320 kilometers (200 mi) away (see again Fig. 16.8). Other well-known artesian systems are found in Olympia, Washington; the western Sahara; and eastern Australia's Great Artesian Basin, which is the largest artesian system in the world.

Groundwater Quality

Because most subsurface water percolates down through a considerable amount of soil and rock, by the time it reaches the zone of saturation it is mostly free of clastic sediment. However, it often carries a large amount of minerals and ions dissolved from the materials through which it passed. As a result of this large mineral content, groundwater is often described as "hard water," in comparison with "softer" (less mineralized) rainwater. Moreover, just as increases in population, urbanization, and industrialization have resulted in the pollution of some of our surface waters, they have also resulted in the pollution of some of our groundwater supplies. For example, subsurface water moving through underground mines in certain types of coal deposits that are widespread in the eastern United States becomes highly acidic. If this **acid mine drainage** reaches the surface, it can have very detrimental effects on the local aquatic organisms.

Other dangers to groundwater quality stem from the percolation of toxic substances into the zone of saturation. Excessive applications of pesticides and incompletely sealed surface or subsurface storage facilities for toxic substances, including gasoline and oil, are situations that can lead to groundwater pollution.

In coastal regions with excessive groundwater pumping, denser salt water from the ocean seeps in to fill the voids. This problem with saltwater replacement has occurred in many localities, notably in southern Florida, New York's Long Island, and Israel.

Landform Development by Subsurface Water

In areas where the bedrock is soluble in water, subsurface water is an important agent in shaping landform features at the surface as well as underground. Underground water is a vital ingredient in subsurface chemical weathering processes, and, like surface water, subsurface water dissolves, removes, transports, and deposits materials.

The principal mechanical role of subsurface water in landform development is to encourage mass movement by adding weight and reducing the strength of soil and sediments, thereby contributing to slumps, debris flows, mudflows, and landslides. Through chemical activity, subsurface water contributes to many other and sometimes quite distinctive processes of landform development. Through the chemical removal of rock materials by carbonation and other forms of solution, and the deposition of those materials elsewhere, underground water is an effective land-shaping agent, especially in areas where limestone is present. Subsurface as well as surface water can dissolve limestone through carbonation or simple solution in acidic water. In many of these areas, surface outcrops of limestone are pitted and pockmarked by chemical solution, especially along joints, sometimes forming large, flat, furrowed limestone platforms (● Fig. 16.9). Wherever water can act on any rock type that is significantly soluble in water, a distinctive landscape will develop.

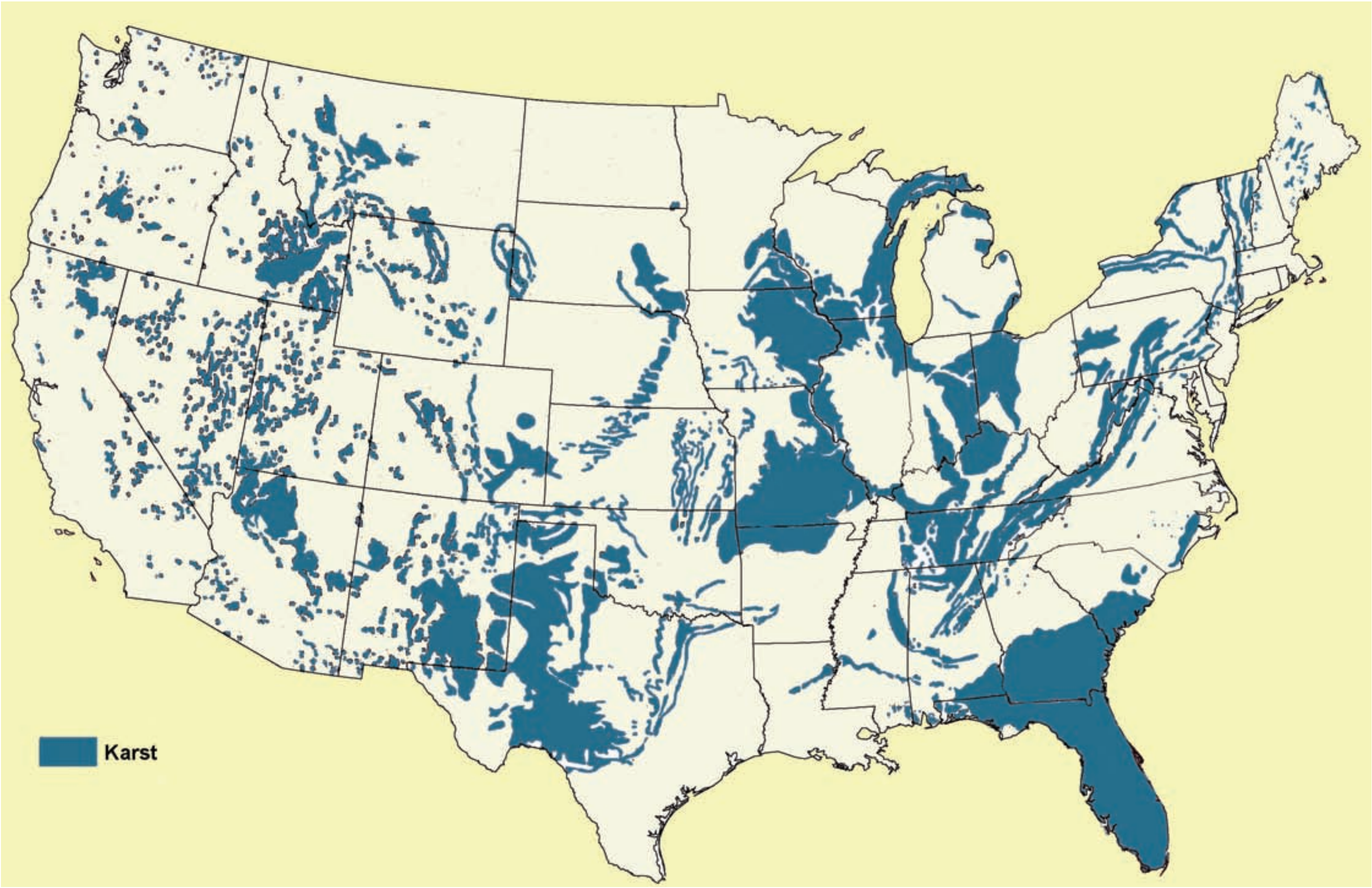
Karst Landscapes and Landforms

Overwhelmingly the most common soluble rock is limestone, the chemical precipitate sedimentary rock composed of calcium carbonate ($CaCO_3$). Landform features created by the solution and reprecipitation (redeposition) of calcium carbonate by surface or subsurface water are found in many parts of the world. The eastern Mediterranean region in particular exhibits large-scale limestone solution features. These are most clearly developed on the Karst Plateau along Croatia's scenic Dalmatian Coast. Landforms developed by solution are therefore called **karst** landforms after this classic locality. Other extensive karst regions are located in Mexico's Yucatán Peninsula, the larger Caribbean islands, central France, southern China, Laos, and many areas of the United States (● Fig. 16.10).

The development of a classic karst landscape, in which solution has been the dominant landforming process, requires several special circumstances. A warm, humid climate with ample precipitation is most conducive to karst development. In arid climates, karst features are typically absent or are not well developed. However, some arid regions have karst features that originated during previous periods of geologic time when the climate was much wetter than it is today. Compared to colder

● **FIGURE 16.9**
Solution of limestone is most intense in fracture zones where the dissolved minerals from the rock are removed by surface water infiltrating to the subsurface. This landscape shows a limestone "platform" where intersecting joints have been widened by solution.

J. Petersen



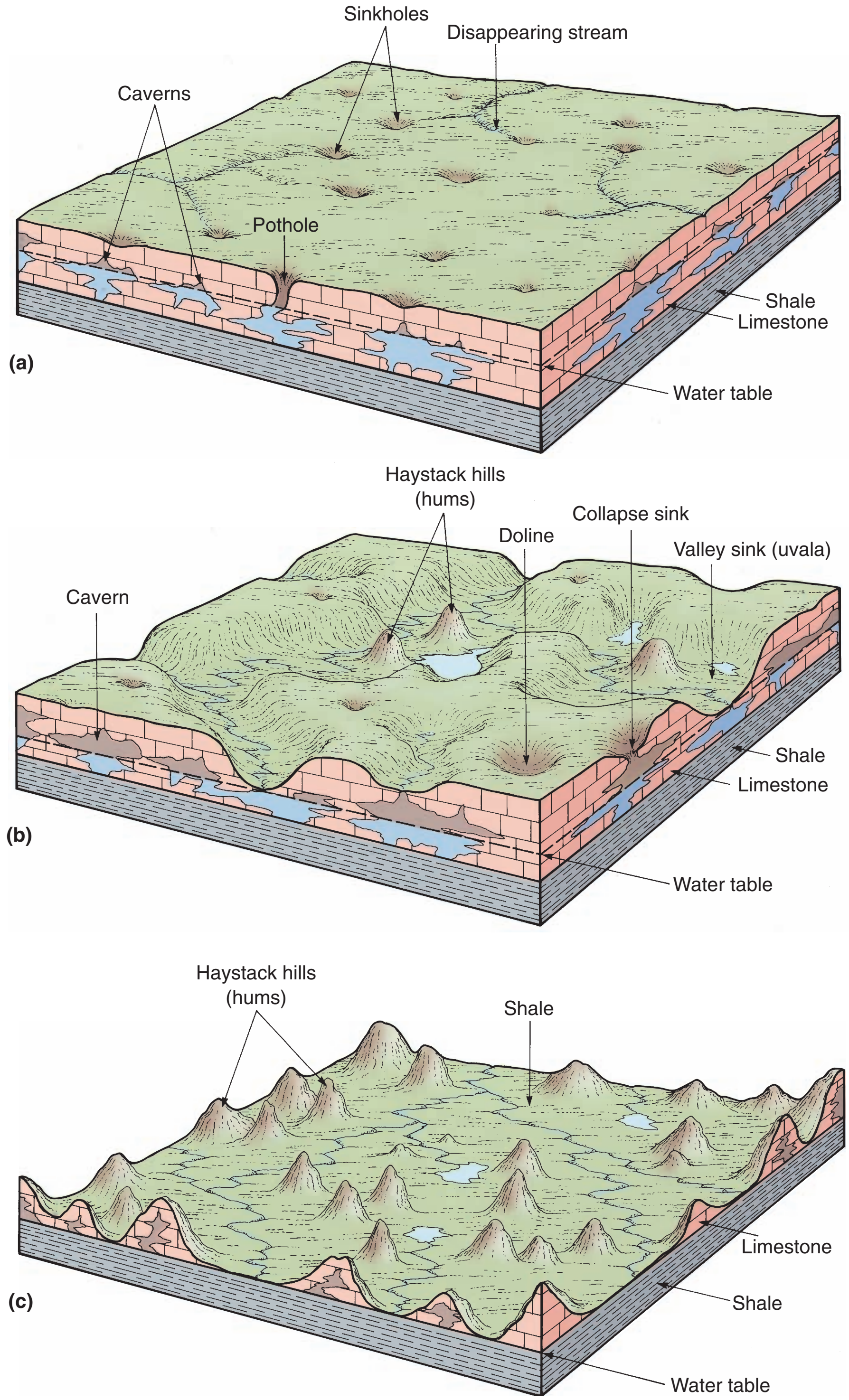
• FIGURE 16.10
The distribution of limestone in the conterminous United States indicates where varying degrees of karst landform development exists, depending on climate and local bedrock conditions.
Where is the nearest karst area to where you live?

humid climates, warmer humid climates have greater amounts of vegetation, which supplies carbon dioxide to subsurface water. Carbon dioxide is necessary for carbonation of limestone and it increases the acidity of the water, which encourages solution in general.

Another important factor in the development of karst landforms is the active movement of subsurface water. This allows water that has become saturated with dissolved calcium carbonate to flow away and become quickly replaced by water unsaturated with dissolved calcium carbonate. Groundwater undergoes vigorous movement when an outlet is available at a low level, such as by a deeply cut stream valley or a tectonic depression. In addition, the greater the permeability of the Earth material, the faster groundwater will flow.

Because infiltration of water into the subsurface tends to be concentrated where cross-cutting sets of joints intersect, these intersections are subject to accelerated solution. Such concentrated solution can cause the development of roughly circular surface depressions, called **sinkholes** or **dolines,** that are prominent features of many karst landscapes (• Figs. 16.11a and b). There are two dominant types of sinkholes identified by their differing formation processes (• Fig. 16.12). If the depressions are due primarily to the solution process at or near the surface and the removal of dissolved rock by water infiltrating downward into the subsurface, the depressions are called **solution sinkholes** (• Fig. 16.13). If the depressions are caused by the caving-in of the land surface above voids created by subsurface solution in bedrock below, they are referred to as **collapse sinkholes** (• Fig. 16.14).

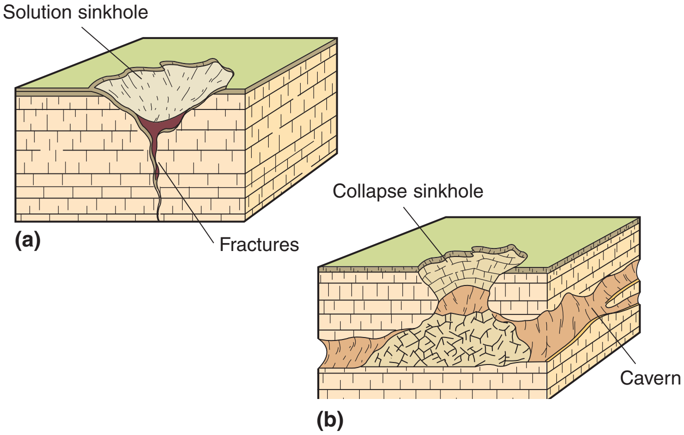
The two processes, solution and collapse, cooperate to create most sinkholes in soluble rocks. Whether the depressions are termed solution or collapse sinkholes depends on which of these two processes was dominant in their formation. Collapse and solution sinkholes often occur together in a region, and they may be difficult to distinguish from one another based on their form. There is a tendency for solution sinkholes to be funnel-shaped, and collapse sinkholes to be steep-walled, but these shapes vary greatly.



• FIGURE 16.11

Karst landscapes can be quite varied. (a) Solution at joint intersections in limestone encourages sinkhole development. Caverns form by groundwater solution along fracture patterns and between bedding planes in the limestone. Cavern ceilings may collapse, causing larger and deeper sinkholes. Surface streams may disappear into sinkholes to join the groundwater flow. (b) Some limestone landscapes have more relief, such as this irregular terrain with merged sinkholes that make karst valleys, called uvalas, and some conical haystack hills. (c) Areas that have experienced more intense solution may be dominated by limestone remnants, with the haystack hills (hums), isolated above an exposed surface of insoluble shale.

Why are there no major depositional landforms created at the surface in areas of karst terrain?



● **FIGURE 16.12**
Sinkholes (dolines) are divided into two major categories based on their principal mode of formation. (a) Solution sinkholes develop gradually where surface water funneling into the subsurface dissolves bedrock to create a closed depression in the landscape. (b) Collapse sinkholes form when either the bedrock or the regolith above a large subsurface void fails, falling into the void.


D. Sack

● **FIGURE 16.13**
Slowly forming solution sinkholes form closed depressions in the landscape. This scene is in southern Indiana.

Sudden collapse of sinkholes is a significant natural hazard that every year causes severe property damage and human injury. Rapidly forming sinkholes may be caused by excessive groundwater withdrawal for human use, or they may occur during drought periods. Either of these conditions will lower the water table, causing a loss of buoyant support for the ground above, followed by collapse. Rapid sinkhole collapse has damaged roads and railroads and has even swallowed buildings.

Despite their humid climates, many karst regions have few continually flowing surface streams. Surface water seeping into fractures in limestone widens the fractures by solution.


© St. Petersburg Times

● **FIGURE 16.14**
This large collapse sinkhole developed in Winter Park, Florida, when a falling water table caused the surface to fall into an underground cavern system during a time of severe drought.
What human activities might contribute to such hazards?

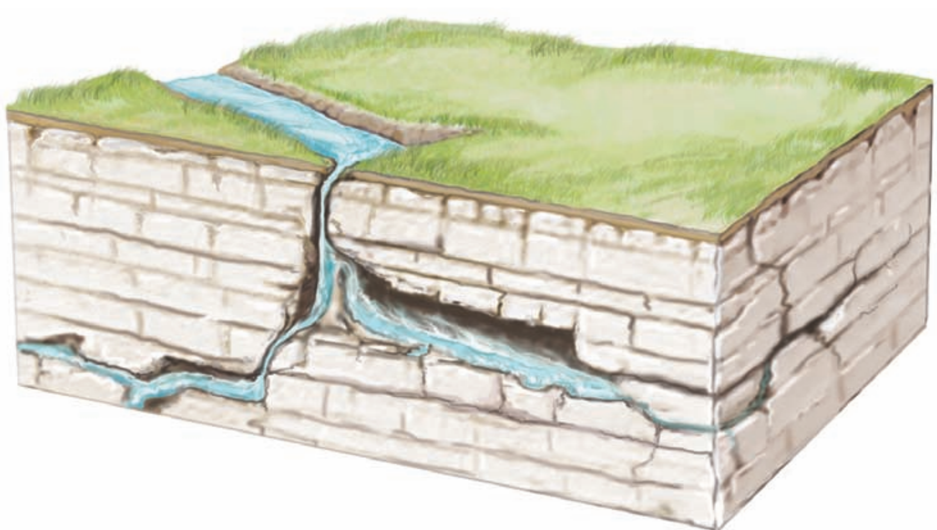
These widened avenues for water flow increase the downward permeability, accelerate infiltration, and direct water rapidly toward the zone of saturation.

Groundwater flowing along joints and bedding planes below the surface can also dissolve limestone, sometimes creating a system of connected passageways within the soluble bedrock (see again Figs. 16.11a and b). If the water table falls leaving these passageways above the zone of saturation, they are called **caverns** or **caves.**

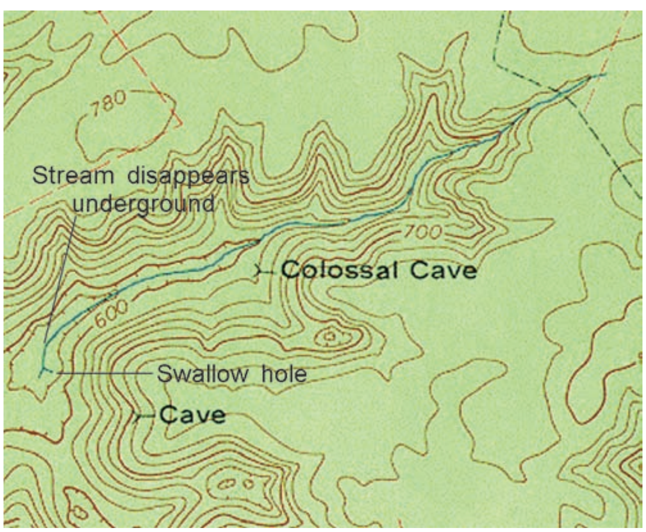
In some cases, surface streams flowing on less permeable bedrock upstream will encounter a highly permeable rock downstream, where it rapidly loses its surface flow by infiltration (see again Fig. 16.9). These are called **disappearing streams** because they "vanish" from the surface as the water flows into the subsurface (● Fig. 16.15a).

In many well-developed karst landscapes, including the Mammoth Cave area of Kentucky, a complex underground drainage system all but replaces surface patterns of water flow. In these cases, the landscape consists of many large valleys that contain no streams. Surface streams originally existed and excavated the valleys, but eventually broke through into a cavern system below. This diverted the surface stream water to underground conduits. The site where a stream disappears into the cavern system is called a **swallow hole** (Fig. 16.15b). In some cases these underground-flowing "lost rivers" reemerge at the surface as springs where they encounter impervious beds below the limestone.

Sinkholes (or dolines), which are also known as *cenotes* in Mexico, may enlarge and merge over time to form larger karst depressions. As sinkholes coalesce, the larger depressions that develop, called **uvalas,** or **valley sinks,** are often linearly arranged along former underground water courses (see again Fig. 16.11b). The terms *doline* and *uvala* are derived from Slavic languages used in the former Yugoslavia.



(a)



(b)

FIGURE 16.15
Disappearing streams and swallow holes are common in some karst areas. (a) A surface stream flows into a solution-widened hole in the ground, the swallow hole, and disappears from the surface, flowing instead through a subsurface cavern system. Flow may emerge back onto the surface at a major spring. (b) A topographic map shows a disappearing stream and a swallow hole. Note the hachured contours that indicate the closed depression into which the stream is flowing.

After intense and long-term karst development, especially in wet tropical conditions, only limestone remnants are left standing above insoluble rock below. These remnants usually take the form of small, steep-sided, and cave-riddled karst hills called **haystack hills, conical hills,** or **hums** (see again Figs. 16.11b and c). Examples of this landscape are found in Puerto Rico, Cuba, and Jamaica. They have been described as "egg box" landscapes because an aerial view of the numerous sinkholes and hums resembles the shape of an egg carton (Fig. 16.16). If the limestone hills are particularly high and steep-sided, the landscape is called **tower karst.** Spectacular examples of tower karst landscapes are found in southern China and Southeast Asia (Fig. 16.17).

Limestone Caverns and Cave Features

Caverns created by the solution of limestone are the most spectacular and best-known karst landforms. Groundwater, sometimes flowing much like an underground stream, dissolves rock, leaving networks of passageways. Should the water table drop to the floor of the cavern or lower, typically resulting from climatic change or tectonic uplift, the caves will become filled with air. Interaction between the cave air and mineral-saturated water percolating down to the cavern from above will then begin to precipitate minerals, especially calcium carbonate, on the cave ceiling, walls, and floor, decorating them with often-intricate depositional forms.

Examples of limestone caverns in the United States are Carlsbad Caverns in New Mexico, Mammoth and Colossal Caves in Kentucky, and Luray and Shenandoah Caverns in Virginia. In fact, 34 states have caverns that are open to the public. Some are quite extensive with rooms more than 30 meters (100 ft) high and with kilometers of connecting passageways. Every year, millions of visitors marvel at the intriguing variety of forms, colors, and passageways that they see and experience on tours of limestone caverns. The vast majority of these features in limestone caverns are related to solution and deposition by groundwater.

FIGURE 16.16
Intense solution in wet tropical environments can form a karst landscape consisting of a maze of hums and intergrown sinkholes.

Courtesy Parris Lyew-Ayee

GEOGRAPHY'S ENVIRONMENTAL SCIENCE PERSPECTIVE

Sudden Sinkhole Formation

Although many sinkholes develop slowly through solution and infiltration of water, regolith, and soil along joint intersections in soluble rocks, others appear almost instantaneously as the ground unexpectedly collapses into subsurface voids, including caverns. The sudden collapse of the ground caused by the creation of a sinkhole is a problem in many areas of the United States that have soluble rocks at or near the surface. An example is shown in the accompanying photographs of a road collapse near Bowling Green, Kentucky.

Earth scientists recognize two types of collapse processes that form sinkholes: regolith collapse (or cover collapse) and bedrock collapse. In both cases, subsurface solution begins long before the surface sinkhole appears.

Sinkhole formation by sudden regolith collapse occurs where vertical gaps in the subsurface rock exist due to solution along joints or other forms of weakness in the rock. The gaps often open to larger passageways at depth. Regolith and soil lie on top of the bedrock and also cross over the gaps as regolith bridges or arches. Initially, the water table lies above the rock within the regolith layer. Sudden regolith collapse is most common after the water table has fallen below the subsurface gaps, such as during drought periods or by excessive pumping from wells. The drop in the water table leaves the regolith in a zone in which some pore spaces fill with air and through which water percolates downward toward the air-filled gap or cavern below. If the force of gravity pulling downward on the soil and regolith exceeds the frictional and cohesive strength holding up the regolith bridge, the regolith collapses into the gap, creating a sinkhole at the ground surface. Adding additional weight to the regolith and soil layer by constructing roads and buildings or by impounding of water at the surface increases the force of gravity and therefore the likelihood that the regolith bridges will suddenly collapse.

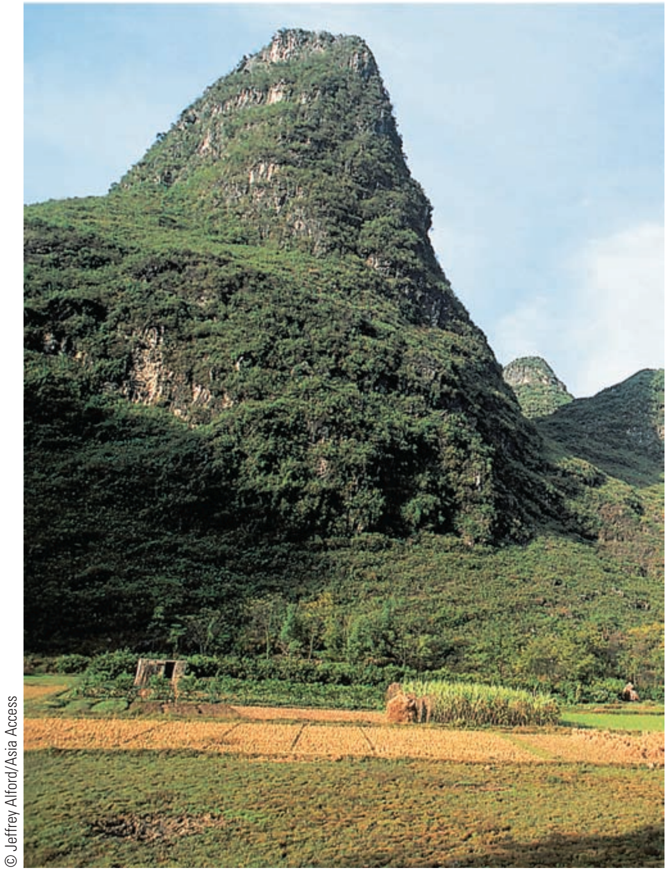
The formation of a sinkhole by bedrock collapse is associated with a growing underground cavern relatively near the ground surface. Caverns can grow vertically as well as horizontally. If continued solution makes the rock roof of the cavern thinner and thinner, eventually the rock can become so thin that it fails, crashing into the cavern void below. A sinkhole is formed when collapse of the bedrock cavern roof causes overlying Earth material up to the ground surface to lose its support and also slump into the hole.

Physical geographers who have examined the Dishman Lane sinkhole in Bowling Green report evidence of cave roof collapse in this case. It is likely that much of the roof collapsed thousands of years ago, but the fact that limestone blocks were found in the rubble indicated that part of the cave roof collapsed in this event. The resulting sinkhole affected over 0.4 hectares (1 acre) of surface area and caused considerable property damage.

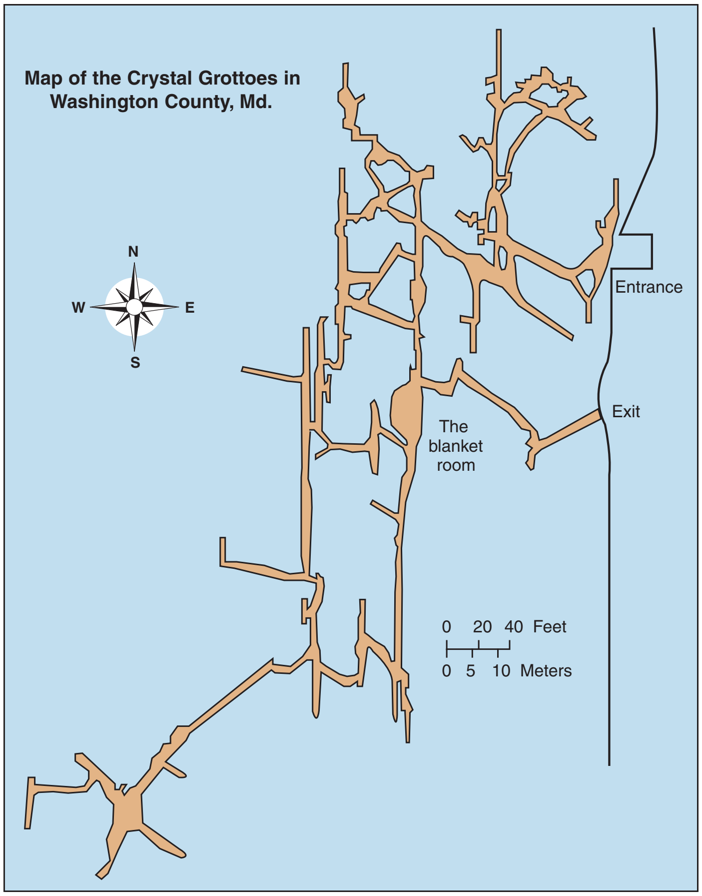
Courtesy of the Center for Cave and Karst Studies at Western Kentucky University

Courtesy of the Center for Cave and Karst Studies at Western Kentucky University

Sinkhole collapse near Bowling Green, Kentucky, caused severe road damage in an area larger than a football field. Luckily, no one was hurt during the rush-hour collapse, although several vehicles were damaged. Fixing the problem required completely filling in the sinkhole with rock and repaving the road at a cost of more than $1 million.



● **FIGURE 16.17**
Guilin, a limestone region in southern China, is famous for its beautiful karst towers (hums).
At one time in the geologic past, could this region have looked much like the landscape in Figure 16.16?



● **FIGURE 16.18**
This map of the Crystal Grottoes in Washington County, Maryland, illustrates the influence of fractures on the growth of the cavern system, as evidenced by the geometric arrangement and spacing of passageways. Caverns develop along zones of weakness, and groundwater flow widens fractures to develop a cave system.
Why are limestone fractures so susceptible to widening by dissolution?

The nature of fracturing that exists in soluble bedrock exerts a strong influence on cavern development in karst regions. Groundwater solution widens the space between opposing surfaces of joints, faults, and bedding planes to produce passageways. The relationship between caverns and fracture distributions is evident on cave maps that show linear and parallel patterns of cave passageways (● Fig. 16.18). Not all caves contain actively flowing water, but all caves formed by solution show some evidence of previous water flow, such as deposits of clay and silt on the cavern floor.

Speleothem is the generic term for any chemical precipitate feature deposited in caves. Speleothems develop in a great variety of textures and shapes, and many are both delicate and ornate. Speleothems develop when previously dissolved substances, particularly calcium carbonate ($CaCO_3$), precipitate out of subsurface water to produce some of the most beautiful and intricate forms found in nature. The dripping water leaves behind a deposit of calcium carbonate called travertine, or dripstone. As these travertine deposits grow downward, they form icicle-like spikes called **stalactites** that hang from the ceiling (● Fig. 16.19). Water saturated with calcium carbonate dripping onto the floor of a cavern builds up similar but more massive structures called stalagmites. Stalactites and **stalagmites** often meet and continue growing to form **columns** or pillars (● Fig. 16.20).

Most people believe that evaporation, leaving deposits of calcium carbonate behind, is the dominant process that produces the spectacular speleothems seen in caves, but that is not the case. Caves that foster active development of speleothems typically have air that is fully saturated with water, having a relative humidity near 100%, so evaporation is minimal. Instead, much of the water that percolates into the cave from above picked up carbon dioxide from the soil and dissolved calcium carbonate by carbonation on its way to the cave. Cave air, in contrast, contains a comparatively low amount of carbon dioxide. When the dripping water contacts the cave air, it therefore releases carbon dioxide gas to the air. This degassing of carbon dioxide from the water essentially reverses the carbonation process, causing the water to precipitate calcium carbonate. Eventually, enough calcium carbonate is

©Tom Bean/Getty Images

FIGURE 16.19
Stalactites form where mineralized water that has percolated down to the cave from above reaches the cave ceiling and deposits some of its dissolved minerals, typically calcium carbonate. These stalactites in the Lehman Caves of Great Basin National Park, Nevada, are hollow and may grow into long, narrow, and very delicate tubes called soda straws.
Why does evaporation of water tend to be only a minor process in the formation of stalactites?

National Park Service–Carlsbad Caverns

FIGURE 16.20
Carlsbad Caverns National Park in New Mexico contains some large speleothems (cavern deposits of dripstone).
How do you explain the presence of this huge cavern in a desert climate?

deposited in this way to form a stalactite, stalagmite, or other depositional cave feature.

Limestone caverns vary greatly in size, shape, and interior character. Some are well decorated with speleothems, and others are not. Many have several levels and are almost spongelike in the pattern of their passageways, whereas others are linear in pattern. The variations in cavern size and form may indicate differences in mode of origin. Some small caves may have formed above the water table by water percolating downward through the zone of aeration. Most, however, developed just below the water table, where the rate of solution is most rapid. A subsequent decline in the water table level, caused by the incision of surface streams, climatic change, or tectonic uplift, fills the cavern with air allowing speleothem formation to begin. Subterranean flow of water deepens some caverns, and collapse of their ceilings enlarges them upward.

Cavern development is a complex process, involving such variables as rock structure, groundwater chemistry, and hydrology, as well as the regional tectonic and erosional history. As a result, the scientific study of caverns, **speleology,** is particularly challenging. Adding to the challenge are the field conditions. Much of our knowledge of cavern systems has come from explorations as deep as hundreds of meters underground by individuals making scientific observations while crawling through mud, water, and even bat droppings in dark, narrow passages (• Fig. 16.21). Recent exploration and mapping of the water-filled caves below the surface in Florida and other karst regions have involved scuba diving. Cave diving in fully submerged, totally dark, and confined passageways, which may contain dangerous currents, is an extremely risky operation.

FIGURE 16.21
Cave exploration is called caving, or spelunking. Here, a spelunker explores Spider Cave in Carlsbad Caverns, National Park. Caving can be exciting but also quite hazardous. It requires knowledge, skill, good equipment, and proper judgment of conditions.
What are some of the potential hazards of caving?

National Park Service–Carlsbad Caverns