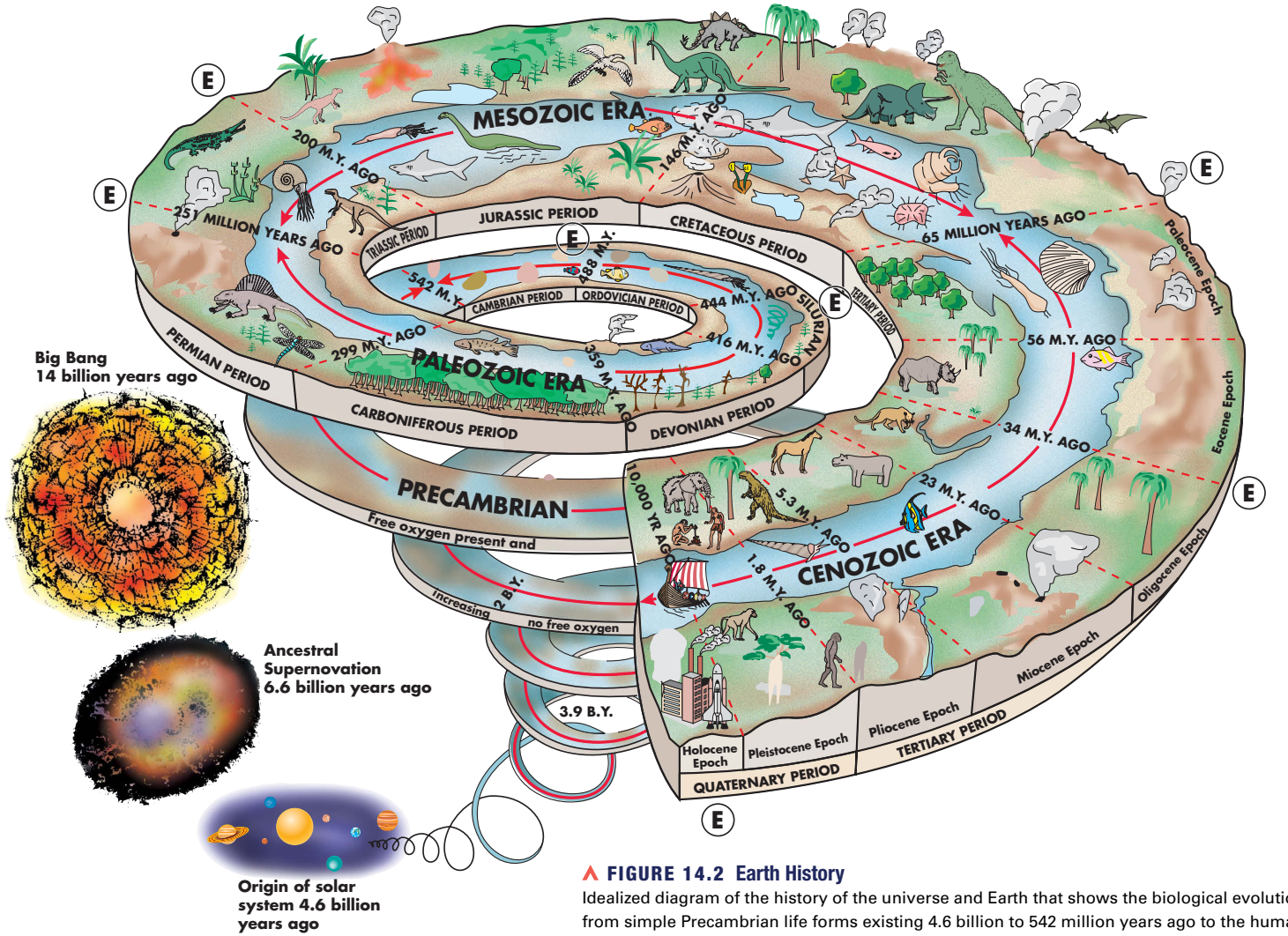
> Born from the wreckage of stars, compressed to a solid state by the force of its own gravity, mobilized by heat of gravity and radioactivity, clothed in its filmy garments of air and water by the hot breath of volcanoes, shaped and mineralized by 4.6 billion years of crustal evolution, warmed and peopled by the Sun, this resilient but finite globe is all our species has to sustain it forever.[2]

Cloud was referring to the original evolution of our planet that started about 4.6 billion years ago. One can go back even further and consider the start of the universe—some 14 billion years ago. The starting point is thought to have been an explosion, known as the "Big Bang." This explosion produced the atomic particles that later formed galaxies, stars, and planets (Figure 14.2). The first stars formed within the first 1 billion years after the Big Bang, and stars continue to form today. A star's life span depends on its mass; large stars have higher internal pressure and burn up more quickly than small stars. Objects with a mass equal to about that of our sun last around 10 billion years, and large stars with masses of 100 times that of our sun last only about 100,000 years. Thus, our sun is now a middle-aged star, about halfway through its life span.

When one of the massive, short-lived stars dies, it does so in a particularly spectacular way—as a supernova. A *supernova* occurs when the star is no longer capable of sustaining its mass and collapses inward, resulting in a high-energy explosion that scatters its mass into the void of space, creating a vast *nebula*. Ultimately, the force of gravity wins out, and the matter within the nebula begins to collapse back inward on itself, forming new stars in what is called a *solar nebula* (Figure 14.3). It is from such a nebula that our sun formed 5 billion years ago. The sun grew by accretion of matter from a flattened pancake-like rotating disk that was dominated by hydrogen and helium molecules, along with trace amounts of dust composed of the other elements of the periodic table. As the solar nebula condensed under gravitational forces, our sun, which contains approximately 99.8 percent of the mass of the solar system, formed at the center; the remaining mass became trapped in solar orbits as rings, similar to the rings around the planet Saturn today. Gravitational forces from the largest, densest particles attracted other particles in the rings until they collapsed into the planetary system we have today (Figure 14.4). During their early history, all the planets in our solar system, including Earth, were bombarded by extraterrestrial objects that ranged from dust-sized particles to objects many kilometers in diameter. However, the bombardment did not cease 4.6 billion years ago; it has continued, although at a lesser rate, to the present.

ASTEROIDS, METEOROIDS, AND COMETS

Trillions of particles remain in our solar system. Astronomers group these particles on the basis of diameter and composition (Table 14.1). They range in size from interplanetary dust a fraction of a millimeter in diameter to larger bodies such as **asteroids** that range in diameter from about 10 m (~30 ft.) to 1000 kilometers (~620 mi.). For the most part, asteroids are

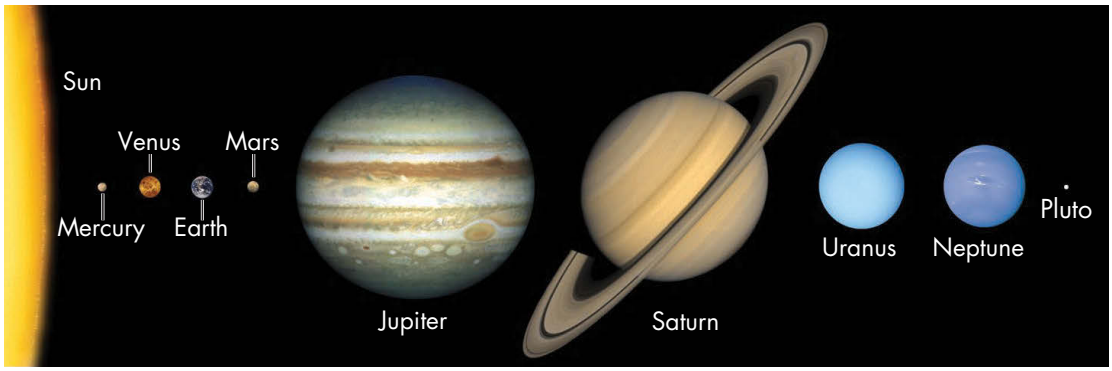


▲ FIGURE 14.2 Earth History

Idealized diagram of the history of the universe and Earth that shows the biological evolution of Earth, from simple Precambrian life forms existing 4.6 billion to 542 million years ago to the humans of today. The curving red arrows in the blue area point to boundaries for the Paleozoic, Mesozoic, and Cenozoic Eras and Precambrian time (the Archean and Proterozoic Eons). Each circled letter E indicates a mass extinction event. *(Based on U.S. Geological Survey, International Commission on Stratigraphy, "International Stratigraphic Chart," 2004; and Cloud, P.,* Cosmos, Earth and Man. *New Haven, CT: Yale University Press, 1978.)*



< FIGURE 14.3 Solar Nebula
Hubble Space Telescope image of the Trifid Nebula—a solar nebula within our own Milky Way Galaxy. The Trifid Nebula is named for the three bands of obscuring interstellar dust. Near the intersection of the dust bands, a group of recently formed bright stars is easily seen. The nebula is about 9,000 light years from Earth. *(Stocktrek Images, Inc./Alamy Stock Photo)*



^ FIGURE 14.4 Sizes in the Solar System
Artist's depiction of objects in our solar system, showing the relative sizes of the sun, planets, and Pluto (dwarf planet). *(NASA)*

found in the *asteroid belt*, which is a region between Mars and Jupiter (Figure 14.5). The asteroids, which are composed of rock material, metallic material, or rock-metal mixtures, would pose no threat to Earth if they remained in the asteroid belt. Unfortunately, they move around and collide with one another, and a number of them are now in orbits that intersect Earth's orbit. Asteroids sometimes break into smaller particles known as **meteoroids** (Table 14.1), which range in size from dust particles to objects a few meters in diameter. When a meteoroid enters Earth's atmosphere, it is known as a **meteor**. Frictional heating of meteors as they streak through the atmosphere produces light, so meteors are sometimes called *shooting stars*. Meteors occurring in large numbers produce the familiar *meteor showers*.

The last type of particle is a **comet**. Comets are distinguished from meteoroids and asteroids by their glowing tail of gas and dust (Figure 14.6). They range in size from a few meters to a few hundred kilometers in diameter, and they are thought to be composed of a rocky core surrounded by ice and covered in carbon-rich dust. In addition to frozen water, the ice contains carbon dioxide (dry ice), carbon monoxide, and smaller

TABLE 14.1 Meteorites and Related Objects

Type	Diameter	Composition	Comments
Asteroid	10 m to 1000 km	Stony or metallic	Strong and hard if made of metal or some rock types; hard types may hit Earth's surface, and weak types will explode in Earth's atmosphere at heights of several to hundreds of kilometers. Most originate in asteroid belt between Mars and Jupiter.
Comet	A few meters to a few hundred kilometers	Frozen water and/or carbon dioxide form an icy core that is surrounded by rock fragments and dust; like a "dirty snowball."	Weak, porous, will often explode in Earth's atmosphere at heights of kilometers to hundreds of kilometers. Most originate outside solar system in the Oort Cloud, 50,000 AU[a] from the sun, or within the solar system in the Kuiper Belt of comets; a tail, pointed away from the sun, forms as the icy core vaporizes and dust particles are shed from the object.
Meteoroid	Larger than dust size to under 10 m	Stony, metallic, or carbonaceous (containing carbon)	Most originate from collisions of asteroids or comets. May be made of strong or weak rock.
Meteor	Dust size to centimeters	Stony, metallic, carbonaceous, or icy	Destroyed in Earth's atmosphere as shooting stars; their light is produced by frictional heating in the atmosphere.
Meteorite	Centimeters to asteroid size	Stony, metallic, or carbonaceous	Object that has actually hit Earth's surface. Stony variety, called a *chondrite*, is most abundant.[b]

[a] AU is the distance from Earth to the sun, about 240,000,000 km (150,000,000 mi.).

[b] There are many types of chondrites. They contain chondrules, which are small (less than 1 mm) spheroidal inclusions that are glassy or crystalline. Planets are constructed from chondrite meteorites (asteroids).

Source: Data from Rubin, A. F. 2002. *Disturbing the solar system.* Princeton, NJ: Princeton University Press, 2002.

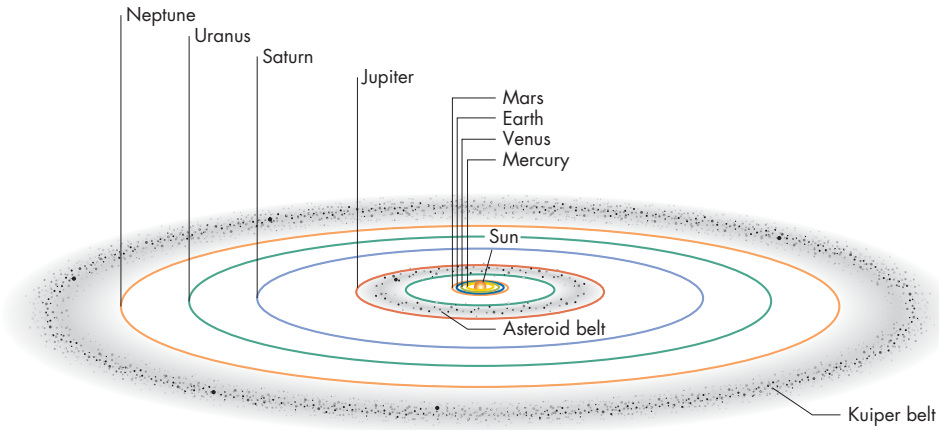


FIGURE 14.5 Diagram of Our Planetary System Showing Asteroid Belt and Kuiper Belt
The Oort Cloud is too far away from the sun to be seen in this perspective. Orbits of the planets and belts are not to scale.

amounts of other compounds. As sunlight heats the comet, the "dirty ice" evaporates to form a mixture of gases. Comets are believed to have originated far out in the solar system, beyond the planet Neptune, and to have been thrown into an area called the Oort Cloud. The Oort Cloud lies beyond the Kuiper Belt and extends out as far as 50,000 times the distance from Earth to the sun.[3] Early in the history of the evolution of Earth, bombardment by asteroids and comets contributed the building blocks of our planet, which was built up from the collision of innumerable smaller bodies.



< FIGURE 14.6 Comet Hale-Bopp
Comet Hale-Bopp, pictured here in the night sky in 1997, remained visible to the naked eye for 18 months. Comets have a nucleus of ice and dust and a tail of evolved gases and dust grains. *(Aaron Horowitz/Corbis)*

14.1 CHECK your understanding

1. Explain how our solar system formed.
2. Describe the differences between an asteroid, meteor, comet, meteoroid, and meteorite.
3. What are meteorites and comets made of?
4. Where do comets and asteroids originate?

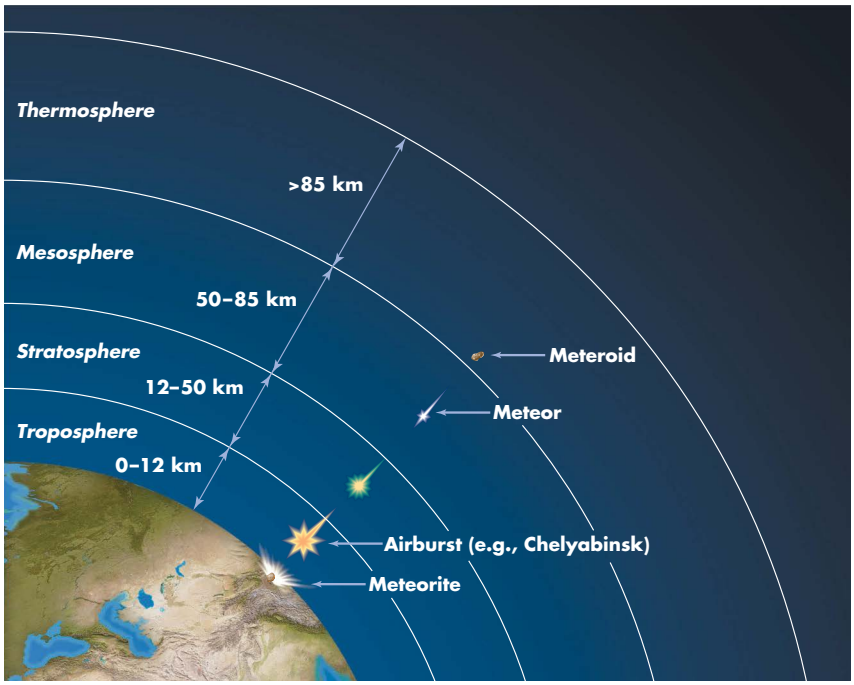
14.2 Airbursts and Impacts

When entering Earth's atmosphere, asteroids, comets, and meteoroids travel at a velocity of about 12 to 72 km per second (~7 to 45 mi. per second).[4] The composition of asteroids and meteoroids varies (see Table 14.1). Some contain carbonaceous material, whereas others are composed of native metals, such as iron and nickel. Others are stony, consisting of silicate minerals such as olivine and pyroxene—common minerals in igneous rocks. Stony meteoroids and asteroids are *differentiated*, meaning that they have undergone igneous, and sometimes metamorphic, processes as part of their geologic histories. As previously mentioned, meteoroids and asteroids are derived from the asteroid belt, between the orbits of Mars and Jupiter, whereas comets come from the Oort Cloud. Regardless of where they come from, when they intersect Earth's orbit and enter our atmosphere, meteoroids, asteroids, and comets undergo remarkable changes as they heat up due to atmospheric friction during descent and produce bright light. A meteoroid entering the atmosphere at about 85 km (~53 mi.) above Earth's surface will become a meteor and emit light (Figure 14.7). It will then either explode in an **airburst** in the atmosphere at an altitude between 12 and 50 km (~7 and 31 mi.), or collide with Earth.[5,6] Once a meteoroid actually strikes Earth, we speak of it as a **meteorite**. Many meteorites have been collected from around the world, particularly from Antarctica where they are concentrated because of particular meteorological conditions. An example of a modern era (1908) large airburst is the Tunguska event of 1908.

14.1 CASE study — The Tunguska Event

On June 30, 1908, shortly after 7 A.M., witnesses in Siberia (see Figure 14.1) reported observing a blue-white fireball with a glowing tail descending from the sky. The fireball exploded above the Tunguska River Valley in a heavily forested, sparsely populated area. Later, calculations would show that the explosion had the force of 10 megatons of TNT—equivalent to 10 hydrogen bombs. Although there were few witnesses close to the event, the sounds from the explosion were heard hundreds of kilometers away, and the blast wave was recorded at meteorological recording sites throughout Europe. A tremendous air blast caused more than 2000 km^2 (~770 $mi.^2$) of forest to be flattened and burned (Figure 14.8). The devastated area was more than twice the size of New York City.

A herdsman in the vicinity of the blast was one of the few people who witnessed the devastation on the



< FIGURE 14.7 Meteoroid Entering Earth's Atmosphere
Idealized diagram showing a meteoroid's entry into the atmosphere, producing a light phenomenon called a meteor. Most meteors are extremely small dust- to sand-size meteoroids. A large meteoroid may break apart in an aerial burst or crash into Earth's surface. *(Modified after R. Baldini: www.th.bo.infn.it/tunguska/impact/fig1_2jpg)*



^ FIGURE 14.8 Tunguska Forest, Siberia, 1908
An aerial blast downed trees over an area of about 2000 km^2 (~770 mi.^{2}). *(World History Archive/Newscom)*

ground. His hut was completely flattened by the blast, and its roof was blown away. Other witnesses a few tens of kilometers from the explosion reported that they were physically blown into the air and knocked unconscious; they awoke to find a transformed landscape of smoke and burning trees that had been blasted to the ground.

At the time of the explosion, Russia was in the midst of political upheaval. As a result, there was no rapid response or investigation of the Tunguska event. Finally, in 1924, geologists who were working in the region interviewed surviving witnesses and determined that the blast from the explosion was probably heard throughout an area of at least 1 million km^2 (~386,000 mi.^{2}), an area the size of Texas and New Mexico combined! They also found that the fireball had been witnessed by hundreds of people. Russian scientists went into the area in 1927, expecting to find an impact crater produced by the asteroid that had apparently struck the area. Surprisingly, they found no crater, leading them to conclude that the devastation had been caused by an aerial explosion (airburst), probably at an elevation of about 7 km (~4.3 mi.). Later calculations estimated the size of the asteroid responsible for the explosion to be about 25 to 50 m (~80 to 160 ft.) in diameter. It was most likely composed of relatively friable (easy to crumble) stony material.[3,4]

The people on Earth were lucky that the Tunguska event occurred in a sparsely populated forested region. Given the rotation of Earth, if the asteroid explosion had occurred only a few hours later it would have threatened St. Petersburg and flattened it by direct impact and with a huge loss of human life. Worse yet, if the fireball had exploded over a large metropolis such as London, Paris, or Tokyo, millions of people would have died. Tunguska-type events are thought to occur on the order of once every 1,000 years.[5]

IMPACT CRATERS

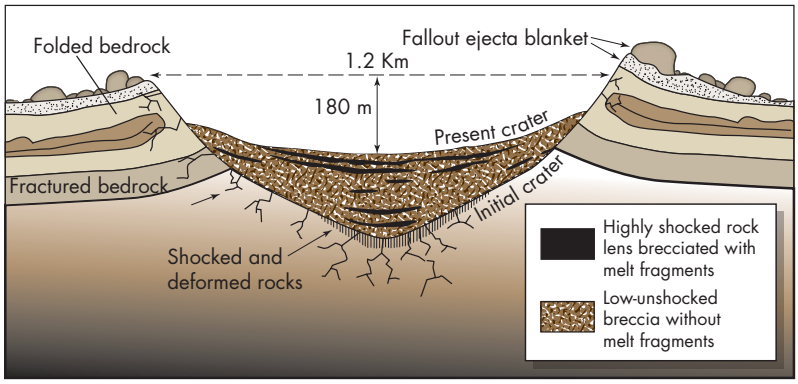
The most direct and obvious evidence for impacts on the surface of Earth comes from studies of the **impact craters** they produce. More than 175 individual craters or small crater fields have been identified worldwide (Figure 14.9).[4,6,7] The 49,000-year-old Barringer Crater in Arizona is perhaps the most famous impact crater in the United States. Also known as "Meteor Crater," it is an extremely well-preserved, bowl-shaped depression with a pronounced, upraised rim (Figure 14.10a). The crater is approximately 1.2 km (~0.7 mi.) in diameter, with a depth of about 180 m (~590 ft.). The rim of the crater rises about 260 m (~850 ft.) above the surrounding Arizona desert. This rim is



▲ FIGURE 14.9 Extraterrestrial Impact Craters of the United States and Canada
Map showing locations of individual craters that have been identified at the surface and in the subsurface. Not shown are more than a half million Carolina Bay craters that cover the coastal plain from Florida to New Jersey. Recently a young crater was discovered in northern Greenland. *(Based on Grieve, R. A. F,* Impact Structures in Canada, *St. Johns, Newfoundland and Labrador: Geological Association of Canada GEOtext 5, 2006; and Evans, K. R., Horton, Jr., J. W., Thompson, M. F., and Warme, J. E, "The Sedimentary Record of Meteorite Impacts: An SEPM Research Conference," The Sedimentary Record, March 2005, pp. 4–69)*



(a)



(b)

< FIGURE 14.10 Simple Impact Crater in Arizona

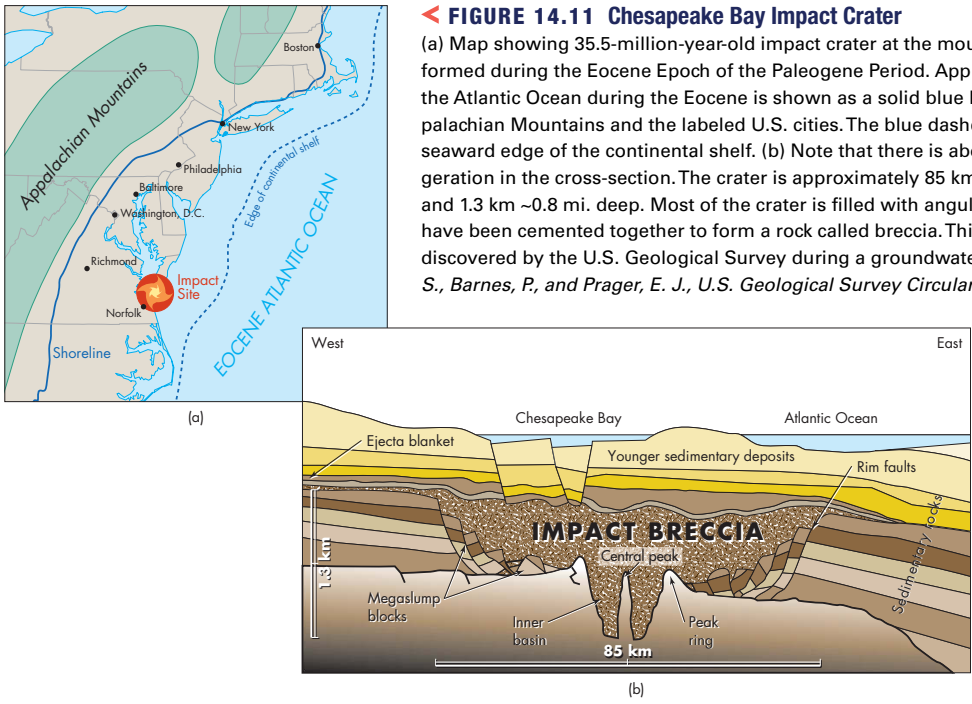
(a) Barringer Crater, Arizona (about 49,000 years old). The crater is about 1.2 km (~0.7 mi.) across and 180 m (~590 ft.) deep. *(Charles O'Rear/Corbis)* (b) Generalized cross-section of features associated with the Barringer Crater. Simple impact craters like this typically have raised rims and no central uplift or peak. *(Based on Grieve, R., and Cintala, M, "Planetary Impacts," in P. R. Weissman, L. McFadden, and T. V. Johnson, eds.,* Encyclopedia of the Solar System. *San Diego, CA: Academic Press, 1999)*

overlain by a layer of debris, referred to as an *ejecta blanket*, which was blown out of the crater upon impact. Today, the ejecta blanket can be identified by the irregular terrain of mounds and depressions that surrounds the crater. The crater we see at the surface today is not nearly as deep as the initial impact crater (Figure 14.10b). Material fragmented by the impact has fallen back into the crater, and some of the walls have collapsed. Rocks that the asteroid hit were shattered and deformed, and the angular, broken pieces have been naturally cemented or fused together to form a rock type known as *breccia*.

When the existence of the Barringer Crater became widely known in the late nineteenth century, there was considerable debate concerning its origin. Ironically, G. K. Gilbert, the famous geologist who postulated that the majority of the moon's craters were formed by impacts, did not believe that Barringer Crater had been formed by impact. The impact origin for the Barringer Crater was later established through careful study and evaluation. This study concluded that the crater formed from the impact of a small asteroid, probably about 25 to 100 m (~80 to 330 ft.) in diameter.[8]

Features that form at the time of impact differentiate impact craters from craters that result from other processes, such as volcanic activity. Impacts involve extremely high velocity, energy, pressure, and temperatures, which are normally not experienced or produced by other geologic processes. Most of the energy of the impact is in the form of kinetic energy, or energy of movement. This energy is transferred to Earth's surface through a shock wave that propagates into Earth. The shock wave compresses, heats, melts, and excavates earth materials. It is this transfer of kinetic energy that produces the crater.[9] The shock can metamorphose some rocks in the impact area, while others are melted and mixed with the materials of the impacting object itself. Most of the metamorphism consists of high-pressure modifications of minerals, such as quartz. These modifications are characteristic of meteorite impact, so they are extremely helpful in confirming the origin of an impact crater.

Impact craters can be grouped into two types, simple and complex. *Simple craters* are typically small, a few kilometers in diameter. Barringer Crater has the features characteristic of a simple impact crater (Figure 14.10b). *Complex impact craters* experience the same processes of vaporization, melting, ejection of material, formation of ejecta rims, and later infilling typical of



< FIGURE 14.11 Chesapeake Bay Impact Crater

(a) Map showing 35.5-million-year-old impact crater at the mouth of Chesapeake Bay, formed during the Eocene Epoch of the Paleogene Period. Approximate shoreline of the Atlantic Ocean during the Eocene is shown as a solid blue line between the Appalachian Mountains and the labeled U.S. cities. The blue dashed line offshore is the seaward edge of the continental shelf. (b) Note that there is about a 13× vertical exaggeration in the cross-section. The crater is approximately 85 km (~53 mi.) in diameter and 1.3 km ~0.8 mi. deep. Most of the crater is filled with angular rock fragments that have been cemented together to form a rock called breccia. This buried crater was discovered by the U.S. Geological Survey during a groundwater study. *(From Williams, S., Barnes, P., and Prager, E. J., U.S. Geological Survey Circular 1199, 2000)*

simple craters, but the shape of a larger, complex crater may be quite different (Figure 14.11). During a period of seconds to several minutes following impact, complex craters may grow to sizes of tens of kilometers to more than 100 km (~60 mi.) in diameter. In these craters, the rim collapses more completely, and the central crater uplifts following the impact. Typically, impact craters on Earth larger than about 6 km (~4 mi.) are complex, whereas smaller craters tend to be of the simple variety.

Geologically, ancient impact craters are difficult to identify because they are commonly either eroded or filled with sedimentary deposits that are younger than the impact. For example, subsurface imaging and drilling below the present Chesapeake Bay has identified a crater about 85 km (~53 mi.) in diameter, now buried by about 1 km (~0.6 mi.) of sedimentary deposits (Figure 14.11). The crater was produced by the impact of a comet or asteroid about 3 to 5 km (~2 to 3 mi.) in diameter about 35.5 million years ago.[10] Compaction and faulting of earth materials above the buried crater may be, in part, responsible for the location and shape of Chesapeake Bay.

A good example of an eroded impact crater, the Manicouagan Crater, can be found northeast of Quebec (Figure 14.12). At this crater, a ring-shaped reservoir about 65 km (~40 mi.) across fills a glacially eroded valley in the impact breccia. The lake outlines



^ FIGURE 14.12 Complex Impact Crater in Quebec

Satellite image of the Manicouagan impact structure northeast of Quebec City in Quebec, Canada. Complex craters typically have a faulted rim and central peak. This type of crater develops when the impact is so large that Earth's crust rebounds from the impact, forming the central peak. The ring-shaped lake is about 65 km (~40 mi.) in diameter. *(NASA)*

TABLE 14.2 Notable Impacts and Airbursts of Extraterrestrial Objects

Age[a]	Feature/Event	Location	Significance
4,450,000,000	Birth of the moon	Earth	Mars-size planetary body collides with Earth to form the moon.
2,023,000,000	Vredefort Dome	South Africa	Earth's oldest and largest terrestrial impact crater.
1,850,000,000	Sudbury Crater	Ontario, Canada	Earth's second largest terrestrial impact crater; rich in nickel and copper ores.
214,000,000	Manicouagan Crater	Quebec, Canada	Tied with Popigai Crater for fourth largest terrestrial impact crater.
64,980,000	Chicxulub Crater	Below Yucatán Peninsula and Gulf of Mexico	Contributed to extinction of large dinosaurs; produced enormous tsunamis; third largest terrestrial impact crater.
35,700,000	Popigai Crater	Siberia, Russia	Tied with Manicouagan Crater for fourth largest terrestrial impact crater; has produced numerous industrial-grade diamonds.
35,500,000	Chesapeake Bay Crater	Buried below Virginia, United States	Largest U.S. impact crater; affects regional groundwater flow.
49,000	Barringer Crater (aka Meteor Crater)	Arizona, United States	First impact crater identified on Earth; training site for Apollo astronauts.
12,800	Younger Dryas Airburst (hypothesis)	Southern Canada	Contributed to extinction of large Pleistocene mammals and the Clovis civilization.
1908	Tunguska Airburst	Siberia, Russia	Destroyed millions of trees
2013	Chelyabinsk Airburst	Russia	Injured about 1,500 people.

[a] Years before 1950, except for 1908 and 2013 events.

Source: Based on Grieve, R. A. F., *Impact Structures in Canada*. St. Johns, Newfoundland and Labrador: Geological Association of Canada, GEOtext 5, 2006.

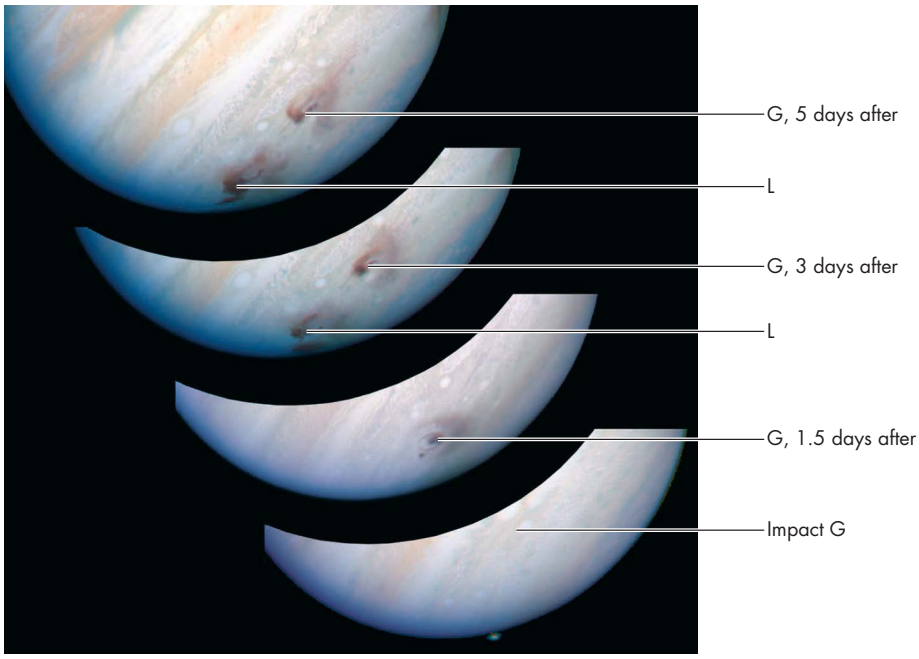
most of the crater, which is estimated to have been originally about 100 km (~62 mi.) in diameter. One of the five largest terrestrial impact craters in the world, the Manicouagan Crater is close to 215 million years old (Table 14.2).[6]

Most detailed remote sensing studies of craters have been conducted on craters on the moon and Mars. Impact craters are much more common on the moon than on Earth for three reasons:

1. Most impact sites on Earth are in the ocean where craters are subsequently buried by marine sediment or destroyed by plate tectonic processes.
2. Impact craters on land are now generally subtle features that are eroded, buried, or covered with vegetation.
3. Smaller meteoroids and comets tend to burn up and disintegrate in Earth's atmosphere before striking the surface.

In 1993, Gene and Carolyn Shoemaker and David Levy discovered a comet, later known as Shoemaker-Levy 9, from photographs they had taken through a telescope on Palomar Mountain in Southern California. Less than a year and a half later, astronomers watched Shoemaker-Levy 9 explode in one of the most tremendous impacts ever witnessed. From the start, the comet was unusual in that it was composed of several discrete fragments with several bright tails, and it was reported as a misshapen comet. Shoemaker-Levy 9 was one of about 50 comets in the Jupiter family that circle between Jupiter and the sun. The comet's orbit was tied to that of Jupiter, and, after years of orbiting the planet, it separated into 21 fragments known as a "string of pearls."

From telescopes on Earth and the Hubble Space Telescope in Earth orbit, astronomers watched as fragments of the comet entered Jupiter's atmosphere at speeds of 60 km (~37 mi.) per second. The fragments then exploded, releasing between 10,000 and 100,000 megatons of energy, depending on their size. More energy was released than if all of Earth's nuclear weapons were detonated at the same time. Hot, compressed gases expanded violently upward from the lower part



< FIGURE 14.13 Spectacular Impact of the Comet Shoemaker-Levy 9G on the Planet Jupiter in 1994
The comet was composed of 21 fragments known as a "string of pearls." One fragment after another entered Jupiter's atmosphere and exploded. From bottom to top, these four images were taken several days apart. The reddish-brown dots and rings mark the impact sites of fragments G and L. The diameter of these rings exceeded the diameter of Earth. *(ESA)*

of Jupiter's atmosphere at speeds as high as 10 km (~6 mi.) per second. Gas plumes from the larger impacts reached elevations of more than 3000 km (~1900 mi.), a height that is around 340 times as high as Mt. Everest, the tallest mountain on Earth. Tremendously large rings developed in Jupiter's atmosphere around the impact sites (Figure 14.13). These rings exceeded the diameter of the Earth! It was truly a remarkable show for astronomers and a sobering event for those who consider that impacts such as this might one day occur on Earth.[3]

After the impact of the fragmented comet on Jupiter and investigations of the Barringer Crater in Arizona and several other craters on Earth, the idea that there could be a catastrophic impact on Earth was finally accepted. At the time of the Tunguska event, several bizarre ideas were suggested to explain it, such as nuclear explosions and the explosion of an alien spaceship!

UNIFORMITARIANISM, GRADUALISM, AND CATASTROPHISM

The idea that Earth could be hit by large objects from outer space was not accepted for many hundreds of years, despite numerous eyewitness accounts in various parts of the world. These accounts may have started with a lethal meteorite that landed in Israel in the year 1420 B.C.[4] Up until the fifteenth century, when Galileo invented the telescope and clearly demonstrated that Earth and the other planets revolve around the sun, the religious establishment did not accept Galileo's ideas; in fact, he was jailed for his beliefs. In 1654, Irish Archbishop Ussher proclaimed that Earth was created in 4004 B.C., making it approximately 6,000 years old. This was the dogma of the time and not to be disputed. However, people studying the formation of mountains, such as the Alps, large river valleys, and other features, had a hard time understanding how these physical features could be formed in only 6,000 years. Based on Archbishop Ussher's "young Earth" belief, early earth scientists were forced to conclude that most of the processes that formed our planet were catastrophic in nature (*catastrophism*). This perspective explained biblical events, such as Noah's Flood, but not much else.

Finally, in 1785, the Scottish doctor James Hutton wrote an influential book that introduced the concept of *gradualism*, or *uniformitarianism*. This concept states that present geological processes may be studied to learn the history of the past—"the present is the key to the past." Hutton also argued that Earth must be much older than 6,000 years to allow the gradual processes of erosion, deposition, and uplift to form mountain ranges and other features on Earth's surface. In 1830, Charles Lyell wrote another

influential book on geology, popularizing the role of gradual processes. He proclaimed that Earth had a long history that could be understood by studying present-day processes and the rock record. After Lyell and other scientists overturned the young Earth idea, they could then explain Earth's history in terms of processes that could be carefully observed, such as uplift and erosion. Charles Darwin was impressed with Charles Lyell's book and applied the ideas of an ancient Earth and uniformitarianism to his concept of biological evolution. The concept of gradualism lasted into the twentieth century and culminated with the discovery of plate tectonics, perhaps the crowning glory of uniformitarianism. The theory of plate tectonics (see Chapter 2) explains the present position and origin of continents, based on the relatively slow processes of seafloor spreading and uplift.

But occasionally, scientists also discovered evidence of the role of catastrophic events. Some scientists pointed to large craters on Earth's surface, which they believed were the result of asteroid impacts. Also, it was well known that there was a number of relatively rapid extinctions during Earth's history in which a large percentage (commonly half or more) of the species of plants and animals perished relatively suddenly. Five of these extinctions are in the relatively distant geologic past; the most recent mass extinction is ongoing today as a result of human activity (see Figure 14.2). The mass extinction that occurred 65 million years ago at the K-Pg (Cretaceous-Paleogene) boundary appears to have been caused, to a great extent, by the impact of an asteroid. The asteroid that struck the Yucatán Peninsula in Mexico was approximately 10 km (~6 mi.) in diameter. Even faced with direct evidence for the impact, many scientists were skeptical that a mass extinction might be triggered by the impact of an asteroid. Also, it wasn't until 1947 that Barringer Crater (Meteor Crater) in Arizona was finally listed as a probable impact event. Up to that time, it was still often referred to as a *cryptovolcanic* event. This means that the volcanic activity was "hidden," yet it produced a crater or disturbed area at the surface. Eventually, Barringer Crater was shown to be the result of an asteroid impact, probably with airbursts; since then, more than 175 other large impact features have been identified on all the continents and on the ocean floor.

These observations have led to a new concept, *punctuated uniformitarianism*. This concept states that although uniformitarianism explains the long geologic record of gradual mountain building, canyon erosion, and landscape construction, periodic catastrophic events do occur and can cause mass extinctions.

14.2 CHECK your understanding

1. Define *airburst*.
2. Where is Tunguska? What happened there? Why is it important to our discussion of natural hazards? How often do events like this one occur?
3. Describe the general characteristics of an impact crater. How can it be distinguished from other types of craters?
4. Why does Earth apparently have so few impact craters?
5. Differentiate between simple and complex craters.
6. Why was Barringer Crater controversial, and why is it important?
7. Explain the significance of Comet Shoemaker-Levy 9.
8. Differentiate between uniformitarianism, gradualism, and catastrophism.
9. What is punctuated uniformitarianism?

14.3 Mass Extinctions

A **mass extinction** is characterized by the sudden loss of large numbers of plants and animals relative to the number of new species being added.[11] Because the geologic time scale was originally based on the appearance and disappearance of various fossil species, mass extinctions generally coincide with the boundaries of geologic periods or epochs of the time scale (Figure 14.14). Most hypotheses for mass extinctions involve relatively rapid climate change. This climate change can be triggered by plate tectonics, volcanic activity, or extraterrestrial impact. Plate tectonics is generally a relatively slow process that moves the position of continents and, thus, habitats to different locations. On occasion, plate movements create new patterns of ocean circulation, which have a major effect on climate. Extremely large volcanic eruptions can also cause significant climate change. Large basaltic eruptions producing huge volumes of *flood basalts* (see Chapter 5) can release large quantities of carbon dioxide, a greenhouse gas, into the atmosphere and cause global warming. In contrast, large explosive volcanic eruptions of more silica-rich lava can inject tremendous quantities of volcanic ash into the upper atmosphere and cause global cooling. Finally, climate change is one of several effects of extraterrestrial impacts or airbursts that can contribute to extinctions.

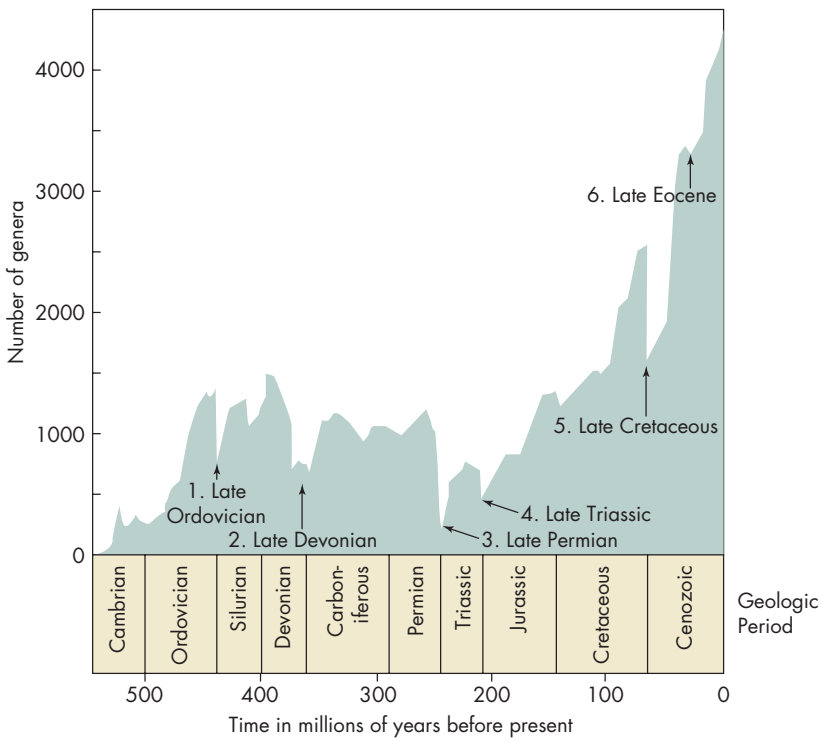
During the past 550 million years of Earth's history, at least six major mass extinction events have occurred. The earliest mass extinction occurred approximately 446 million years ago, near the end of the Ordovician Period (Figure 14.14). One of the largest mass extinctions in Earth's history, with around 100 families of animals becoming extinct, this event coincided with a major continental glaciation in the Southern Hemisphere. In fact, it appears that this event was actually two extinctions: one when the climate cooled, and the other when the climate warmed following the glacial interval. The largest recorded mass extinction occurred near the end of the Permian Period, about 250 million years ago, when 80 to 85 percent of all living species died out (Figure 14.14).[12] Although there is now evidence for an impact at the Permian-Triassic boundary, scientists also believe that this mass extinction may not have been caused by a single catastrophe but may have spanned a period of about 7 million years. The extinction also corresponds to eruption of the massive Siberian flood basalts, which likely emitted voluminous greenhouse gases to the atmosphere and may have dramatically changed the climate. In addition, sea-level fall and assembly of the supercontinent of Pangaea at this time would have dramatically reduced the area of shallow marine environment, where many of the affected species lived.

The third mass extinction at the Triassic–Jurassic boundary (Figure 14.14), 202 million years ago, also appears to have been related to volcanic activity and climate change. Large amounts of carbon dioxide were released from basaltic volcanic eruptions associated with the breaking apart of the supercontinent Pangaea. These eruptions may have produced the largest volume of basaltic lava ever released by volcanoes on land. Earth's temperatures, which were already 3°C (~5°F) warmer than today, increased another 3° to 4°C (~5° to 7°F) at the end of the Triassic Period. This rapid climate change resulted in the extinction of plants and animals on land and in the ocean. Half of all the genera of marine animals became extinct in this event (Figure 14.14).[12]

Another tremendous mass extinction event took place at the end of the Cretaceous Period (K) and beginning of the Paleogene Period (Pg). Known as the *K-Pg boundary*, this event was sudden and most likely caused by the impact of a giant asteroid. The K-Pg extinction brought an end to the large dinosaurs, which had been at the top of the food chain for 100 million years or more. Their demise allowed small mammals to diversify and evolve into the approximately 4,000 species, including humans, that are alive today. Species in the oceans of the world also evolved and diversified following the K-Pg extinction.

A fifth mass extinction took place near the end of the Eocene Epoch about 34 million years ago. Although there is some evidence for an asteroid or comet impact at that time, most scientists link this extinction to climate change brought on by plate tectonics. The movement of tectonic plates at this time allowed a cold ocean current to develop around Antarctica; the resulting cooling produced the Antarctic ice cap, which is still present today. This resulted in a global cooling and drying of the climate.[12]

The final mass extinction occurred near the end of the Pleistocene Epoch. This extinction of mammals, reptiles, amphibians, birds, fish, and plants continues today. The initial cause of this event was first thought to be some combination



▲ FIGURE 14.14 Mass Extinction Events
Biodiversity diagram illustrating the increasing diversification of life through the Phanerozoic Period, punctuated by six mass extinction events which are named for the geologic period in which they occurred.

of overhunting by Stone Age man and climate change. However, new evidence indicates that it may have been initiated by the airburst of a comet, discussed below. In many ways, this mass extinction continues today due to human activities, including loss of habitat from land-use changes, widespread deforestation, the application of pesticides and other chemicals, and human-induced global warming.[11]

14.2 CASE study

K-Pg Boundary Mass Extinction

One of the great geologic detective stories of the past 50 years is the investigation of the K-Pg (Cretaceous-Paleogene) mass extinction. We now have evidence that 64,980,000 years ago, an asteroid with a diameter of about 10 km (~6 mi.) hit Earth along the northern shore of what is now the Yucatán Peninsula. That event altered Earth's history forever. Although much of the physical landscape of Earth remained unchanged after the impact, the planet's inhabitants were largely affected. Approximately 70 percent of all land and marine genera and their associated species died off (see Figure 14.14). Some reptiles, such as turtles, alligators, and crocodiles, and some birds, plants, and smaller mammals survived, either because of their habitat requirements or their location at the time of the impact. Not all areas experienced widespread wildfires following the impact, and some plants and animals were better adapted to subsequent changes in climate.[13] The impact contributed to the demise of the large dinosaurs on land and swimming reptiles in the oceans. Extinction of these animals set the stage for the evolution of mammals. This evolution eventually produced primates and humans. What would the world look like today if the K-Pg extinction had never happened? There's a good chance that humans never would have evolved!

Since this extinction has been so important for our evolution, we will look more closely at how scientists developed the hypothesis that the K-Pg mass extinction was caused by the impact of a large asteroid. The story is full of intrigue, suspense, rivalries, and cooperation—typical of many of the great scientific discoveries.[14] Scientists with backgrounds in geology, physics, chemistry, biology, geophysics, and astronomy worked together to develop and test the hypothesis that the K-Pg mass extinction was triggered by an impact. Walter Alvarez, a professor at the University of California, asked the question that started it all: What is the nature of the boundary between rocks of the Cretaceous and Paleogene Periods?

Alvarez was interested in Earth's history and, particularly, in reading that history as recorded by rocks. Early in his studies of the K-Pg boundary, Alvarez teamed up with his physicist father, Luis, and they decided to measure the concentration of a platinum-group metal called *iridium* in the thin clay layer that marks the K-Pg boundary in Italy. Walter Alvarez and colleagues had initially gone to the site in Italy to study the magnetic history of Earth. What they found at the K-Pg boundary was a very thin layer of clay (Figure 14.15), and it seemed that the extinction of many species occurred abruptly at the clay layer—fossils found in rocks below this clay boundary marker were simply not there in the rocks above the clay.[14]

Alvarez and his fellow scientists then asked the question: How much time was involved in the deposition of the clay layer? Was it a few years, a few thousand years, or millions of years? The approach they took was to measure the amount of iridium in the clay. They chose iridium because it is found in small concentrations in meteorites and because the global rate of accumulation of meteorite dust on Earth is constant. The deep ocean floor accumulates meteoritic dust like a tabletop or picture frame in your home—the longer ocean floor sediment sits undisturbed, the more iridium it will accumulate. Clay washing into the ocean from the land can cover previously deposited meteorite dust. The faster the rate of sedimentation, the more diluted the meteorite dust becomes. Slow rates of sedimentation allow time for more meteorite dust to accumulate in ocean deposits.

What Walter Alvarez and his colleagues found was entirely unexpected. The team had anticipated measuring approximately 0.1 part per billion of iridium in the



▲ FIGURE 14.15 Evidence for Impact
The Cretaceous/Paleogene (K-Pg) boundary in Italy lies in a thin clay layer. The scientist on the left is pointing to the layer below his left knee. This layer has an anomalously high concentration of the metal iridium. High concentrations of this metal are found in extraterrestrial objects such as meteorites. Its presence here is consistent with an asteroid impact. *(Walter Alvarez)*

clay layer, which they thought would represent slow accumulation through time. If the clay layer were deposited rapidly, then the amount of iridium would be even less. What they actually found was about 3 parts per billion—30 times as much as expected. As you recall from our discussion of CO_2 concentration in the atmosphere (see Chapter 12), 3 parts per million (ppm) is a very small quantity, and 3 parts per billion (ppb) is 1,000 times smaller than 3 ppm! Although 3 ppb is an extremely small amount of iridium, it was much more than could be explained by their previous hypothesis of slow deposition over time. They reevaluated the data, this time including samples that had been removed for treatment before measurement, and got a final value of about 9 ppb, which is nearly 100 times as great as expected. This discovery led them to a new hypothesis: The iridium might be the remains of a single asteroid impact. The team's iridium discovery, along with its hypothesis of an extraterrestrial cause for the extinction at the K-Pg boundary, was published in 1980.[15] In that paper, the team also reported elevated concentrations of iridium in deep sea sediments in Denmark and in New Zealand, all at the K-Pg boundary. Although the discovery of the iridium anomaly at several places around the world made the team more confident of its impact hypothesis, the scientists still had no crater. This absence prompted other scientists to search for potential craters that formed 65 million years ago.[14]

Would it be possible to find the crater? The K-Pg crater might have been completely filled with sediment and no longer recognizable, or the crater might have been on the ocean floor and subsequently destroyed by plate subduction. Fortunately, the site of the crater was identified in 1991.[16] Geologists in Mexico studying the structural geology of the Yucatán Peninsula discovered what they determined to be a buried impact crater with a diameter of at least 180 km (~112 mi.). The crater, named Chicxulub for a nearby village, is nearly circular and has a clear boundary between unfractured rocks within the crater and fractured rocks outside the crater. About half of the crater lies beneath the seafloor of the Gulf of Mexico and half beneath sedimentary rocks and vegetation on the northern end of the Yucatán Peninsula (Figure 14.16).

On land, researchers found a semicircular pattern of sinkholes, known to the Mayan people as *cenotes*, which corresponded directly to the edge of the proposed impact crater. The cenotes range from about 50 to 500 m (~160 to 1640 ft.) in diameter. They were presumably formed by the chemical weathering of fractured limestone on the outside of the crater boundary. Thus, both the distribution of fractured rock and the cenotes must be related to the circular structure because there are no other geologic features in the area that could explain the curved pattern. The crater, which is now filled with other rock, is believed to have been as deep as 30 to 40 km (~19 to 25 mi.) at the time of impact. However, subsequent slumping and sliding of materials from the sides soon filled in much of the crater, and sedimentation over the past 65 million years completely buried the structure.

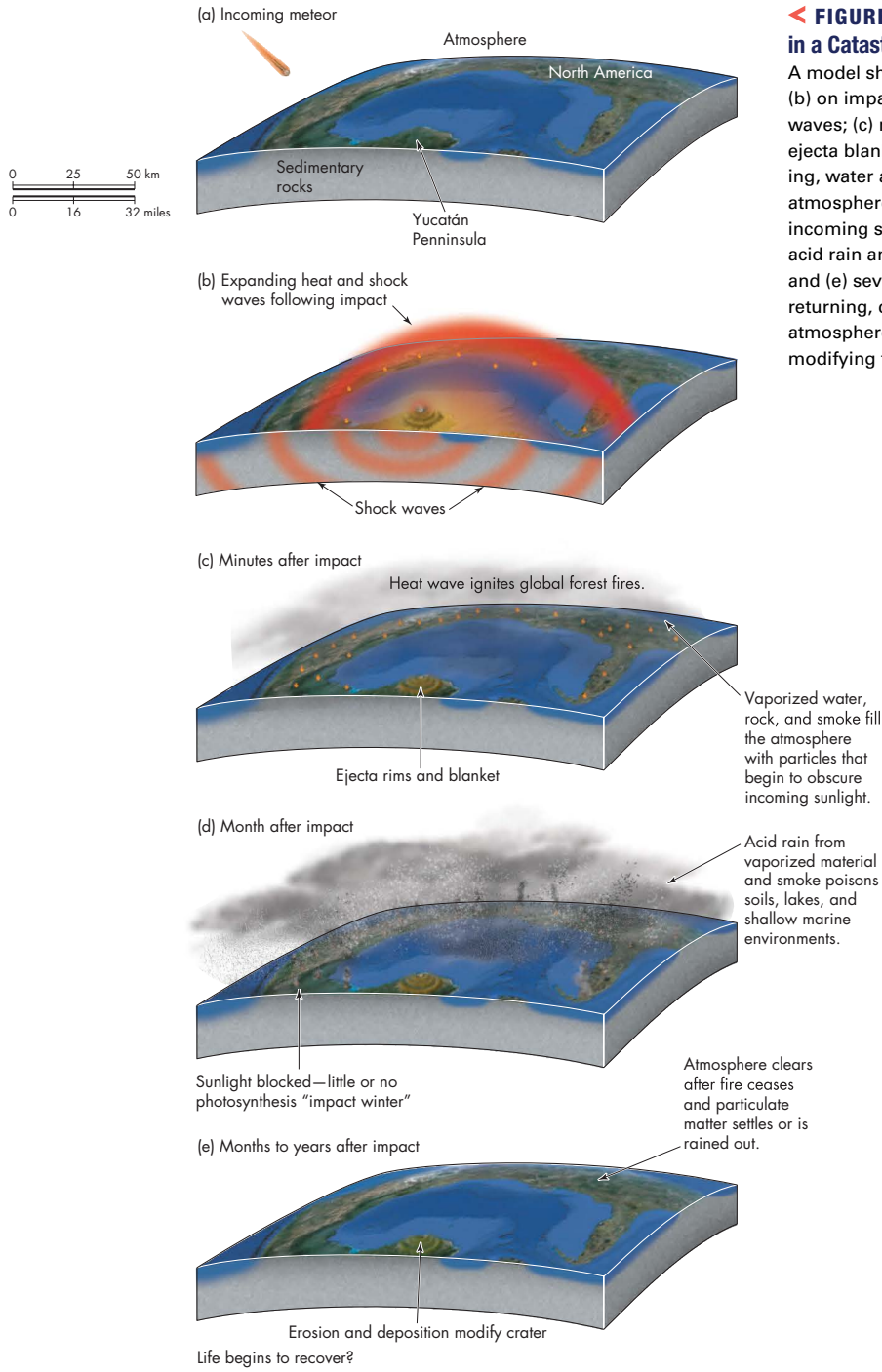


FIGURE 14.16 Large Impact Crater in Mexico
Map showing location of the Chicxulub impact crater on the north shore of the Yucatán Peninsula in Mexico. This crater is buried below sedimentary rocks on the peninsula and the seafloor of the Gulf of Mexico. Formed by an asteroid impact about 65 million years ago, the age of this crater coincides with the Cretaceous/Paleogene (K-Pg) mass extinction. *(Detlev van Ravenswaay/Science Source)*

When drilling within the crater, geologists found glassy melt rock, interpreted to be impact breccia. The force of the impact excavated the crater, fractured the rock on the outside, and produced the breccia. The glassy nature of the breccia suggests that sufficient heat was present to melt rocks immediately following impact.[17] Another study of the crater found glass mixed in with and overlain by the breccia, as well as evidence of shock metamorphism commonly associated with impact features.[18] Most scientists now believe that the asteroid impact that struck the area nearly 65 million years ago did, in fact, contribute significantly to the K-Pg mass extinction.

After identifying the site of the crater and the evidence to support its existence, questions naturally arose regarding how such an event could cause a global mass extinction.[14] The asteroid that formed the Chicxulub crater was huge; its diameter is estimated at about 10 km (~6 mi.). By comparison, many jet aircraft fly at cruising altitudes of around 10 km above Earth's surface. The summit of Mt. Everest is not as high as 10 km, but it is close. Consider, too, that the asteroid struck the atmosphere of Earth at a speed of about 30 km (~19 mi.) per second, which is about 150 times faster than a jet airliner travels. The amount of energy that was released is estimated to have been about 100 million megatons, roughly 10,000 times as great as the entire nuclear arsenal of the world.

Walter Alvarez and numerous other geologists, physicists, paleontologists, and astronomers have reconstructed a likely sequence of events for the impact and its aftermath (Figure 14.17). The hole blasted in Earth's crust was nearly 200 km (~125 mi.) across and 40 km (~25 mi.) deep. At an altitude of 10 km (~6 mi.) in the upper atmosphere, and moving at 30 km (~19 mi.) per second, the asteroid would have taken less than half a second to reach Earth and almost instantaneously produce the large crater. When it



< FIGURE 14.17 Sequence of Events in a Catastrophic Impact

A model showing (a) incoming asteroid; (b) on impact, with a fireball and shock waves; (c) minutes after impact with an ejecta blanket forming, wildfires starting, water and nitrogen vaporizing in atmosphere, and a dust cloud blocking incoming sunlight; (d) a month later with acid rain and little or no photosynthesis; and (e) several months later with sunlight returning, dust and acid washed out of the atmosphere, and erosion and deposition modifying the crater.

contacted Earth, shock waves quickly crushed the rocks beneath, filling in all the cracks, partially melting the rocks, producing the breccia, and blasting bits and pieces high into the atmosphere. All this activity probably took about 2 seconds as the shock wave and heat vaporized rocks on the outer fringes of the impact. The tremendous amount of debris built a huge ejecta blanket around the crater. A gigantic cloud of vaporized rocks and gases would have produced an equally large fireball that rose up and formed a huge mushroom cloud. The explosion itself and the rising materials would likely have been sufficient to accelerate and eject material far beyond Earth's surface. Particles of rock were blasted into ballistic trajectories before they fell back to the ground. The fireball would have produced sufficient heat to set fires around the globe. Vaporization of gypsum salts in the bedrock and ocean water produced sulfuric acid in the atmosphere. Additional acids were added as a result of burning nitrogen in the atmosphere. Thus, following the impact, acid rain probably fell for a long period.

The dust ejected in the atmosphere circled Earth, and for months, essentially no sunlight reached the lower atmosphere. The lack of sunlight stopped photosynthesis on land and in the ocean. Acid rain is toxic to many living things, particularly terrestrial and shallow marine plants and animals. As a result, the food chain virtually stopped functioning because the base of the chain had been greatly damaged. Part of the impact occurred in the ocean and would have significantly disturbed the seafloor, generating tsunamis that could have reached heights of more than 300 m (~1000 ft.). These waves raced across the Gulf of Mexico and inundated parts of North America.[14,19] Wildfires ravaged southern North America, all of Central America, and parts of South America, Africa, Asia, and Australia.[13] The climate first cooled from lack of sunlight and then significantly warmed as aerosols and carbon dioxide from the pulverized limestone of the Yucatán Peninsula enhanced the greenhouse effect. Finally, large numbers of ferns restored plant cover on the burned landscape.[12]

The ultimate result of the asteroid impact was a global catastrophic killing, which we refer to as a mass extinction. Although evidence indicates that some species of dinosaurs were dying off before the impact, the event certainly seems to be responsible for wiping out the remaining large dinosaurs. So many other species of terrestrial and marine animals and plants died that there is little doubt that a massive impact was the likely cause of their extinction. Should such an event occur again, the loss of species would be immense. It might well mean the extinction of humans and many of the larger mammals and birds. These extinctions would lead the way to yet another period of rapid evolution.

What we have learned from the K-Pg extinction is sobering. We know that impacts from objects as large as 10 km (~6 mi.) in diameter are rare and occur only every 40 to 100 million years or so. However, large impacts are not the only hazard from comets, asteroids, and meteoroids. Smaller impacts are much more probable, and they can wreak havoc on a region, causing great damage and loss of life.

14.3 CASE study IMPACT AND MASS EXTINCTION 12,800 YEARS AGO

Imagine a North American landscape with grasses, low shrubs, and clusters of coniferous spruce trees, along with mammoths, short-faced bears bigger than grizzly bears, camels larger than today's two-humped Bactrian camels, dire wolves, and large, lumbering ground sloths. Add to your image a small hunting party of Clovis people—men and women dressed in fur clothing with large spears, waiting near a watering hole for an unsuspecting mammoth (Figures 14.18 and 14.19). This would have been a typical day toward the end of the Ice Age, the Pleistocene Epoch, around 12,800 years ago. Along the horizon to the north, you would have seen the massive white and blue Laurentide ice sheet, a vast continental glacier about 100 m (~330 ft.) high at its edges. Returning to the same area just years later, you would find that everything has changed—the large animals and people are gone, and the ice sheet has advanced a considerable distance; a glacial interval has begun, known as the *Younger Dryas*—a geologically abrupt period of even colder climatic conditions that lasted about 1,300 years, named after tundra fossil pollen of the dryas plant.[20,21] What happened? This is a question that has perplexed geologists, paleontologists, and archeologists for more than two centuries.

Until the 1790s, most scientists and scholars didn't seriously entertain the idea that large Ice Age mammals, such as the mammoths and mastodons, were extinct. Even President Thomas Jefferson, who had written about the buried remains of a ground sloth found in West Virginia, thought that the large animals might be alive somewhere in the western frontier. It wasn't until 1796 that the French naturalist Georges Cuvier demonstrated that mammoths and mastodons, relatives of elephants, were indeed extinct.[22]



< FIGURE 14.18 Mastodons Die in Mass Extinction

Large mammals, such as these mastodons in an Indiana bog, roamed North America at the end of the Pleistocene Epoch. They, and their elephant relatives, the mammoths, disappeared in a mass extinction at the end of the Pleistocene. A new hypothesis proposes that an airburst of a comet over the Laurentide ice sheet contributed to their extinction. *(Daniel Eskridge/Stocktrek Images/Getty Images)*



^ FIGURE 14.19 Clovis Projectile Points

The Clovis people fashioned distinctive fluted projectile points from chert and used them as spear tips and butchering knives to hunt and butcher mammoths, mastodons, and other now extinct animals. For several centuries, this technology was widespread in North America until it disappeared around 12,900 years ago at the start of the Younger Dryas glaciation. *(Robert McGouey/Alamy)*

The possible cause of the extinction of the megafauna and the termination of the Clovis culture has been a longstanding and controversial subject. Major competing hypotheses to explain the extinction of the megafauna are (1) overkill by humans; (2) abrupt cooling (i.e., rapid climate change); and (3) extraterrestrial impact.

The first hypothesis has shortcomings. Human overkill seems unlikely in light of the large numbers of animals that became extinct, including many species that the paleoamericans evidently did not regularly hunt. Abrupt cooling definitely happened, but only at higher latitudes; what is being debated is the cause. Was the cooling due to regular climate shifts that have occurred frequently during Earth's history, or was it something very different?[20]

The conclusion is that the extinction of Pleistocene megafauna during the latest Pleistocene period was unique and was too abrupt and too widely distributed to have resulted from human overkill or climatic cooling.[20]

At many Clovis sites, archaeologists have identified what is known as a "black mat," a thin layer of carbonaceous, dark, organic-rich clays (Figure 14.20). The base of the black mat coincides with the Younger Dryas Boundary (YDB), the geologic boundary between earth material older and younger than 12,800 years ago, after which there is no evidence for "in-place" remains of the megafauna or artifacts from the Clovis culture. Murray Springs, Arizona, is a well-known and well-studied Clovis site, where the last (youngest) mammoth bones and Clovis tools are directly in contact with the base of the black layer. At that site it is apparent that the termination of Pleistocene megafauna and Clovis culture was sudden, coinciding with the beginning of deposition of the black mat.[20,23,24]

Another geologic mystery about the time of the Younger Dryas is the thousand-yearlong Younger Dryas cooling episode that brought the Pleistocene Epoch to a close. Several events occurred at the YDB that suggest that the Laurentide, European (Fennoscandian) and Greenland ice sheets that once covered parts of the Northern Hemisphere became especially unstable:

> Meltwater drainage from a huge North American glacial lake, Lake Agassiz, shifted abruptly from the Mississippi to other outlets via the St. Lawrence River to the Atlantic Ocean and the McKenzie River to the Arctic Ocean.



< FIGURE 14.20 Black Layer at the Younger Dryas Boundary
Called the "black mat," this carbon-rich layer at the Murray Springs, Arizona, mammoth-kill site is draped over mammoth bones that were butchered by Clovis hunters. The base of the black mat (white arrow) contains a layer (the Younger Dryas boundary) with abundant materials of cosmic impact origin. A black layer of similar composition marks this Younger Dryas boundary in many places in North America and Europe. *(GeoScience Consulting)*

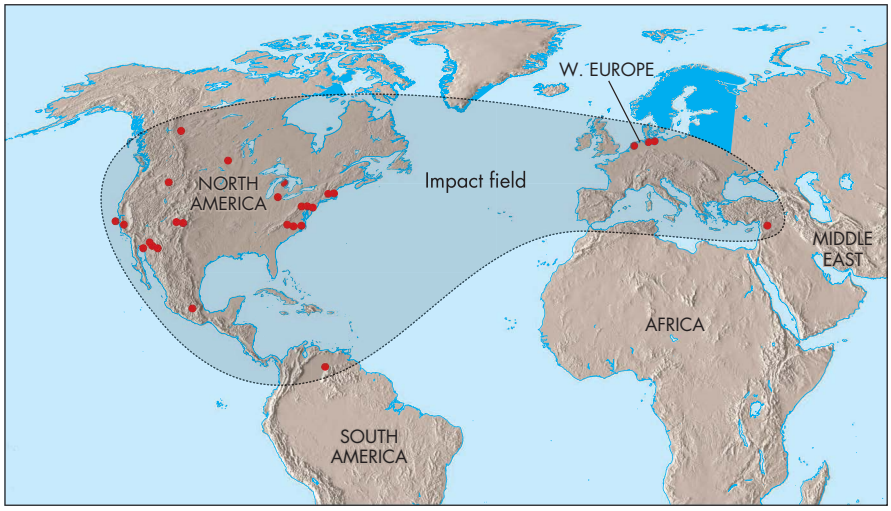
- All the margins of the ice sheet began to destabilize and melt rapidly with significant freshwater discharge into the surrounding oceans.
- A large armada of icebergs calved off the ice sheets and floated south into the North Atlantic.
- This polar and subpolar freshwater cap caused a major reduction in the Atlantic Ocean conveyor belt, the ocean current system that moderates temperatures in southern Greenland and Europe (see Chapter 12).[20]
- Massive, abrupt cooling over much of the Northern Hemisphere outside of the tropics, with a return to near ice-age climate.

What caused this unusual combination of abrupt ice-sheet melting and instability that coincided with climatic cooling? A theory has been proposed that explains the major and abrupt extinction of Pleistocene megafauna, the disappearance of the Clovis culture, and destabilization of the ice sheet were triggered by an extraterrestrial (cosmic) impact at the YDB 12,800 years ago.

Evaluation of several Clovis sites, selected because they were well documented and dated, supports the hypothesis of a major extraterrestrial impact ~12,800 years ago. Evidence of such an event is found on four continents (North America, South America, Western Europe, Western Asia as well as in the Greenland ice sheet (Figure 14.21); Many sites are in North America including Santa Rosa Island in the Santa Barbara Channel, California.[25,26]

Analysis of over 300 dates from 23 locations has pinned down the event to be with 95 percent confidence at 12,835–12,735 Years ago (CalB.P.)[27] This means that the date of the YDB event is likely a worldwide time marker, a so-called datum horizon, that is synchronous and can be traced over at least four continents.

Existing evidence suggests that the YDB Episode was triggered by the impacts of many low-density



< FIGURE 14.21 Possible Younger Dryas Impact Field
Red dots show 27 sites where evidence has been collected for the ~12,800-year-old YDB impact. *(Modified after Wittke, J. H. and 27 others. 2013. Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 years ago.* Proceedings of the Natural Academy of Sciences. *PNAS early edition. pnas.org/cgi/doi10.1073/pnas.)*

extraterrestrial objects (from a fragmented comet) that exploded widely in the atmosphere over the Northern Hemisphere including the Great Lakes Region. The Laurentide ice sheet covering much of Canada became partially destabilized by the proposed event, especially at its edges, and consequently released its meltwater from proglacial lakes to the oceans. Scientists hypothesize that many objects exploded over the continents and the ice sheet, setting off heat flashes and shock waves and generating intense winds (hundreds of kilometers per hour) over wide areas of Earth. The event also would have spawned fireballs leading to widespread biomass burning. This led to habit loss through destruction of forests and grasslands. Also, the soot and ash produced by the biomass burning was so abundant and dense that it blocked sunlight for days to weeks with loss of photosynthesis and food production. These factors in combination with the abrupt cooling led to the extinction of many of the large Pleistocene animals.[20]

Physical evidence for a cosmic impact at the Younger Dryas boundary includes the discovery of a variety of markers that resulted from cosmic impact, including high temperature meltglass and magnetic microspherules, carbon spherules, charcoal and soot, and other evidence of intense wildfires.[26] Also an abundance peak of nanodiamonds (including those thought to be formed only by cosmic impact) has been identified in the impact layer compared with their relative scarcity in sediments above and below. Crucially, analysis of ice from the Greenland ice sheet at precisely the beginning of the Younger Dryas identified a major platinum (Pt) abundance anomaly (peak) that was caused by the impacting comet. Following the discovery of the Pt anomaly in the Greenland ice sheet, several sites in the USA where the YDB had been reliably located by careful C-14 dating (see Appendix D) were revisited in search of the Pt anomaly. The Pt anomaly was identified in four well-dated sites in the western USA and Ohio. Also the anomaly was identified in another seven sites the along the U.S. eastern seaboard at a level considered to be the YD onset (and the YDB layer) based mostly on archaeological changes[28,29]

The discovery of the Pt anomaly in the Greenland ice sheet and subsequently in other terrestrial sites is the most convincing evidence yet of the YDB impact event. The previous careful work on the YDB sites in North America and Europe allowed researchers to test exactly the right levels in the ice sheet in search of cosmic impact evidence. The resulting fortuitous discovery of the Pt abundance anomaly in the ice sheet in turn prompted a search, and its subsequent discovery, in terrestrial sites. This research is a clear illustration of how scientific work progresses from one discovery leading to others.

As scientists continue to test YDB theory, more data will be forthcoming, and we will learn more about the catastrophic event that brought about the demise of the Pleistocene megafauna, the end of the Clovis culture, and the anomalous abrupt return to near-glacial conditions that lasted for about 1,000 years.[20,30] As the hypothesis continues to be thoroughly tested, it is likely that more direct physical evidence of the cosmic impact will be discovered including the possible discovery of large impact craters hidden on the ocean floor and/or under the ice sheets. Recently a young 30 km (19 mi.) diameter crater was discovered in northern Greenland. Although the date of this crater is not known, the impact likely occurred less than 100,000 years ago and could be as young as ~13,000 years old.

The discovery of the YDB event has important implications for recent human history. Evidence exists for human population declines in North America and Western Europe that coincided with significant cultural shifts in the hunter/gatherers of that time. In North America the broadly distributed successful Clovis culture suddenly disappeared, and, following a hiatus in human activity over broad areas, was replaced by a diversity of local cultures. In Western Europe, cultures known for their cave paintings declined; and in Syria, agriculture began as hunter-gatherer groups changed to hunter-cultivator societies. The harsh times of the cold and drier Younger Dryas evidently made food gathering more difficult and uncertain compared to the deliberate cultivation of crops.[26]

If the theory is confirmed, as the bulk of the evidence suggests, it perhaps may be considered as the most important theory advanced since that of plate tectonics revolution in the late 1960s. Should such a cataclysmic event occur in the future, civilization as we know it would almost certainly disappear (see Case Study 14.4: Professional Profile).

14.3 CHECK your understanding

1. Define *mass extinction*.
2. What are the hypotheses for the cause of mass extinctions?
3. When was the greatest mass extinction in Earth's history?
4. What is the cause of the K-Pg mass extinction, and what is the main evidence to support the event?
5. What is the main evidence supporting the hypothesized Younger Dryas impact event?
6. Assuming that the hypothesized Younger Dryas impact is correct, what would the consequences be if such an event were to happen in the future?

CASE study

14.4 Professional Profile

Emeritus Professor James Kennett, University of California, Santa Barbara

Professor James Kennett (Figure 14.4A) was born and received his early education in Wellington, New Zealand. The wonderful geologic exposures of his native country, especially in the Nelson area where his grandparents farmed, fostered a boyhood interest in geology. Kennett received B.S. and Ph.D. degrees at Victoria University of Wellington where he began to meld his interests in marine geology and the history of life. Kennett and his wife Diana immigrated to the United States in 1966 expressly to participate in the great American science enterprise then blossoming.

A member of the U.S. National Academy of Sciences, Kennett is a world leader in marine geology. He has published over 250 papers and four books. In 1982 he published the now classic college textbook *Marine Geology*, which is a major synthesis within a plate tectonic framework of Earth's oceanographic and climatic evolution. Kennett is considered a pioneer in developing paleo-oceanography (integrative studies of past ocean history) as a new field. The thread tying his discoveries together is a fundamental understanding of the evolution of the global environment, in particular climate and ocean circulation and their effects on the development of life, especially marine life.

Jim Kennett says he has been blessed by being associated with many wonderful graduate and undergraduate students and by being closely linked with colleagues who have helped discover much about how our Earth has operated in its past. He has been a major advisor to 20 doctorate and numerous Master's students, many of whom have contributed enormously to our understanding of the Earth's environmental evolution.

Kennett's work is notable for creating and testing a number of innovative hypotheses, including the potential role of marine methane emissions in influencing abrupt climate change. His questions are often controversial, as is the case for most new scientific ideas that precipitate a paradigm shift. Kennett tests important hypotheses that change the way we perceive how Earth works, and he is a master of the scientific method that calls for careful collection and analysis of data.



< FIGURE 14.4.A Professor James Kennett
Kennett in the remarkable Takoro Canyon of Southern Taiwan, which has some of the highest rates of tectonic uplift in the world. While in Taiwan, Jim presented his first lecture at the National Taiwan University about the YDB Impact hypothesis. *(Photograph courtesy of James Kennett)*

Over the last 17 years, Kennett and his many colleagues (especially Allen West, Ted Bunch, and his son, Douglas Kennett) have been addressing the question (hypothesis) of whether or not a major cosmic impact (possibly consisting of many airbursts) 12,800 years ago caused a wide range of otherwise enigmatic environmental and biologic changes on Earth. This YDB cosmic impact hypothesis is posited to have triggered an abrupt and anomalous cooling at the onset of the Younger Dryas, the extinction of the majority of the large North American Ice Age animals, and abrupt human cultural and population changes in the Americas and Europe and parts of the Middle East. Such an event in the future would end civilization as we know it.

The hypothesis of a major cosmic impact occurring only a few thousand years ago and causing major environmental, biotic, and human consequences, is perhaps the most important geologic and anthropologic discovery in decades. It may well explain a wide range of enigmatic events that have puzzled scientists for years: abrupt climate cooling when Earth should have remained warm; abrupt extinction of most of the large and abundant mammals over North America, including mammoths, giant sloths, camels, and horses; abrupt changes in human culture (including the disappearance of the widely distributed Clovis culture over North America and the cave-painting Magdelanian culture of Western Europe), in association with clear reductions in human population over broad regions; and the rise of agriculture in Syria. Kennett continues to point out that, although a wide range of data now supports a major cosmic impact (e.g., peak abundances in nanodiamonds, high-temperature melt-glass and spherules, platinum) at many sites on land in North America, Western Europe, Syria, and the Greenland ice sheet (a giant depository of material settling out of the atmosphere), this hypothesis requires further testing and evaluation.

14.4 Linkages with Other Natural Hazards

The impact or airburst of an asteroid or comet is a direct cause for a number of other natural hazards, including tsunamis, wildfires, earthquakes, mass wasting, climate change, and, possibly, volcanic eruptions. Most impacting objects land in the world's oceans, and large objects will cause tsunamis. The asteroid that hit the Yucatán Peninsula close to 65 million years ago created large, complex tsunamis that spread across the Gulf of Mexico and are recorded in sedimentary deposits in Mexico, Texas, Alabama, and Cuba. Researchers have estimated that waves 200–300 m (~660–1000 ft.) high originated from the impact blast and subsequent landslides in the Gulf of Mexico.[19]

Wildfires of regional or global extent have resulted from three well-documented airbursts or impact events: the K-Pg boundary, the Younger Dryas boundary, and the Tunguska events. Superheated clouds of gas and debris apparently reach temperatures capable of drying out and then igniting living vegetation. Computer simulations suggest that wildfire patterns following a large impact are complex and involve rock blasted into space that then returns to Earth on the other side of the planet. If it is any consolation, the simulations suggest that these wildfires did not burn the entire land surface of Earth.[13]

Seismic waves from a large impact most likely activate numerous landslides, both on the land and under the water. For example, the asteroid that formed the Chicxulub impact on the Yucatán Peninsula appears to have produced a **M** 10 earthquake and caused the mass wasting of the continental slope of North America as far north as the Grand Banks of Newfoundland.[22]

Both the asteroid that created the Chicxulub Crater at the K-Pg boundary and the probable airburst at the end of the Pleistocene Epoch caused global changes in climate. Impacts on land can inject large quantities of dust into the atmosphere. This dust, combined with smoke from wildfires, would result in global cooling for a number of years after any major impact. The global cooling would then be followed by a prolonged period of global warming from the large amounts of carbon dioxide and other greenhouse gases produced by post-impact wildfires.[13]

Extraterrestrial impacts have also been hypothesized to produce large volcanic eruptions by causing melting and instability in Earth's mantle.[31] This melting could result in huge eruptions of lava, referred to as flood basalts, and create large igneous provinces on land. These provinces contain 100 times more lava than from any historic volcanic eruptions.[32] In the geologic past, these eruptions appear to have produced global changes to the atmosphere and oceans and contributed to major extinctions of life.

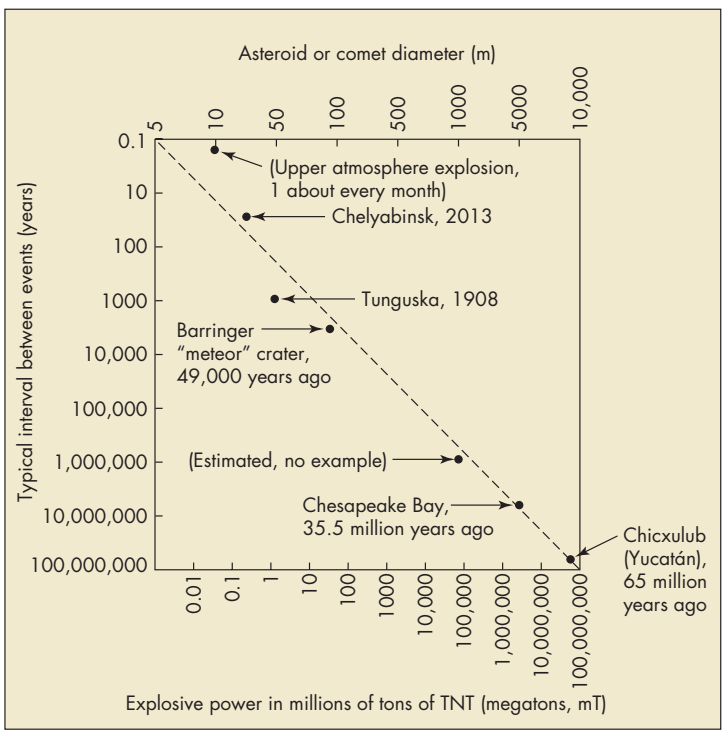
14.4 CHECK your understanding

1. Explain the various hazards linked to a large extraterrestrial impact in the future.

14.5 Minimizing the Impact Hazard

RISK RELATED TO IMPACTS

The total risk of a hazardous event is related both to the probability that it will occur and to the consequences, should it take place. Consequences include the concepts of resiliency, exposure, vulnerability, adaption, mitigation, hazard perception, and social media. Thus, risk can be thought of as the product of hazard, exposure, and vulnerability (see Figure 1.11). The consequences of a large airburst or direct impact from a large extraterrestrial object several kilometers in diameter would be catastrophic. Although seven out of ten such events would likely occur over or in the oceans, the enormous size of an asteroid or comet would mean that the effects would be felt worldwide. Certainly, there would be significant differences, depending on the site of impact or airburst, but the overall consequences would constitute a global catastrophe with high potential for mass extinction. On Earth, events of this magnitude probably have return periods of tens to hundreds of millions of years (Figure 14.22). Smaller objects, on the order of a few tens of meters, would cause a regional catastrophe if they produced an airburst or surface impact near a populated area. The size of the devastated area would be on the order of several thousand square kilometers. Even a small impact could result in millions of deaths if the event occurred over or in an urban region. Smaller but regionally significant events are sometimes called "Tunguska-type" events, after the 1908 airburst in Siberia.



▲ FIGURE 14.22 Energy from Impact
Estimate of the relationship between the energy of Earth impact and time interval between events for various sizes of asteroids or comets. Also shown is the estimated diameter for the impacting comet or asteroid. *(Based on Weissman, P. R., McFadden, L., and Johnson, T. V., eds.,* Encyclopedia of the Solar System. *San Diego, CA: Academic Press, 1999; and Brown, P., Spalding, R. E., ReVelle, D. O., Tagliaferri, E., and Worden, S. P., "The Flux of Near-Earth Objects Colliding with the Earth," Nature 420: 294–96, 2002.)*

Airbursts from asteroids with diameters of about 50 to 100 m (~165 to 330 ft.) are capable of causing catastrophic damages to a region about every 1000 years (Figure 14.22). Using the Tunguska event as typical of one that could occur on our planet every thousand years, an urban area is likely to be destroyed every few tens of thousands of years. The basis for this assessment comes from the distribution of 300 small asteroids known to have exploded in the atmosphere. Extrapolation of the data allows estimates to be made for larger, more damaging events.[7]

Predictions of the likelihood and type of future impacts contain enormous statistical uncertainty. Deaths caused by an impact during a typical century may range from zero to as high as several hundred thousand. Computer-run simulations suggest that during a given century, approximately 450 deaths per year may be attributed to an impact. A truly catastrophic event could kill millions of people; averaging this number over thousands of years produces a relatively high average annual death toll.

MINIMIZING THE IMPACT HAZARD

It is only recently that scientists and policy makers have appreciated the risk of an impact of an asteroid or comet. Are we

helpless, or is there something that can be done to minimize the hazard? The first and foremost need is to identify nearby objects in our solar system that might threaten Earth. Identification and categorization of comets and asteroids that cross Earth's orbit are already in progress and could be scaled up to include objects in smaller size classes. The additional size classes would include objects with diameters less than 50 m (~160 ft.), those 50 meters to several hundred meters, and those with a diameter of several kilometers. A program known as Spacewatch, which has been operating since 1981, is attempting to inventory the region surrounding Earth, with expansion to the entire solar system. Another program, known as the Near-Earth Asteroid Tracking Project (NEAT), was started in 1996. The objective of this program, which is supported by the National Aeronautical and Space Administration (NASA), is to study the size distribution and dynamic processes associated with **near-Earth objects** (NEOs) and, specifically, to identify those objects with a diameter greater than 1 km (~3300 ft.).

NEOs either reside and orbit between Earth and the sun or have orbits that intersect with Earth's orbit. Although these objects include numerous meteoroids, asteroids, and comets, only the asteroids and comets that are tens of meters to a few kilometers in diameter are a significant hazard (Figure 14.23). If a NEO with a diameter of a few tens of meters were to burst in the atmosphere or impact Earth's surface, we would experience a Tunguska-type event of regional destruction. A NEO of several kilometers in diameter would cause a global catastrophe.

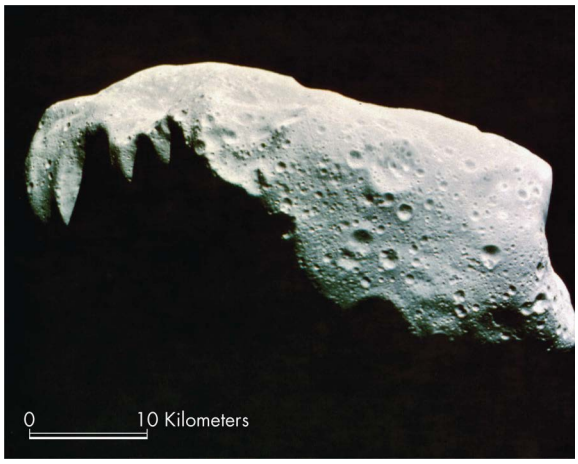


FIGURE 14.23 Asteroid 243 Ida
Numerous impact craters on the surface of asteroid 243 Ida show that collisions between objects in the asteroid belt are common. Ida is approximately 52 km (~32 mi.) long and orbits the sun at a distance of 441 million km (~274 million mi.). It takes nearly five years for Ida to complete one orbit of the sun. Photograph taken by the NASA Galileo spacecraft in 1993. *(JPL/NASA)*

As mentioned earlier, most asteroids originate in the asteroid belt located between Mars and Jupiter (see Figure 14.5). If an asteroid remains in the belt, it does not become a NEO; however, if an asteroid is disturbed by a collision or by the gravitational pull of Jupiter, its orbit may become more elliptical, crossing Earth's orbit, or enter the space between the sun and Earth. The current estimate of Earth-crossing asteroids with diameters larger than 100 m (~330 ft.) is close to 85,000. Larger Earth-crossing asteroids are scarcer. An estimated 1,100 have a diameter greater than 1 km (~3300 ft.), and 30 are greater than 5 km (~3 mi.).[33]

Comets, the other type of NEO, are generally a few kilometers in diameter and have an expanding stream of gas and dust that produces a spherical cloud around the comet. A tail of gas and dust is "blown" out from the cloud by the force of solar radiation, sometimes called the solar wind; thus, the tail is always directed away from the sun. Many of the dust and gas particles burn up in the atmosphere when Earth's orbit passes through a comet's tail. This creates streams of meteors, referred to as a meteor shower. Halley's Comet is the most famous and perhaps the best studied of all comets because of a 1986 spacecraft mission to observe it. The expedition found that the comet is a fluffy, porous body with little strength. In fact, the entire nucleus of Halley's Comet is about 20 percent ice and, therefore, it must have 80 percent empty space, consisting of a network of cracks and voids between loosely cemented materials.[4] Halley's Comet visits the space above Earth approximately once every 76 years, giving every generation a chance to view it. Of the 10,000 NEOs identified as of July 2013, only 93 of the objects have a gaseous tail when they approach the sun and are classified as comets.[34] An estimated 15 percent of the other objects are thought to be extinct comet nuclei that no longer generate a tail when heated by solar radiation.[33]

NEOs, both asteroids and comets, apparently have a relatively short life span. Consequently, new NEOs must continuously be ejected from the asteroid belt to explain the large number thus far identified. Likewise, the orbits of some comets from the outer solar system are perturbed by planets or other objects and eventually become NEOs as well.

NEO observation programs utilize telescopes with digital imaging devices. Using these devices, astronomers take three to five images of a given area of the night sky at intervals of 10 to 60 minutes. Computer software is then used to compare the images to identify

fast moving objects.[31–33,35] The programs and systems used to identify NEOs are expected to intensify in the future, and increasing numbers of objects will be cataloged. This is a first step toward evaluating the potential hazard from NEOs. However, evaluation will take a long time because many of the objects have orbits that may not bring them close to Earth for decades, and the average amount of time between potentially catastrophic impacts is at least thousands of years for the smallest objects. The good news is that most of the objects identified as being potentially hazardous to Earth will likely not collide with our planet until several thousand years after they have been discovered. Therefore, we will have an extended period of time to learn about a particular extraterrestrial object and attempt to develop appropriate technology to minimize the hazard.[4]

By one estimate, about 20 million extraterrestrial bodies in near-Earth orbits have the potential for a significant impact.[4] Only about 4 percent of these bodies are likely to penetrate Earth's atmosphere and excavate a crater. More than half are structurally weak and prone to explode at altitudes of about 30 km (~19 mi.) above Earth's surface. Although these explosions are spectacular, they are not a significant hazard at the surface of Earth. The remaining objects, which constitute about 40 percent of the total population of objects, are moderately strong, stony asteroids (see Table 14.1). These relatively slow moving asteroids can penetrate the atmosphere and produce a serious threat at the surface of Earth. Such bodies produce Tunguska-type events.

Identifying all these objects will be extremely difficult; with a diameter of only 25 m (~80 ft.), they are difficult to identify and track.[4] It is currently impossible for us to identify and catalog the estimated 10 million small asteroids or comets. We are much better prepared to identify and track objects of a few hundred meters to a kilometer or so in diameter. In 2007, NASA proposed to Congress that existing surveys be extended in order to identify 90 percent of potentially hazardous NEOs greater than 140 m (~460 ft.) in size by 2020.[33]

As survey efforts to identify smaller objects increase, more NEOs that are potentially hazardous to Earth will be detected. Communication of this hazard to the public and public officials must be both timely and authoritative. As with earthquake predictions, pending impacts must be evaluated by committees of scientists before predictions should be acted upon. The International Astronomical Union established a technical review process for predictions, which has had mixed results.[36] NASA's NEO Program Office maintains a website (http://neo.jpl.nasa.gov) that classifies potentially hazardous NEOs, based on the Torino Impact Hazard Scale (Table 14.3).

Once a large NEO is recognized to be on a collision path with our planet, options available to avoid or minimize the hazard from an airburst or crater-forming event

TABLE 14.3 The Torino Impact Hazard Scale

No Hazard	0	Low collision hazard or object will burn up in atmosphere.
Normal	1	Object will pass near Earth with collision extremely unlikely.
	2	Somewhat close encounter; collision unlikely and does not merit public attention.
Merits Attention by Astronomers	3	Close encounter with localized destruction possible; merits public attention if collision less than a decade away.
	4	Close encounter with regional destruction possible; merits public attention if collision less than a decade away.
	5	Close encounter with serious, but uncertain, regional destruction threat; merits contingency planning if less than a decade away.
Threatening	6	Close encounter with serious, but uncertain, global catastrophe threat; merits contingency planning if less than three decades away.
	7	Very close encounter with unprecedented, but still uncertain, global catastrophe threat; merits international contingency planning if less than a century away.
	8	Collision will occur with object capable of localized destruction on land or tsunami if offshore; once every 50 to 100 years.
Certain Collisions	9	Collision will occur with object capable of regional devastation or major tsunami; once every 10,000 to 100,000 years.
	10	Collision will occur with object capable of global climatic catastrophe that threatens civilization; once every 100,000 years or more.

Source: Based on Morrison, D., Chapman, C. R., Steel, D., and Binzel, R. P. "Impacts and the Public: Communicating the Nature of the Impact Hazard," in *Mitigation of Hazardous Comets and Asteroids*, ed. M. J. S. Belton, T. H. Morgan, N. H. Samarasinha, and D. K. Yeomans, pp. 353–90. New York: Cambridge University Press, 2004.

are somewhat limited. The largest events are the real killers, and there would be no safe place on the planet. All living things within the blast area would be killed immediately; those farther away are likely to be killed in the ensuing months from the cold and the destruction of the food chain. Even if we could identify and intercept the object, blowing it apart into smaller pieces would likely cause more damage than would one impact from the larger body because each of the smaller pieces, some of which would become radioactive in the explosion, would rain down upon Earth. A more plausible approach would be to try to gently divert the object so that it misses Earth. Let's assume we identify a 400 m (~1300 ft.) diameter asteroid that we believe will strike Earth in approximately 100 years. In all likelihood, the body has been crossing Earth's orbit for millions of years without an impact, and if it were possible to slightly nudge it and change its orbit, it would miss, rather than strike, Earth. This scenario is not unlikely because the probability that we would identify the object at least 100 years before impact is about 99 percent. We have the technology to change the orbit of a threatening asteroid with small nuclear explosions that are close enough to the asteroid to nudge it, but far enough away to avoid breaking it up. NASA has determined that such a "standoff" explosion would be 10 to 100 times more effective than non-nuclear alternatives, such as pulsed lasers or focused solar radiation, in changing the orbit of a potentially hazardous object.[36] To do so would require a coordinated mission between the world's military and space agencies, and the cost of such an expedition would likely exceed $1 billion. However, this seems a small price to pay, considering the potential damages from a Tunguska-type event in an urban area.

Another option for smaller events might be evacuation. If, months in advance, we could precisely predict the point of impact, evacuation is theoretically possible. However, evacuating an area of several thousand square kilometers would be a tremendous and likely impossible undertaking.[4]

In summary, we continue to catalog extraterrestrial objects that intersect Earth's orbit. We are beginning to think about our options to minimize the hazard. Given the potential long-term warning before an object would actually strike the surface of Earth, we may be able to devise methods to intercept and minimize the hazard by nudging the object into a different orbit so that it misses Earth.

14.5 CHECK your understanding

1. How is the risk of extraterrestrial impact determined?
2. How might near-Earth objects (NEOs) be identified?
3. Explain how the risk of dying from an asteroid impact is greater than the risk of a car accident.
4. How might the hazard of an extraterrestrial impact be minimized?

APPLYING the 5 Fundamental Concepts

The Chelyabinsk Meteor, February 2013

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

The Chelyabinsk meteor that entered the atmosphere above Russia on February 15, 2013, was a small asteroid, about 18 m (~60 ft.) in size. It entered the atmosphere at a high speed of about 19 km (~13 mi.) per second, exploding at an elevation of about 23 km (~15 mi.) (see chapter-opener photograph and Figure 14.1).[1] That object is the largest known asteroid to have entered Earth's atmosphere since the Tunguska event of 1908, which caused a much wider zone of damage in a remote area of Siberia. The Chelyabinsk meteor, fireball, and blast were video-recorded by numerous people on the ground and were also recorded by sensors monitored by the U.S. government.

Approaching Earth at a low angle (~17°), the Chelyabinsk meteor entered the upper atmosphere and began to slow. Compression

of atmospheric gases in front of the advancing meteor generated massive amounts of heat, causing the meteor to erupt into a fireball as it streaked across the sky before finally exploding and producing a tremendous shock wave. Most of the damage to the more than 7,000 buildings affected by the explosion consisted of blown out windows (Figure 14.24), but the shockwave did cause the roof of a zinc factory to collapse. Numerous small meteorites from the blast fell to Earth; scientists collected some of these from an area near a 6 m (~18 ft.) diameter hole that was found penetrating a frozen lake (Figure 14.25a and b). Eight months later, a 1.5 m (~5 ft.) long meteorite fragment weighing about 600 kg (~1,300 lb.) was recovered from the bottom of the thawed lake. The recovered meteorites are chondritic in composition (see Table 14.1), similar to that of many other meteorites that have been collected around Earth. Meteorite density was about 3.6 g per cm^3 (3.6 times that of water), and the total weight of the Chelyabinsk meteor is estimated at about 11,000 tons.[37]

One of most important aspects of the event is not just the size of the fireball, which was huge, but also the point at which it exploded. The explosion occurred higher in the atmosphere than most airbursts we have observed in recent decades. With the explosive force equivalent to 20 to 30 World War II–type atomic bombs,[1] had the airburst been lower in the atmosphere, say, less than 2500 m (~6500 ft.), catastrophic damage would have resulted. Should such an event occur lower in the atmosphere over a large urban area, millions of deaths could occur. This is a somewhat unnerving thought when you consider that the Chelyabinsk impact was completely unexpected.

Given this potential scenario, what can we do in the future to minimize the hazard from extraterrestrial impacts from objects on the order of a few tens to hundreds of meters or more in diameter? Unfortunately, the answer to that question at the present time is that we can do nothing. However, the effects of an impact could



FIGURE 14.24 Damage from Chelyabinsk Airburst
Broken glass from blown-out windows produced most of the injuries following the Chelyabinsk airburst. *(Andrei Ladygin/Russian Look/MCT/Newscom)*



(a)

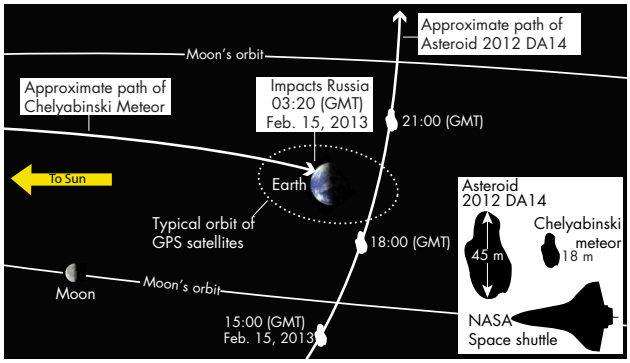


(b)

FIGURE 14.25 Chelyabinsk Impact
(a) Small fragments (note number in circle on paper) of the Chelyabinsk meteorite *(Krasilnikov/ZUMA Press/Newscom)*; (b) Holes in ice covering a lake where a meteorite fragment hit. *(epa European pressphoto agency by b.v./Alamy)*

be minimized if we were able to predict when and where a strike might occur and if there was enough time to evacuate.

As mentioned in the chapter opener, at the time of the Chelyabinsk impact, astrophysicists from around the world were watching asteroid 2012 DA14, which was to pass by Earth later that day. Since its discovery the previous year, scientists had been closely tracking 2012 DA14 because its orbit intersected Earth's. Nearly three times the size of the Chelyabinsk meteor, a direct impact from 2012 DA14 would be catastrophic. Fortunately, astrophysicists were able to quickly calculate its trajectory and determine that the asteroid would not impact Earth on this orbit, but its path would bring it within 30,000 km (~19,000 mi.) of Earth, close enough to pass between us and our global positioning satellites. Having dodged the proverbial bullet, scientists were focused on collecting as much data from the close fly by of 2012 DA14 as possible, when Chelyabinsk hit us from behind. Given the infrequency of large Earth-crossing extraterrestrial objects, it is difficult to believe that these two meteors passing Earth within 16 hours of each other are not somehow related. However, analysis of the Chelyabinsk meteor trajectory clearly shows that its orbit was unrelated to that of 2012 DA14 (Figure 14.26).



▲ FIGURE 14.26 Cosmic Coincidence
Just 16 hours after the Chelyabinski meteor exploded above Russia, Asteroid 2013 DA14 passed beneath the orbits of Earth's Global Positioning Satellite (GPS) network. Although closely timed, the distinctly different paths of the two asteroids indicates that the objects were not related to one another.

So how is it that we were able to track astroid 2012 DA14 for an entire year and completely miss the Chelyabinsk meteor? These smaller objects, although capable of catastrophic damage, are not easily identified. The U.S. Congress has mandated a program that calls for NASA to identify 90 percent of those objects that are 150 m and larger in diameter. However, funds appropriated to do so have been insufficient to date. The technology, however, is available, and as it improves, it could identify these larger objects and eventually allow for even smaller NEOs to be recognized. Once they are identified and if time were permitting, the effects of an impact could be minimized by evacuation of the impact area. It may even be possible to intercept the object and attempt to deflect its orbit such that it would not strike Earth.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. Scientific advances allow us to monitor large asteroids crossing Earth's orbit. Discuss why the Chelyabinsk event came as a surprise.
2. Given what you know about our ability to identify and track asteroids that have potential to inflict catastrophic damage to Earth, discuss the risk we face from extraterrestrial impacts of varying sizes.
3. What other hazards could have been linked to an airburst or impact event on the scale of the Chelyabinsk meteor event?
4. The Chelyabinsk meteor is the only meteor known to have caused a large number of injuries. How is population and land use linked to human injuries, deaths, and economic losses from small extraterrestrial impacts?
5. Assuming that the next extraterrestrial impact can be predicted, how might loss of lives and property from these impacts be minimized?

CONCEPTS in review

14.1 Earth's Place in Space

LO:1 Differentiate between asteroids, meteoroids, and comets.

- The evolution of Earth most likely started about 14 billion years ago with the so-called explosion of the "Big Bang" that produced atomic particles that later formed galaxies, stars, and planets. Our sun formed about 5 billion years ago from a solar nebula, and Earth formed about 4.6 billion years ago.
- Asteroids, meteoroids, and comets are extraterrestrial objects that can intercept Earth's orbit. Small objects may burn up in the atmosphere and be visible as meteors at night. Depending on their size, velocity, and composition, large objects from a few cm to 1000 km in size may disintegrate in the atmosphere in an airburst or hit the surface of Earth as a meteorite.



KEY WORDS

asteroid (p. 560), **comet** (p. 562), **meteor** (p. 562), **meteoroid** (p. 562)

14.2 Airbursts and Impacts

LO:2 Describe the physical processes associated with airbursts and impact craters.

- A meteoroid entering the atmosphere at about 85 km (53 mi.) above Earth's surface at a velocity of 12–72 km per second (~7 to 45 mi per second) will become a meteor and emit light. It will then either explode in an airburst in the atmosphere at an altitude of 12–50 km (~7–31 mi.) or collide with Earth.
- Objects that impact Earth's surface produce both simple and complex craters. Many craters have yet to be identified because they are severely eroded, lie on the seafloor, or are buried by more recent deposits.



KEY WORDS

airburst (p. 564), **impact crater** (p. 566), **meteorite** (p. 564)

14.3 and 14.4 Mass Extinctions Linkages with Other Natural Hazards

LO:3 Suggest the possible causes of mass extinction and provide examples.

LO:4 Evaluate the evidence for the impact hypothesis that produced the mass extinction at the end of the Cretaceous Period.

- Large objects can cause local to global catastrophic damage and mass extinction of life. The best-documented impact occurred 65 million years ago at the end of the Cretaceous Period (K-Pg



KEY WORDS

mass extinction (p. 571)

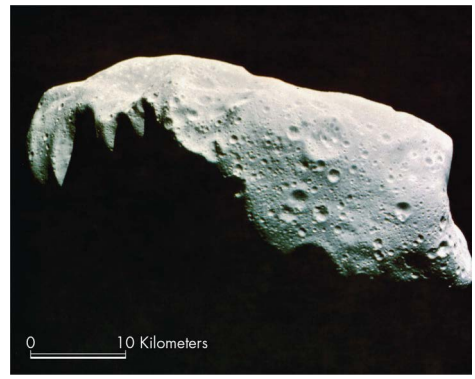
boundary) and likely produced the mass extinction of many species, including the large dinosaurs.
- Recent studies suggest that an airburst may have been responsible for the extinction of many large Pleistocene mammals and the disappearance of the Clovis people at the start of the Younger Dryas period 12,800 years ago.
- Many linkages exist between impacts of comets and asteroids with Earth and other natural hazards. For example, a hit in the ocean can cause a tsunami. An impact on land would cause large-scale fires across the landscape. Linkages to atmospheric hazards would include cooling of the atmosphere, acid rain, and fallout of particulates that would be harmful to life. A truly large comet or asteroid could be what is sometimes termed a "planet cleansing" event that would cause mass extinction of much of the life on Earth.

14.5 Minimizing the Impact Hazard

LO:5 List the physical, chemical, and biological consequences of an impact from a large asteroid or comet.

LO:6 Analyze the risk of impact or airburst of extraterrestrial objects and suggest how that risk might be minimized.

- Risk assessment is difficult for events with long return periods (in this case, large objects striking Earth). Nevertheless, the potential consequences from an impact of a large comet or asteroid are so large that the product of the probability of occurring, which is very small, and the likelihood of major, worldwide exposure and vulnerability, which are regional to global, produces a relatively large risk, compared to other hazards that we normally think about. However, the probability of such an impact is so low in any one year that it is beyond our ability to comprehend the event ever happening.
- Sufficient studies of comets and asteroids and their interaction with planets enable us to make fairly straightforward predictions of the return time when an object of a particular size would impact Earth. For example, an event the size of Tunguska occurs on average every 1,000 years. On the other hand, the return period for an impact of an asteroid the size of the one that struck the Yucatán Peninsula 65 million years ago occurs approximately every 100 million years. Because the consequences of being struck by a large asteroid or comet are so great, there is an effort to identify near-Earth objects, and an impact hazard scale has been developed.
- Programs such as Spacewatch and NEAT (Near-Earth Asteroid Tracking) can, with high certainty, identify NEOs of diameters greater than a few hundred meters at least 100 years before possible impact. There are about 10 million smaller, potential Tunguska-type objects that could produce catastrophic damage to urban areas. Identifying all these objects will be extremely difficult. Thus, we are particularly vulnerable to impacts from these smaller objects.



KEY WORDS

near-Earth objects (p. 583)

- The human population of Earth today is about 7 billion, compared to about 1 billion in 1830. Thus, an event in 1830 that might have killed a million people would likely kill more than 10 million people today.
- The most encouraging note is that a large comet or asteroid would probably be seen a hundred years or more before it is likely to strike Earth. Therefore, we might have time to try to minimize the hazard through a variety of physical means. Smaller events that might catastrophically damage an urban area are more difficult to identify. If we assume that we might see such an object a year or so before impact, there might be time to evacuate if we can accurately predict where it will strike. However, evacuation of large urban centers with millions of people is difficult.

CRITICAL thinking questions

1. Summarize what has been learned from the 1908 impact in Russia.
2. Describe the likely results if a Tunguska-type event, were it to occur over or in central North America. If the event were predicted with 100 years' warning, what could be done to mitigate the effects, if changing the object's orbit were not possible? Outline a plan to minimize death and destruction.
3. How would the effects of an asteroid impact in water differ from those of an asteroid impact on land? Consider what would happen physically and chemically with water and how the impact craters might differ.
4. Compare the velocity of an asteroid or comet, seismic waves, and sound waves. Why do they differ?
5. How did the effects of the impact at the K-Pg boundary differ from the proposed airburst at the Younger Dryas boundary?

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