Chapter 17 KARST AND HYDROTHERMAL PROCESSES

IN STUDYING TOPOGRAPHIC DEVELOPMENT, WE PAY A GREAT deal of attention to the role of water. We noted that water running across the ground is a significant external shaper of terrain, and we will see that coastal waters produce distinctive landforms around the margins of oceans and lakes. In both cases, the water moves rapidly, and much energy is expended in erosion, transportation, and deposition.

In this brief chapter, we focus on water beneath the surface, which, because it is confined, functions in a much more restricted fashion than surface water. Underground water is largely unchanneled and therefore generally diffused, and it moves very slowly for the most part. Consequently, it is almost totally ineffective in terms of hydraulic power and other kinds of mechanical erosion. However, underground water can leave a distinctive mark on the surface landscape through a variety of solution processes associated with the development of karst and hydrothermal features—the topic of this chapter.

As you study this chapter, think about these key questions:

- **How do dissolution and precipitation processes affect bedrock such as limestone?**
- **How do limestone caverns develop?**
- **How do subsurface processes influence surface landforms in areas of karst topography?**
- **What conditions are necessary for hydrothermal features to develop?**

The Impact of Solution Processes on the Landscape

The mechanical effects of underground water have only a limited influence on topographic development (recall from Chapter 9 that *underground water* refers to any water beneath the surface, whereas the term *groundwater* specifically refers to water below the water table within the zone of saturation). Some subsurface mechanical weathering does take place, but the surface landscape is rarely directly affected by it, although certain forms of mass wasting (such as earthflows and slumps) are facilitated when loose materials are lubricated by underground water.

Through its chemical action, however, underground water is an effective shaper of the topographic landscape. Water is a solvent for certain rock-forming minerals, dissolving them from rock and then carrying them away in solution and depositing them elsewhere. Under some circumstances, the aboveground results of this dissolution are widespread and distinctive.

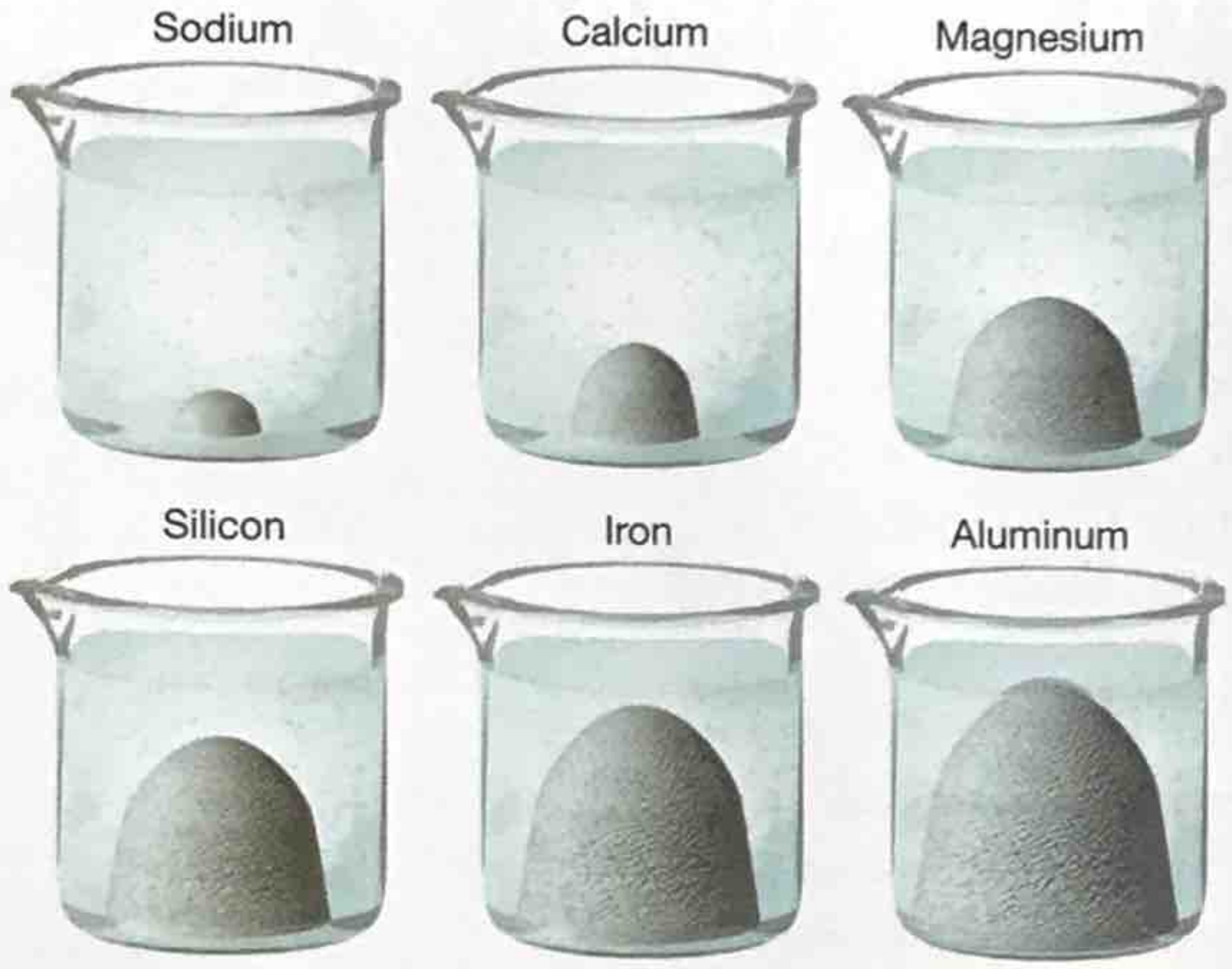
Underground water also affects surface topography via the creation of such hydrothermal features as hot springs and geysers, formed when hot water from underground is discharged at the ground surface.

SOLUTION AND PRECIPITATION

The chemical reactions involving underground water are relatively simple. Although pure water is a relatively poor solvent, almost all underground water is laced with enough chemical impurities to make it a good solvent for the compounds that make up a few common minerals (Figure 17-1). Basically, underground water is a weak solution of

Seeing Geographically

Stokkur Geyser, in the Haukadalur geothermal area in south-central Iceland. Describe the general topography around the geyser. What suggests that some of the rocks around the geyser have been deposited by minerals originally dissolved in the geyser? What factors do you think determine the distribution of plants visible on this landscape?



▲ **Figure 17-1** Relative solubility in water of some common rock-forming elements. The "lumps" in each beaker represent the proportion of the element that remains undissolved in a given amount of water. Sodium and calcium can be almost completely dissolved, for instance, whereas iron and aluminum are essentially insoluble.

carbonic acid (H_2CO_3) because it contains dissolved carbon dioxide gas—as we first saw in Chapter 15, the resulting *carbonation* can lead to the dissolution of bedrock.

Dissolution Processes: Dissolution is the removal of bedrock through the chemical action of water. Dissolution is an important weathering and erosional process for all rocks, but it is particularly effective on carbonate sedimentary rocks, especially limestone. A common sedimentary rock, limestone is composed largely of calcium carbonate ($CaCO_3$), which reacts strongly with carbonic acid solution to yield calcium bicarbonate, a compound that is very soluble in (and thus easily removed by) water. Other carbonate rocks, such as gypsum and even the metamorphic rock marble, undergo similar reactions. Dolomite is a calcium magnesium carbonate rock that dissolves almost as quickly as limestone. In simplified form, the chemical equations for the dissolution of limestone and dolomite are as follows:

$$\underset{\substack{\text{limestone}\\\text{(calcium}\\\text{carbonate)}}}{CaCO_3} + \underset{\text{water}}{H_2O} + \underset{\substack{\text{carbon}\\\text{dioxide}}}{CO_2} \rightarrow \underset{\substack{\text{calcium}\\\text{bicarbonate}}}{Ca(HCO_3)_2}$$

$$\underset{\text{dolomite}}{CaMg(CO_3)_2} + \underset{\text{water}}{2H_2O} + \underset{\substack{\text{carbon}\\\text{dioxide}}}{2CO_2} \rightarrow \underset{\substack{\text{calcium}\\\text{bicarbonate}}}{Ca(HCO_3)_2} + \underset{\substack{\text{magnesium}\\\text{bicarbonate}}}{Mg(HCO_3)_2}$$

These reactions are the most notable dissolution processes. Water percolating down into carbonate bedrock dissolves and carries away a part of the rock mass. Because limestone and related rocks are largely composed of soluble minerals, great volumes of rock are sometimes dissolved and removed, leaving conspicuous voids in the bedrock. This action occurs more rapidly and on a larger scale in humid climates, where abundant precipitation provides plenty of water containing dissolved carbon dioxide necessary for dissolution. In arid regions, evidence of dissolution action is unusual except for relict features dating from a more humid past.

Although reactions with carbonic acid are the most common processes involved in the dissolution of carbonate rocks, recent studies suggest that in some locations sulfuric acid (H_2SO_4) may also be important. For example, it appears that Lechuguilla Cave in New Mexico was at least in part enlarged through dissolution of limestone by sulfuric acid, formed when hydrogen sulfide (H_2S) from deeper petroleum deposits combined with oxygen in the groundwater.

Role of the Bedrock Structure: Bedrock structure is also a factor in dissolution. A profusion of *joints* and *bedding planes* permits groundwater to penetrate the rock readily. That the water is moving also helps because, as a given volume of water becomes saturated with dissolved calcium bicarbonate, it can drain away and be replaced by fresh unsaturated water that can dissolve more rock. Such drainage is enhanced by some outlet at a lower level, such as a deep subsurface stream.

Most limestone is resistant to mechanical erosion and often produces rugged topography. Thus, its ready solubility contrasts notably with its mechanical durability—a vulnerable interior beneath a durable surface.

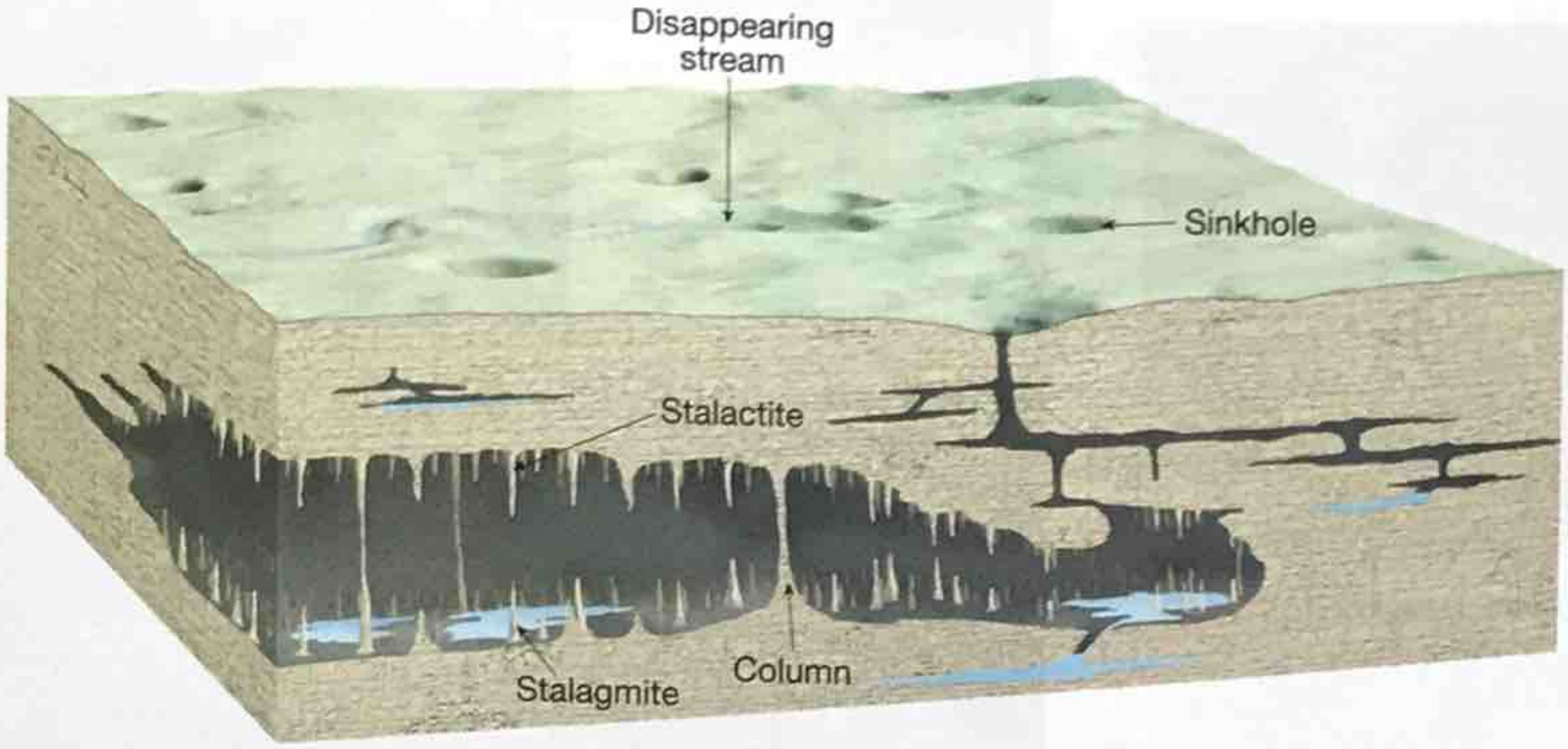
Learning Check 17-1 **Why is limestone so susceptible to *dissolution*? (Answer on p. AK-5)**

Precipitation Processes: Complementing the removal of calcium carbonate is its precipitation from solution. Mineralized water may trickle in along a cave roof or wall. The reduced air pressure in the open cave induces precipitation of the minerals the water is carrying.

One other type of precipitation is worth mentioning despite its scarcity because of its dramatic distinctiveness. Hot springs and geysers nearly always provide an accumulation of precipitated minerals, frequently brilliant white but sometimes orange, green, or some other color due to associated algae. Wherever it comes in contact with magma, groundwater becomes heated, and this water sometimes finds its way back to the surface through a natural opening so rapidly that it is still hot when it reaches the open air. Hot water is generally a much better solvent than cold, and so a hot spring or geyser usually contains a significant quantity of dissolved minerals. When exposed to the open air, the hot water precipitates much of its mineral content as its temperature and the pressure on it decrease, and as the dissolved gases that helped keep the minerals in solution dissipate or as algae and other organisms living in it secrete mineral matter. These deposits (such as *travertine*, *tufa*, and *sinter*) contain a variety of calcareous minerals and take the form of mounds, terraces, walls, and peripheral rims (see Figure 17-17).

It should be noted, however, that the solubility of carbon dioxide *decreases* as water temperature increases. Thus, cool water often is more potent than hot water as a solvent for calcium carbonate.

Learning Check 17-2 **How do rocks such as *travertine* and *tufa* form?**



◀ **Figure 17-2** Caverns are formed by solution action of underground water as it trickles along bedding planes and joint systems.

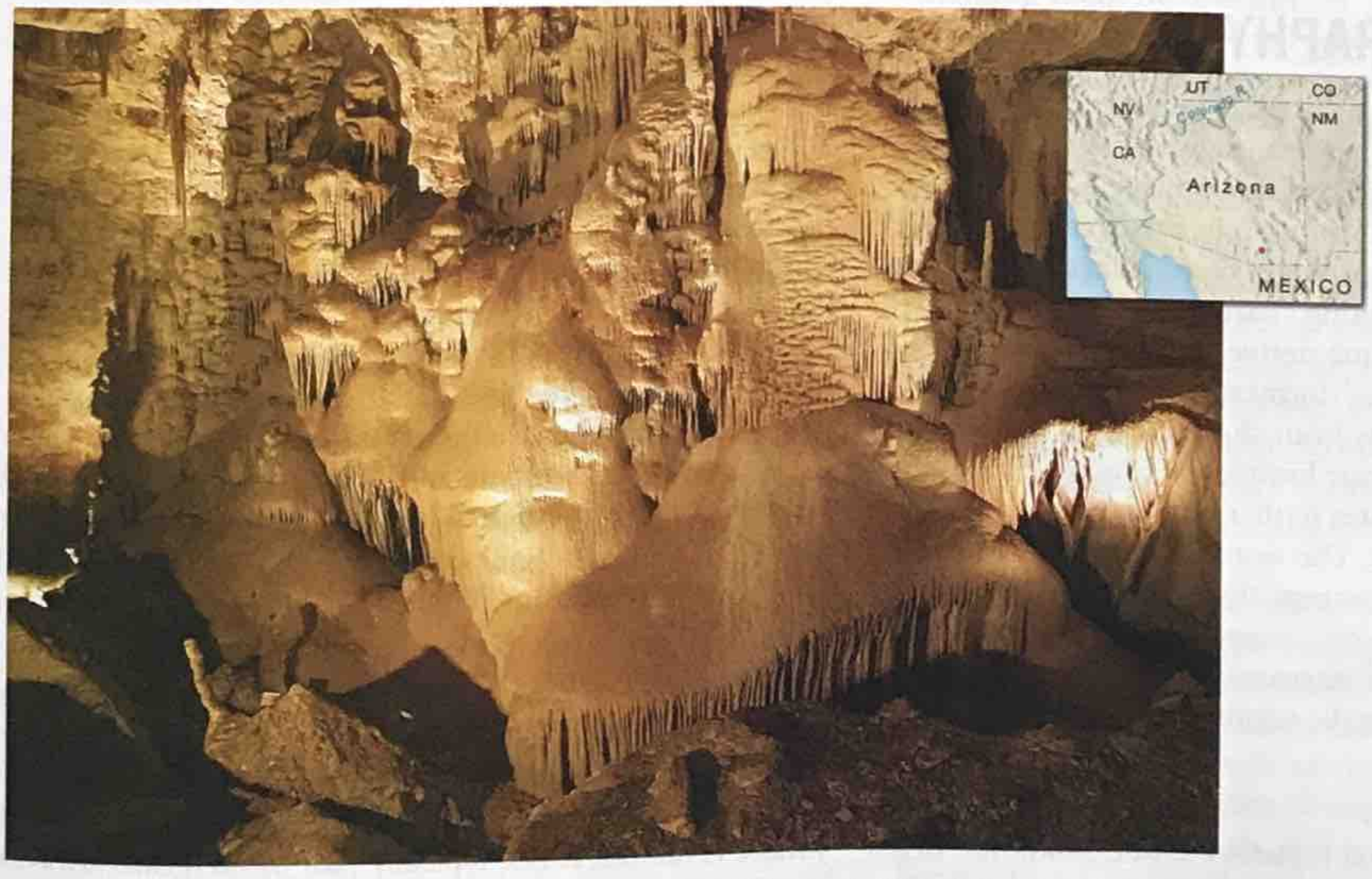
CAVERNS AND RELATED FEATURES

Some of the most spectacular landforms produced by dissolution are not visible at Earth's surface. Solution along joints and bedding planes in limestone beneath the surface often creates large open areas called **caverns**. The largest of these openings are usually more expansive horizontally than vertically, indicating a development along bedding planes. In many cases, however, the cavern pattern has a rectangularity that demonstrates a relationship to the joint system (Figure 17-2).

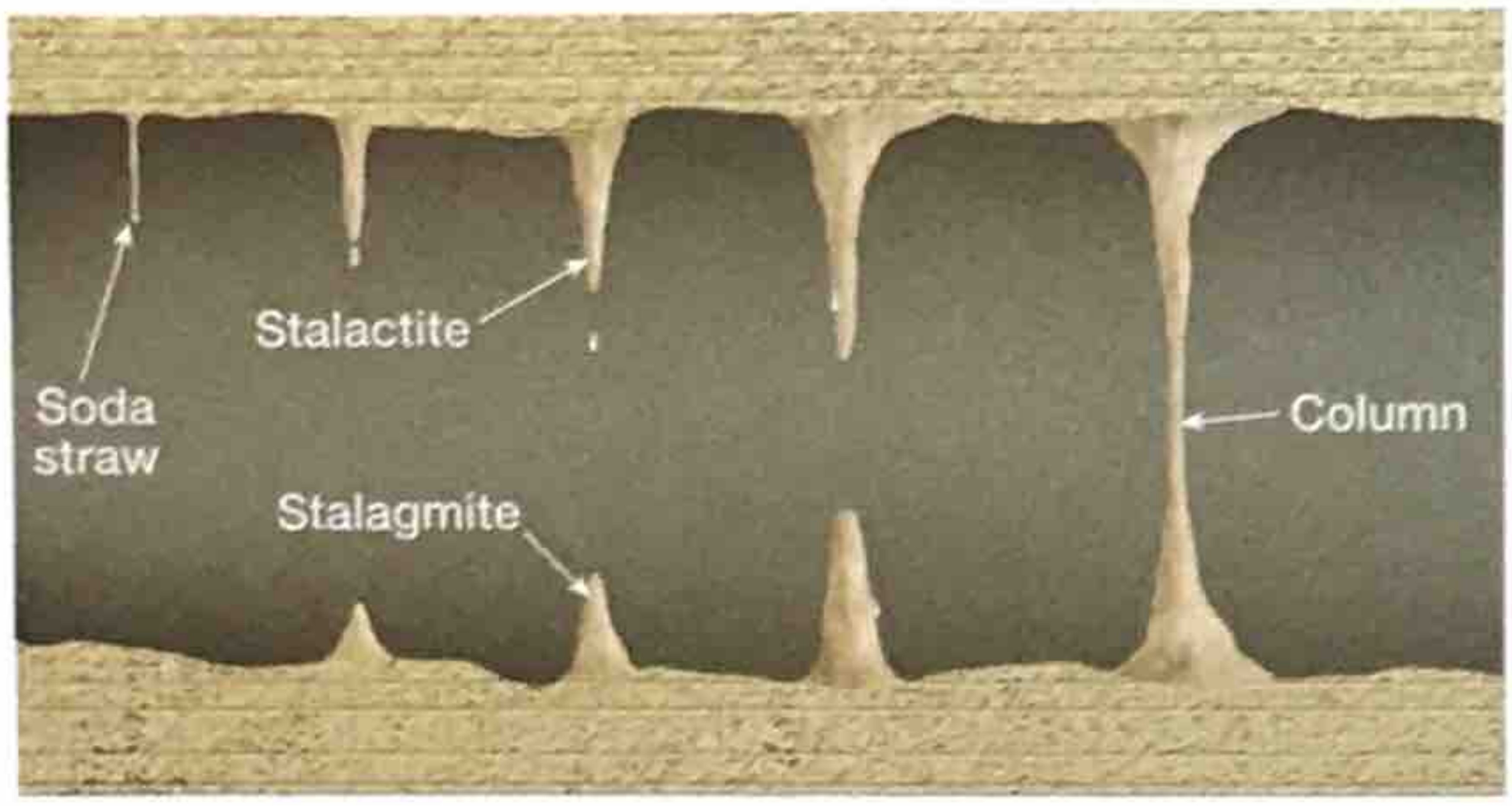
Caverns are found almost anywhere there is a massive limestone deposit at or near the surface. The state of Missouri, for example, has more than 6000. Caverns often are difficult to find because their connection to the surface may be extremely small and obscure, or nonexistent. Beneath the surface, however, some caverns are very extensive (Mammoth Cave in Kentucky has more than 630 kilometers [390 miles] of known passages), with an elaborate system of galleries and passageways, usually very irregular in shape and sometimes including massive openings ("rooms") scattered here and there along the galleries. A stream may flow along the floor of a large cavern, adding another dimension to erosion and deposition.

Speleothems

There are two principal stages in cavern formation. First there is the initial excavation, wherein percolating water dissolves the carbonate bedrock and leaves voids. This dissolution is followed, often after a drop in the water table, by a "decoration stage" in which ceilings, walls, and floors are decorated with a wondrous variety of **speleothems** (Figure 17-3). These forms are deposited when water



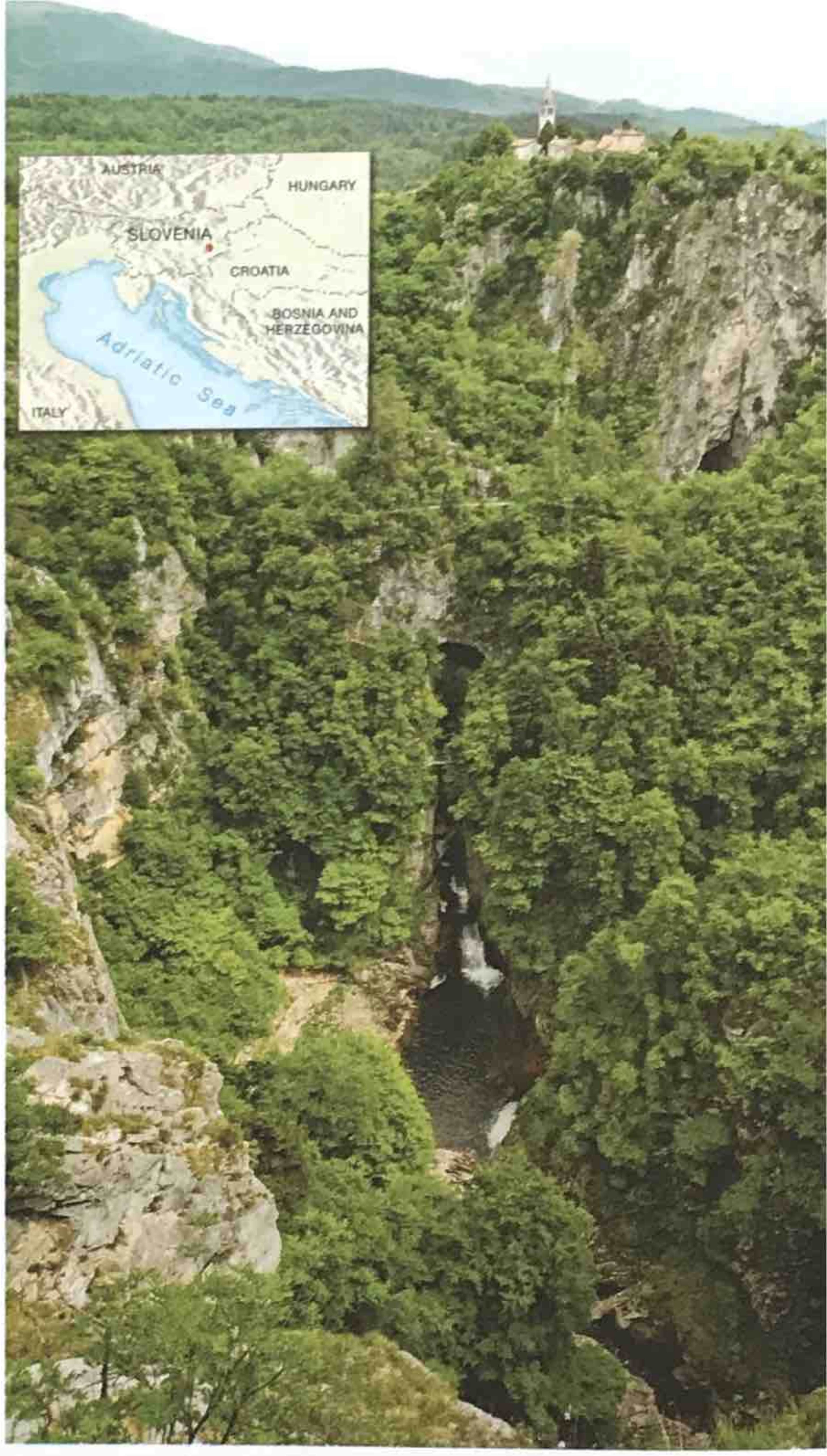
▲ **Figure 17-3** A multitude of stalactites hang from the ceiling of this room in Arizona's Kartchner Caverns. The smooth, gently-rounded surfaces are often referred to as *flowstone*.



▲ **Figure 17-4** The development of soda straws, stalagmites, stalactites, and columns.

leaves behind the compounds (principally carbon dioxide and calcite) it was carrying in solution. Once out of solution, the carbon dioxide gas diffuses into the cave atmosphere, and calcite is deposited. Much of the deposition occurs on the sides of the cavern, but the most striking features are formed on the roof and floor. Where water drips from the roof, a pendant structure grows slowly downward like an icicle—a **stalactite**. Where the drip hits the floor, a companion feature, a **stalagmite**, grows upward. Stalactites and stalagmites may extend until they meet to form a *column* (Figure 17-4). In some caverns, long, slender *soda straws* hang down from the ceiling; little more than one water drop wide, these delicate hollow tubes may eventually grow into stalactites.

Learning Check 17-3 **Explain the two stages of *cavern* development.**



▲ **Figure 17-5** Irregular topography and collapsed caves are prominent in the karst region of Primorska in Slovenia

KARST TOPOGRAPHY

In many areas where the bedrock is limestone or similarly soluble rock, dissolution has been so widespread and effective that a distinctive landform assemblage has developed at the surface, in addition to whatever caves may exist underground. The term **karst** (a Germanized form of an ancient Slavic word meaning "barren land") is applied to this topography. The name derives from the Kras or Krš Plateau region of Slovenia (formerly part of Yugoslavia), a rugged hilly area that has been shaped almost entirely by solution action in limestone formations (Figure 17-5).

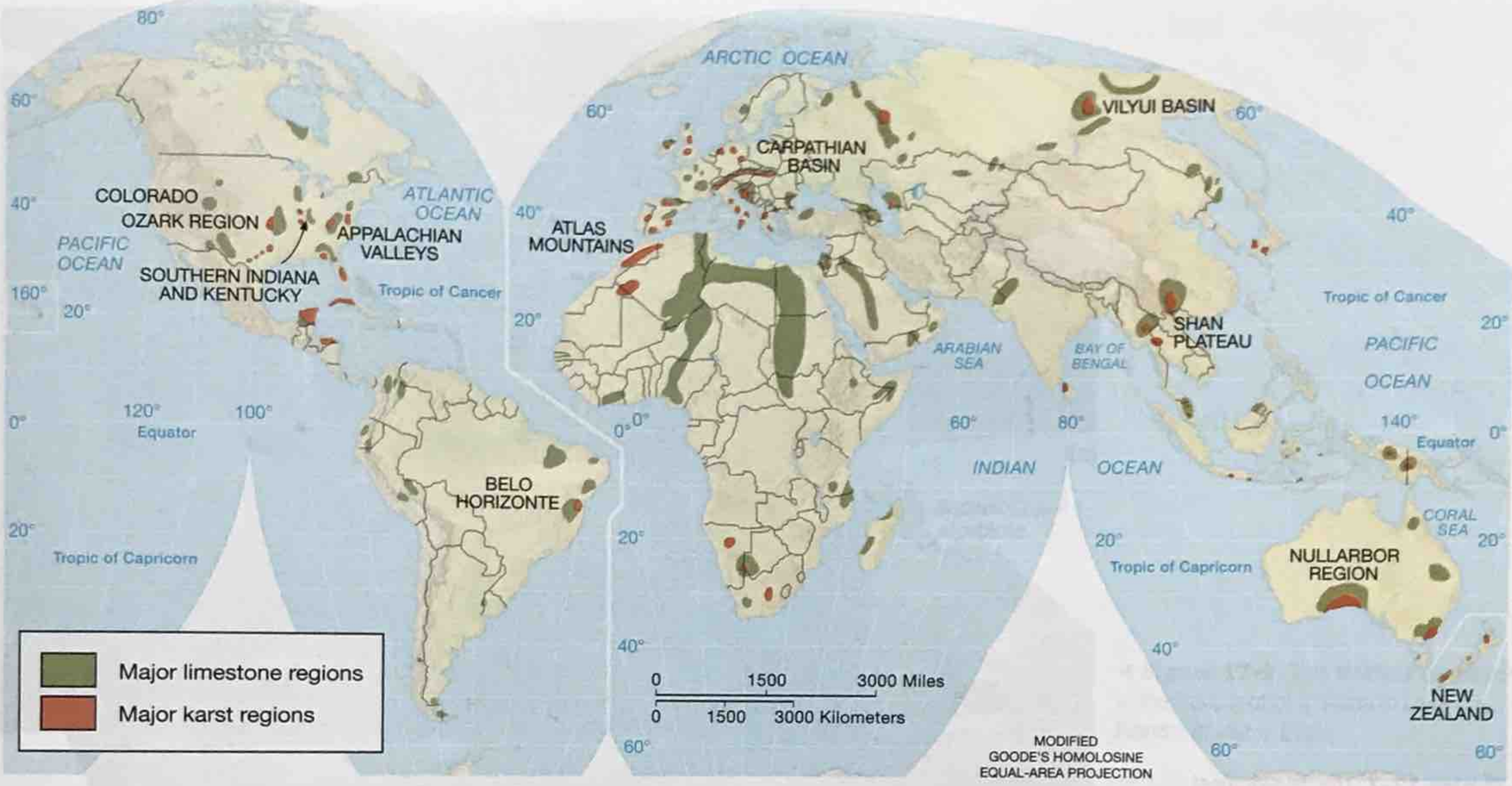
The term *karst* connotes both a set of processes and an assemblage of landforms. The word is used as the catchall name of a cornerstone concept that describes the special landforms that develop on exceptionally soluble rocks, although there is a broad international vocabulary to refer to specific features in specific regions.

Karst Landforms

Typical landforms in karst regions include sinkholes, disrupted surface drainage, and underground drainage networks that have openings formed from solution action. The openings range in size from enlarged cracks to huge caverns.

Karst landscapes usually evolve where there is massive limestone bedrock. However, karst features may also occur where other highly soluble rocks—dolomite, gypsum, or halite—predominate. Karst landforms are worthy of study not only because of their dramatic appearance but also because of their abundance. It is estimated that about 10 percent of Earth's land area has soluble carbonate rocks at or near the surface; in the conterminous United States, this total rises to 15 percent (Figure 17-6).

Sinkholes: The most common surface features of karst landscapes are **sinkholes** (also called *dolines*), which occur by the hundreds and sometimes by the thousands. Sinkholes are rounded depressions formed by the dissolution of surface carbonate rocks, typically (but by no means always) at joint intersections. The sinkholes erode more rapidly than the surrounding area, forming closed depressions. Their



▲ **Figure 17-6** Major limestone and karst regions of the world.

sides generally slope inward at the angle of repose (usually 20° to 30°) of the adjacent material, although some have more gentle side slopes. A sinkhole that results from the collapse of the roof of a subsurface cavern is called a **collapse sinkhole** (or *collapse doline*); these may have vertical walls or even overhanging cliffs (Figure 17-7a/b).

Sinkholes range in size from shallow depressions a few meters in diameter and a few centimeters deep to major features kilometers in diameter and hundreds of meters deep. The largest are associated with tropical regions, where they develop rapidly and where adjacent holes often intersect.

The bottom of a sinkhole may lead into a subterranean passage, down which water pours during a rainstorm. More commonly, however, the subsurface entrance is blocked by rock rubble, soil, or vegetation, and rains form temporary lakes until the water percolates away. Indeed, sinkholes are the karst equivalent of river valleys, in that they are the fundamental unit of both erosion and weathering.

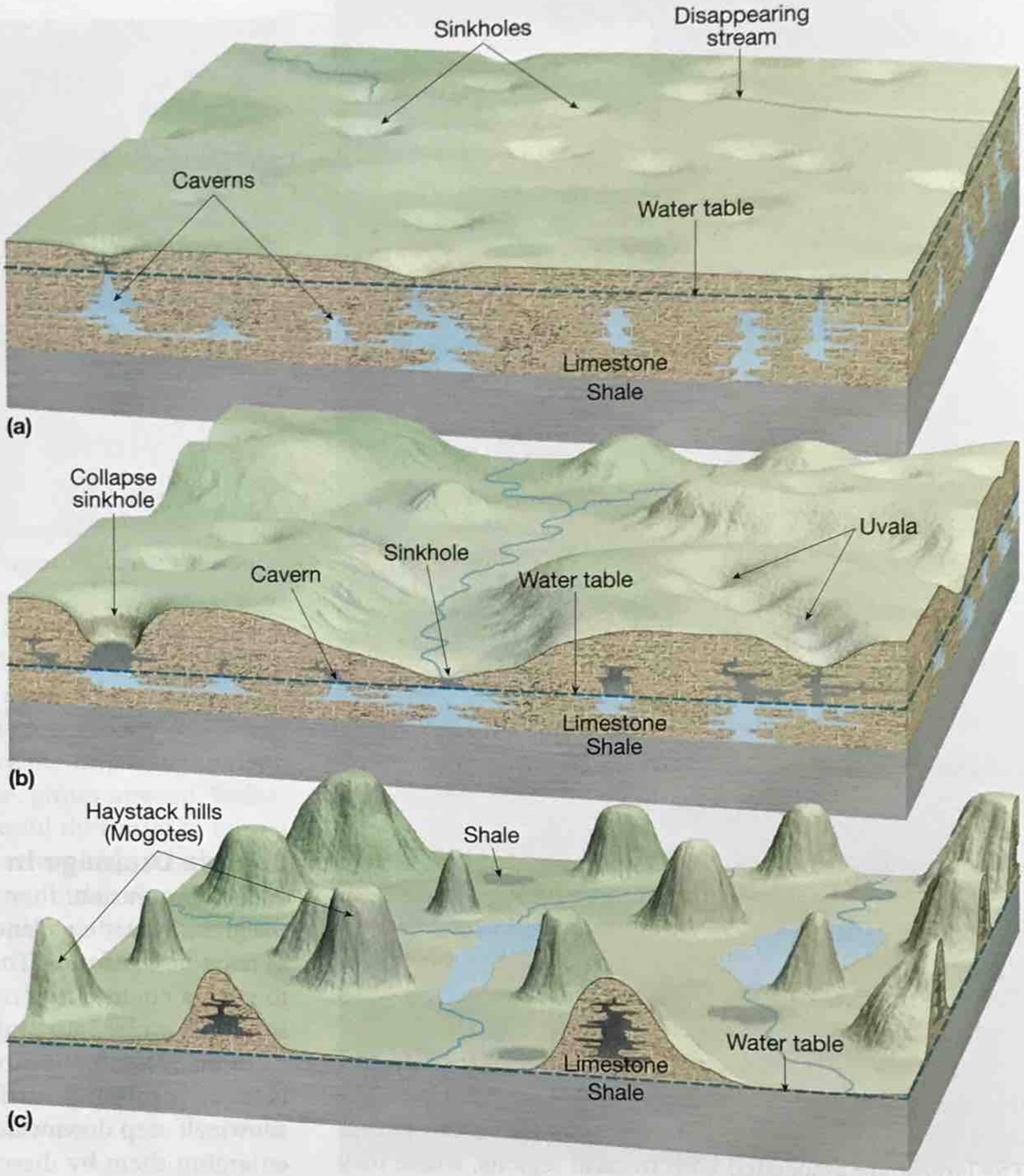
In many karst locations, depressions dominate the landscape. Sinkholes are commonplace in central Florida and parts of the Midwest, particularly Kentucky, Illinois, and Missouri. For example, at the University of Missouri in Columbia, both the football stadium and the basketball fieldhouse are built in sinkholes, and parking lots around them occasionally sink.

Apart from the ubiquity of sinkholes, karst areas show considerable topographic diversity. Where the relief is slight, as in central Florida, sinkholes are the dominant features. Where the relief is greater, however, cliffs and steep slopes alternate with flat-floored, streamless valleys. Limestone bedrock exposed at the surface tends to be pitted, grooved, etched, and fluted with a great intricacy of erosive detail.

Surface Drainage in Karst Areas: Where sinkholes occur in profusion, they often channel surface runoff into the groundwater circulation, leaving networks of dry valleys as relict surface forms. The Serbo-Croatian term **uvala** refers to such a chain of intersecting sinkholes. In many cases, sinkholes evolve into uvala over time.

In many ways, the most notable feature of karst regions is what is missing: surface drainage. Most rainfall and snowmelt seep downward along joints and bedding planes, enlarging them by dissolution. Surface runoff that does become channeled does not usually go far before it disappears into a sinkhole or joint crack—such streams are often termed **disappearing streams** (see Figure 17-7a). The water that collects in sinkholes generally percolates downward, but some sinkholes have distinct openings at their bottom, called **swallow holes**, through which surface drainage can pour directly into an underground channel, often to reappear at the surface through another hole some distance away. Where dissolution has been effective for a long time, there may be a complex underground drainage system that has superseded any sort of surface drainage network. An appropriate generalization concerning surface drainage in karst regions is that valleys are relatively scarce and mostly dry.

Tower Karst: Residual karst features, in the form of very steep-sided hills, dominate some parts of the world (Figure 17-7c). These formations are sometimes referred to as **tower karst** because of their almost vertical sides and conical or hemispheric shapes. Such towers are sometimes riddled with caves. The tower karst of southeastern China, adjacent parts of northern Vietnam, and southern Thailand is world famous for its spectacular scenery (Figure 17-8), as are the *mogotes* (haystack hills) of western Cuba.



▶ **Figure 17-7** The development of karst topography. (a) Landscape dominated by sinkholes and disappearing streams. Dissolution of bedrock below the water table may leave openings that develop into caverns. (b) Where underground caverns collapse, a collapse sinkhole forms. Streams may disappear into sinkholes through swallow holes. If the water table drops enough to leave open caverns, speleothems may gradually develop. (c) Tower karst topography consists of residual towers of limestone (haystack hills or mogotes).

▲ **Figure 17-8** Spectacular tower karst hills (mogotes) in Guilin, China.

◀ **Figure 17-9** This sinkhole developed in the front yard of a house in Lake City, Florida, in March 2005.

Learning Check 17-4 **What is a *sinkhole* and how does one form?**

Groundwater Extraction and Sinkhole Formation: Human activities can have direct and immediate consequences in some areas of karst topography. For example, most of central Florida is underlain by massive limestone bedrock, which is particularly susceptible to the formation of sinkholes and collapse sinkholes. This process is accelerated when the water table drops. Sinkholes have been forming in Florida for a long time, with several thousand of them having appeared in the twentieth century. Indeed, most of central Florida's scenic lakes began as sinkholes.

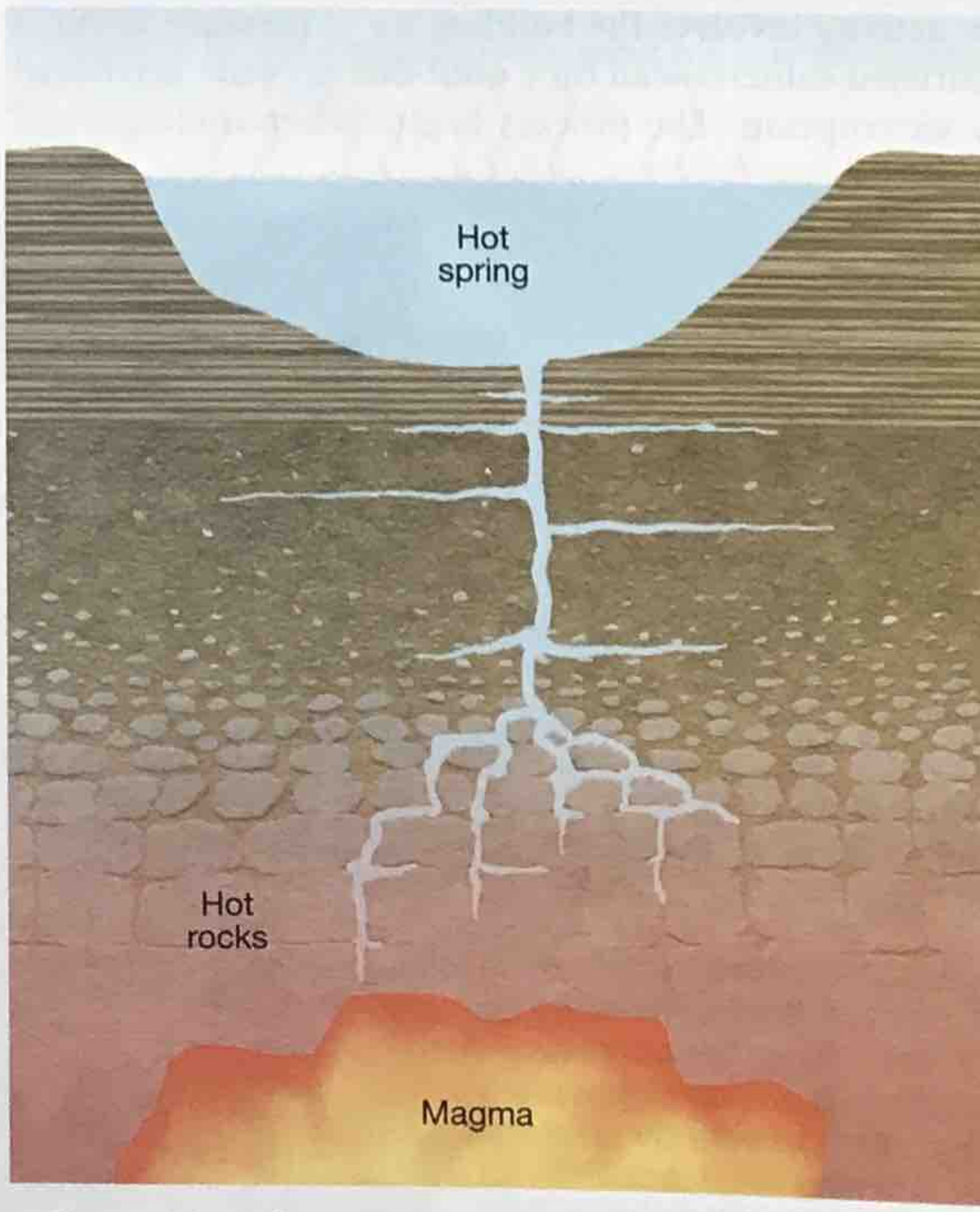
The population growth that Florida has experienced in recent decades put a heavy drain on its underground water supply, causing a drawdown of the water table. As a result, the number and size of Florida sinkholes increased to a disturbing pace, reaching a rate of about one per day in the early 1980s, although the tempo has slowed since then (Figure 17-9).

HYDROTHERMAL FEATURES

In many parts of the world, there are small areas where hot water comes to the surface through natural openings. Such outpouring of hot water, often accompanied by steam, is known as **hydrothermal activity** and usually takes the form of either a hot spring or a geyser.

Hot Springs

The appearance of hot water at Earth's surface usually indicates that the underground water has come in contact with heated rocks or magma and has been forced upward through a fissure by the pressures that develop when water is heated (Figure 17-10). The usual result at the surface is a **hot spring**, with water bubbling out either continuously or intermittently. The hot water invariably contains a large amount of dissolved mineral matter, and a considerable proportion of this load is precipitated out as soon as the



▲ **Figure 17-10** Cross section through a hot spring.

water reaches the surface and its temperature and the pressure on it both decrease.

The deposits around and downslope from hot springs can take many forms. If the opening is on sloping land, terraces are usually formed. Where the springs emerge onto flat land, there may be cones, domes, or irregular concentric deposits. Since calcium carbonate is so readily soluble in water containing carbonic acid, the deposits of most springs are composed largely of massive (*travertine*) or porous (*tufa* or *sinter*) accumulations of calcium carbonate. Various other minerals are also contained in the deposits on occasion, especially silica, but are much less common than calcium compounds.

Sometimes the water bubbling out of a hot spring builds a continually enlarging mound or terrace. As the structure is built higher, the opening through which the hot water comes to the surface also rises, so that the water is always emerging above the highest point. As the water flows down the sides of the structure, more deposition takes place there, thus broadening the structure as well, often with brilliantly colored algae, which add to the striking appearance as well as contribute mineral secretions to the deposit (Figure 17-11).

Geysers

A special form of intermittent hot spring is the geyser. Hot water usually issues from a geyser only sporadically, and most or all of the flow is a temporary ejection (called an *eruption*) in which hot water and steam spout upward. Then the geyser subsides into apparent inactivity until the next eruption.

Eruption Mechanisms: The basic principle of geyser activity involves the building up of pressure within a restricted subterranean tube until that pressure is relieved by an eruption. The process begins when underground water seeps into subterranean openings that are connected in a series of narrow caverns and shafts. Heated rocks and/or magma are close enough to these storage reservoirs to provide a constant source of heat. As the water accumulates in the reservoirs, it is heated to 200°C (400°F) or higher, which is much above the boiling point at sea level and normal pressure. (Such superheating is possible because of the high underground water pressure.) At these high temperatures, much of the water becomes steam. The accumulation of steam deep in the tube along with boiling water higher up eventually causes a great upward surge that sends water and steam showering out of the geyser vent. This eruption releases the pressure, and when the eruption subsides, underground water again begins to collect in the reservoirs in preparation for a repetition of the process.

A tremendous supply of heat is essential for geyser activity. Recent studies in Yellowstone Park's Upper Geyser Basin indicate that the heat emanating from that basin is at least 800 times greater than the heat flowing from a nongeyser area of the same size.

Learning Check 17-5 **Describe the conditions that typically lead up to a geyser eruption.**

Eruption Patterns: Some geysers erupt continuously, indicating that they are really hot springs that have a constant supply of water through which steam is escaping. Most geysers are only sporadically active, however, apparently depending on the accumulation of sufficient water to force an eruption. Some eruptions are very brief, whereas others continue for many minutes. The interval between eruptions for most geysers is variable. Most erupt at intervals of a few hours or a few days, but some wait years or even decades between eruptions. The temperature of the erupting water

▶**Figure 17-11** The sides and bottoms of hot springs are often brilliantly colored by algal growth. This is Beauty Pool in Yellowstone National Park. The black area at the bottom of the pool is the opening to the fissure that brings hot water to the surface. The water temperature of this hot spring is typically about 77°C (170°F).

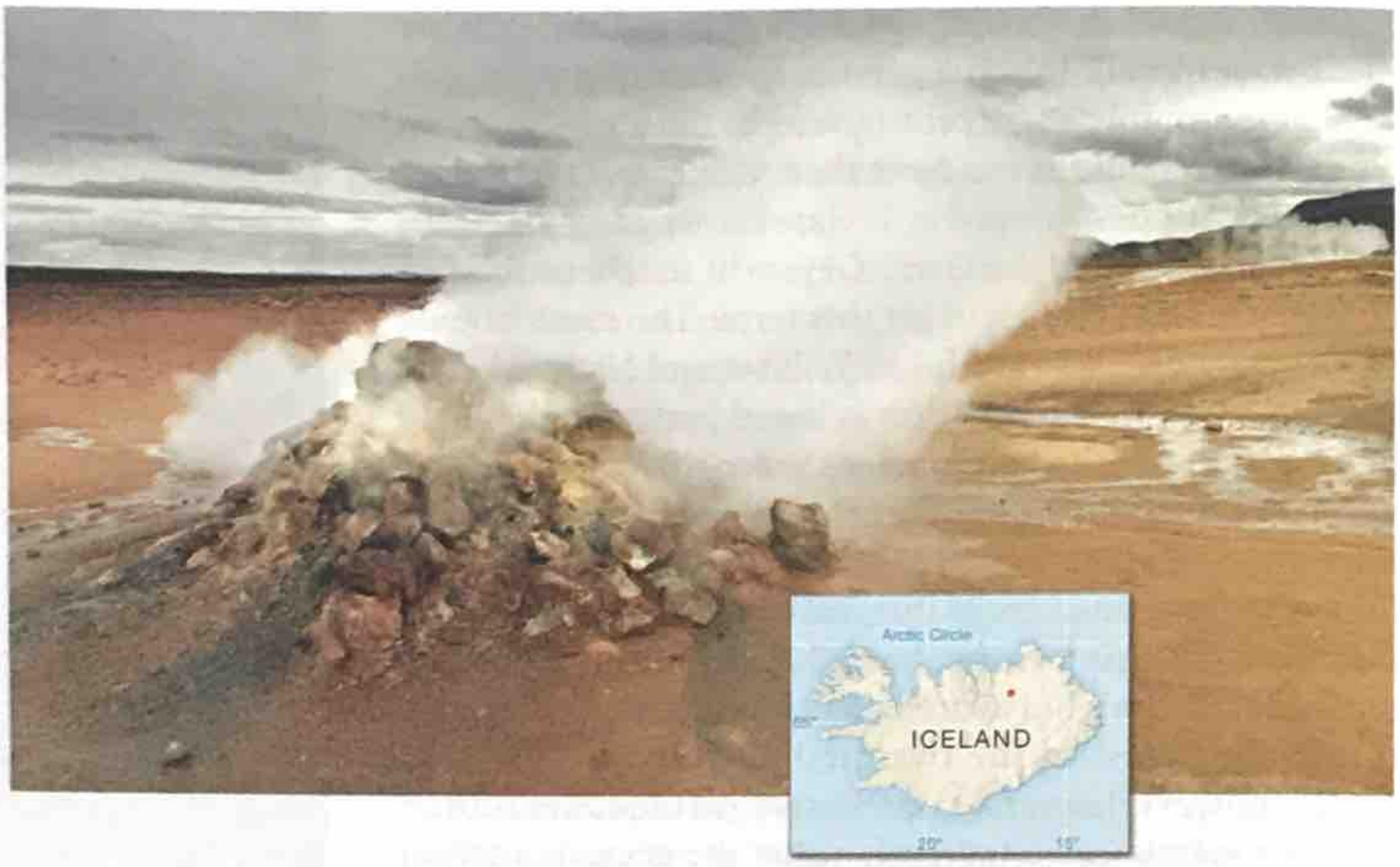
generally is near the boiling point for pure water (100°C or 212°F at sea level). In some geysers, the erupting water column goes up only a few centimeters in the air, whereas in others the column rises to more than 45 meters (150 feet).

Geyser comes from the Icelandic word *geysir* ("to gush" or "to rage"), the Great Geysir in southern Iceland being the namesake origin for this term. The most famous of all geysers is Old Faithful in Yellowstone National Park (Figure 17-12). Its reputation is based partly on the force of its eruptions (the column goes more than 30 meters or 100 feet high) but primarily on its regularity. Since first timed by scientists more than a century ago, Old Faithful maintained an average interval of 65 minutes between eruptions (ranging from about 30 minutes to 120 minutes), day and night, winter and summer, year after year throughout most of the twentieth century. In the early 1980s, however, several consecutive earthquakes on the Yellowstone plateau apparently upset the geyser's internal plumbing. Over the last few decades, Old Faithful's average interval between eruptions has been about 90 minutes, typically varying between 44 and 125 minutes. Thus, Old Faithful has become slightly more erratic, which is to say, more like other geysers.

Mineral Deposits: The deposits resulting from geyser activity are usually much less notable than those associated with hot springs. Some geysers erupt from open pools of hot water, throwing tremendous sheets of water and steam into the air but usually producing relatively minor depositional features. Other geysers are of the "nozzle" type and consequently build up a depositional cone and erupt through a small opening in it (Figure 17-13). Most deposits resulting from geyser activity are simply sheets of precipitated mineral matter spread irregularly over the ground.

▲ **Figure 17-12** Yellowstone's Old Faithful geyser in all its eruptive grandeur.

◄ **Figure 17-13** Most geysers erupt from vents or hot pools, but some build up prominent depositional "nozzles" through which water is expelled. This is Castle Geyser in Yellowstone National Park.



▶ **Figure 17-14** A fumarole is like a geyser except that it erupts no liquid water; it sends out only steam. This scene is from near Mývatn Lake, Iceland.

Fumaroles

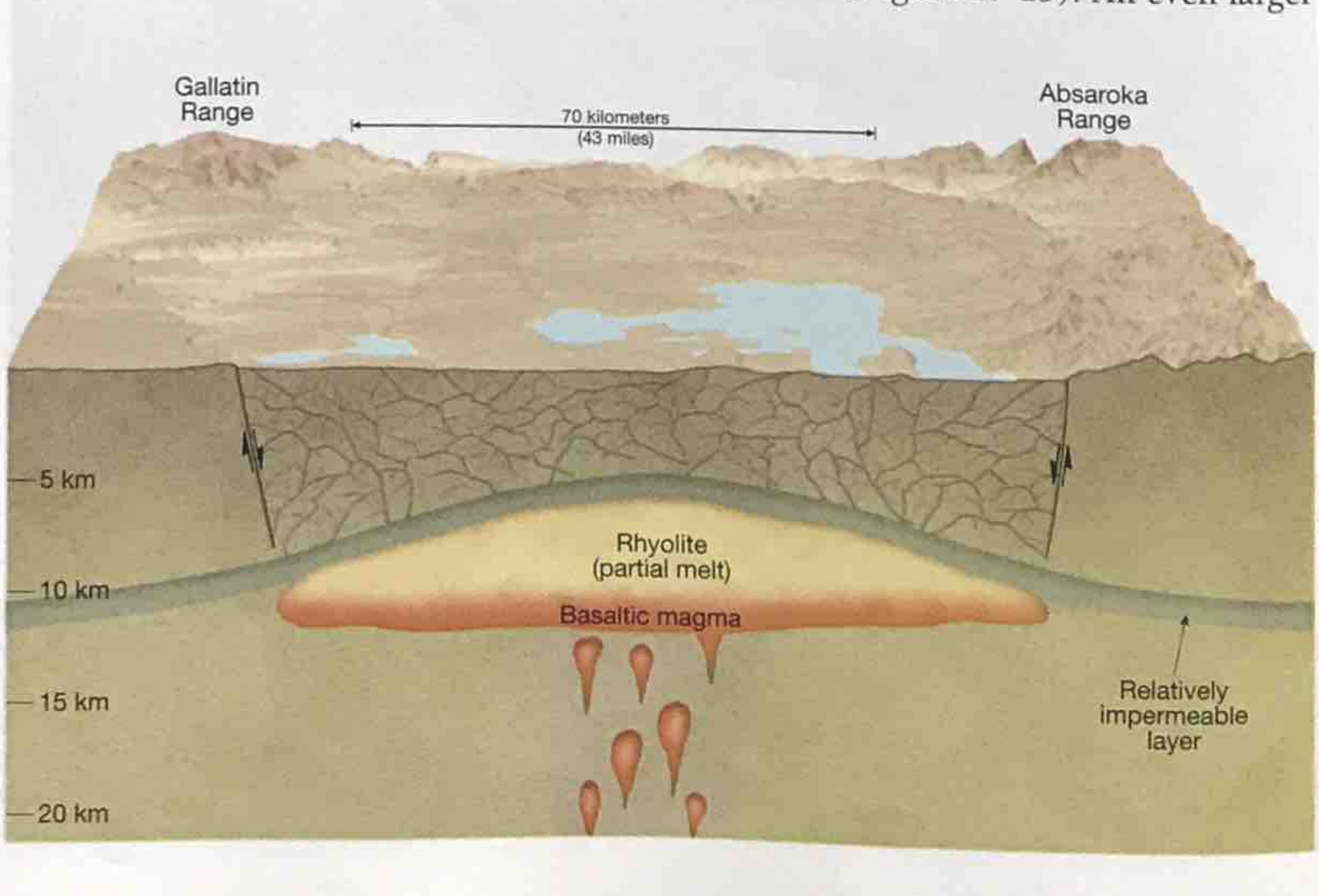
A third hydrothermal feature is the **fumarole**, a surface crack directly connected to a deep-seated heat source (Figure 17-14). For some reason, very little water drains into the tube of a fumarole. The water that does drain in is instantly converted to steam by the heat, and a cloud of steam is then expelled from the opening—often with an accompanying roaring or hissing sound. Thus, a fumarole is marked by steam issuing either continuously or sporadically from a surface vent; in essence, a fumarole is simply a hot spring that lacks liquid water.

In many places around the world, people have tapped hydrothermal resources as a source of clean energy—see the box "Energy for the 21st century: Geothermal Energy."

Hydrothermal Features in Yellowstone

Hydrothermal features are found in many volcanic areas, being particularly notable in Iceland, New Zealand, Chile, and Siberia's Kamchatka Peninsula. By far the largest concentration, however, occurs in Yellowstone National Park, located mostly in northwestern Wyoming, which contains about 225 of the world's 425 geysers as well as more than half of the world's other hydrothermal phenomena.

Geologic Setting: The Yellowstone area consists of a broad, flattish plateau bordered by extensive mountains (the Absaroka Range) on the east and by more limited highlands (particularly the Gallatin Mountains) on the west. The bedrock surface of the plateau is almost entirely volcanic materials, although no volcanic cones are in evidence. About 640,000 years ago, a catastrophic volcanic eruption here ejected about 1000 cubic kilometers (240 cubic miles) of pyroclastics—about 1000 times more material than the 1980 Mount St. Helens eruption—covering the surrounding region with thick deposits of volcanic ash, and resulting in the formation of a 70 kilometer (43 mile) diameter caldera (Figure 17-15). An even larger



▶ **Figure 17-15** Schematic west–east cross section through the Yellowstone Plateau showing the extent of the Yellowstone Caldera and the magma chamber below.

Geothermal Energy

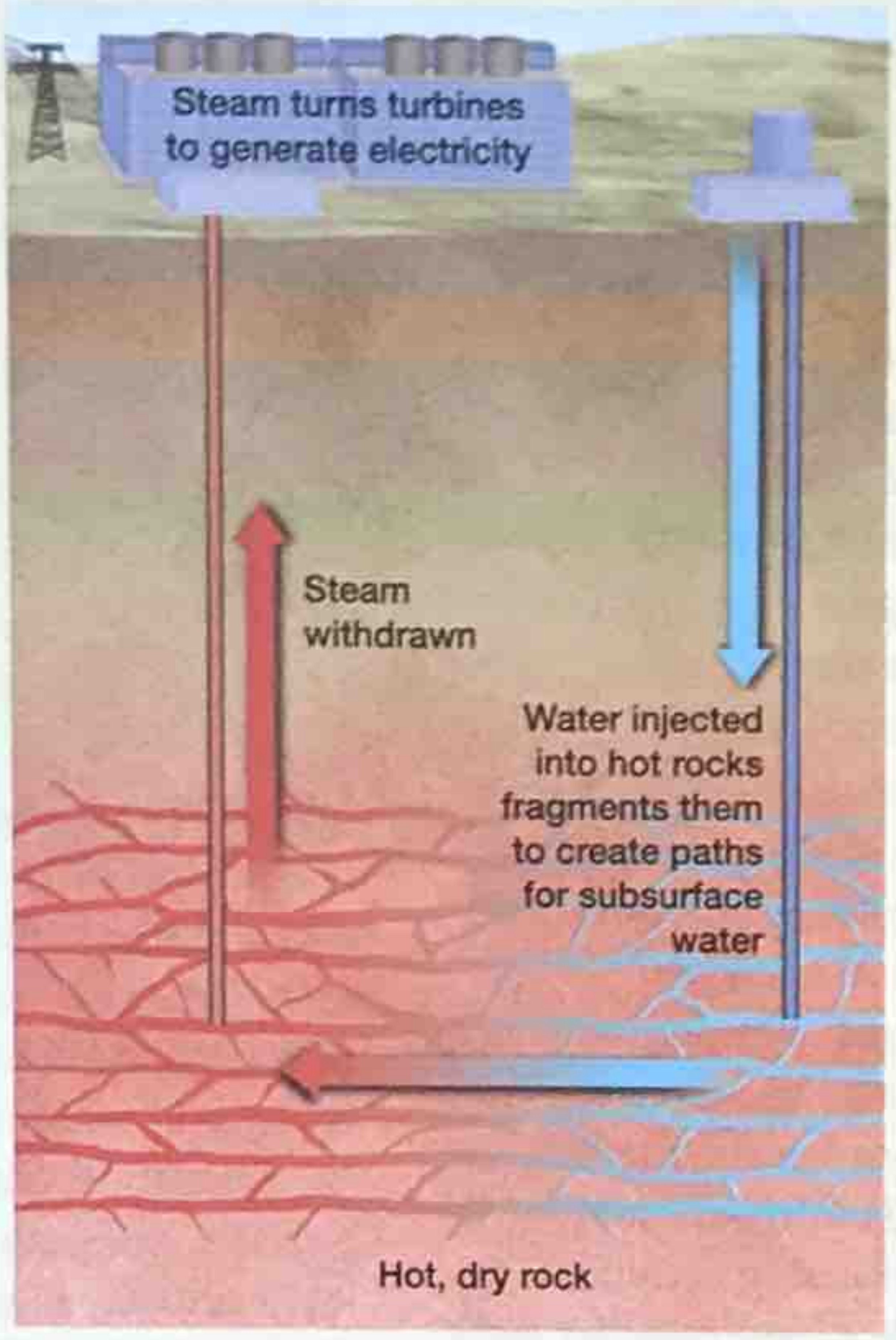
▸ Karl Byrand, University of Wisconsin Colleges

Geothermal technology harnesses the heat of Earth's interior either to warm buildings directly or to generate electricity. Geothermal heat exists throughout Earth's interior because of the radioactive decay of certain elements, as well as because of the conduction of heat from Earth's core.

Geothermal Technology: Geothermal technology includes geothermal heat pumps that consist of shallow piping systems (around three meters in depth) incorporating a pump that can draw heat from the ground in the winter and return it to the ground in the summer as a way to heat and cool a small structure. In geothermally active regions, steam from the ground can be used directly to heat a structure.

Larger-scale technologies that can harness even more geothermal energy include *dry steam*, *closed-loop*, and *enhanced geothermal systems* (EGS).

- The dry steam process—the most common geothermal technology—directly extracts steam from inside Earth to turn a turbine. Once used, the steam is then condensed and returned to the ground to be reheated naturally and used again.
- A closed loop system uses subterranean pipes filled with fluids such as isobutane and pentafluoropropane, which have a lower boiling point than water, thus requiring less heat to create steam.
- An EGS pumps cold water directly under ground to fragment geothermally active, but dry, rock to create paths of subsurface water flow (Figure 17-A). It is estimated that the energy potential for EGS alone is 200 gigawatts (GW) in the United States and 60 GW in Europe.



▲ **Figure 17-A** Electrical generation using an enhanced geothermal system. Water is injected into hot, but dry rock. The steam produced is then extracted to power the electrical generator turbines.

Advantages and Disadvantages: Geothermal energy generation provides energy day and night, is self-sustaining, virtually inexhaustible, and free of combustion-based emissions. Although CO_2, a known greenhouse gas, is released from Earth's interior during extraction of steam, the amount is considerably smaller than the amount generated by coal-fired facilities. According to the Department of Energy, to generate 1 megawatt of electricity, on average a geothermal facility releases 27 to 40 kilograms (60–90 pounds) of CO_2, whereas a coal-fired one creates 900 kilograms (2000 pounds).

Under certain conditions, dry steam systems are not self-sustaining. If a power plant's water or steam extraction rate exceeds the natural recharge rate, a reduction in steam pressure may result. It is estimated that more than 250 geysers worldwide have been depleted for this reason.

The other major disadvantage associated with geothermal energy generation is the possibility of induced seismicity—microearthquakes caused by well drilling, water extraction, and the injection of water into the ground. For instance, in 2006 operations at a geothermal power plant in Basel, Switzerland, were halted after several earthquakes. Because geothermal facilities operate within already seismically active regions, it can be difficult to distinguish natural seismic activity from induced seismicity. However, in the Basel case, it was relatively clear that the injection of water into the plant's well caused the earthquakes.

The greatest risk of seismic activity is associated with the EGS process. EGS continues to be developed and tested because it can capture geothermal energy in regions without adequate groundwater flow. A study from Australia, which has the world's largest EGS project, and studies at facilities in California, determined that the potential for induced microearthquakes exists, but that the risk is negligible.

Geography of Geothermal Technology: As of 2012, about 70 countries have implemented geothermal energy to produce more than 11,000 MW globally. The United States leads production, with more than 3000 MW of installed capacity (Figure 17-B), whereas in Europe, Italy, Iceland, and Turkey have a collective installed capacity of nearly 1600 MW. Other regions expanding or exploring geothermal technology include Indonesia, Latin American, and the Caribbean nations, and the East Africa Rift Valley.

▲ **Figure 17-B** Geothermal power generation facilities at The Geysers in northern California.

eruption took place about 2.1 million years ago, and geologists think that future eruptions of the Yellowstone volcano are a distinct possibility.

Hydrothermal Conditions: The uniqueness of Yellowstone's geologic setting stems from the presence of a large, shallow magma chamber beneath the plateau—thought to be the result of a hot spot formed by a mantle plume rising up from the mantle. Test boreholes and geophysical studies reveal a high thermal gradient, in which the temperature increases with depth at a rate of about 67°C per 100 meters (36°F per 100 feet), and indicate that the top of the magma chamber is perhaps only 8 kilometers (5 miles) below the surface. Between 2004 and 2010, the ground in the caldera rose by 25 centimeters (10 inches)—most likely as a result of swelling of the magma chamber below; since 2010, the ground has subsided—a cycle of ground movement volcanologists have observed in the past. This shallow magma pool provides the heat source—the most important of the three conditions necessary for the development of hydrothermal features.

The second requisite is an abundance of water that can seep downward and become heated. Yellowstone receives copious summer rain and a deep winter snowpack (averaging more than 250 centimeters or 100 inches).

The third necessity for hydrothermal development is a weak or broken ground surface that allows water to move up and down easily. Here, too, Yellowstone fits the bill, for the ground surface there is very unstable and subject to frequent earthquakes, faulting, and volcanic activity. Consequently, many fractures and weak zones provide easy avenues for vertical water movement.

Learning Check 17-6 **Identify three conditions that make Yellowstone ideal for the development of hydrothermal features.**

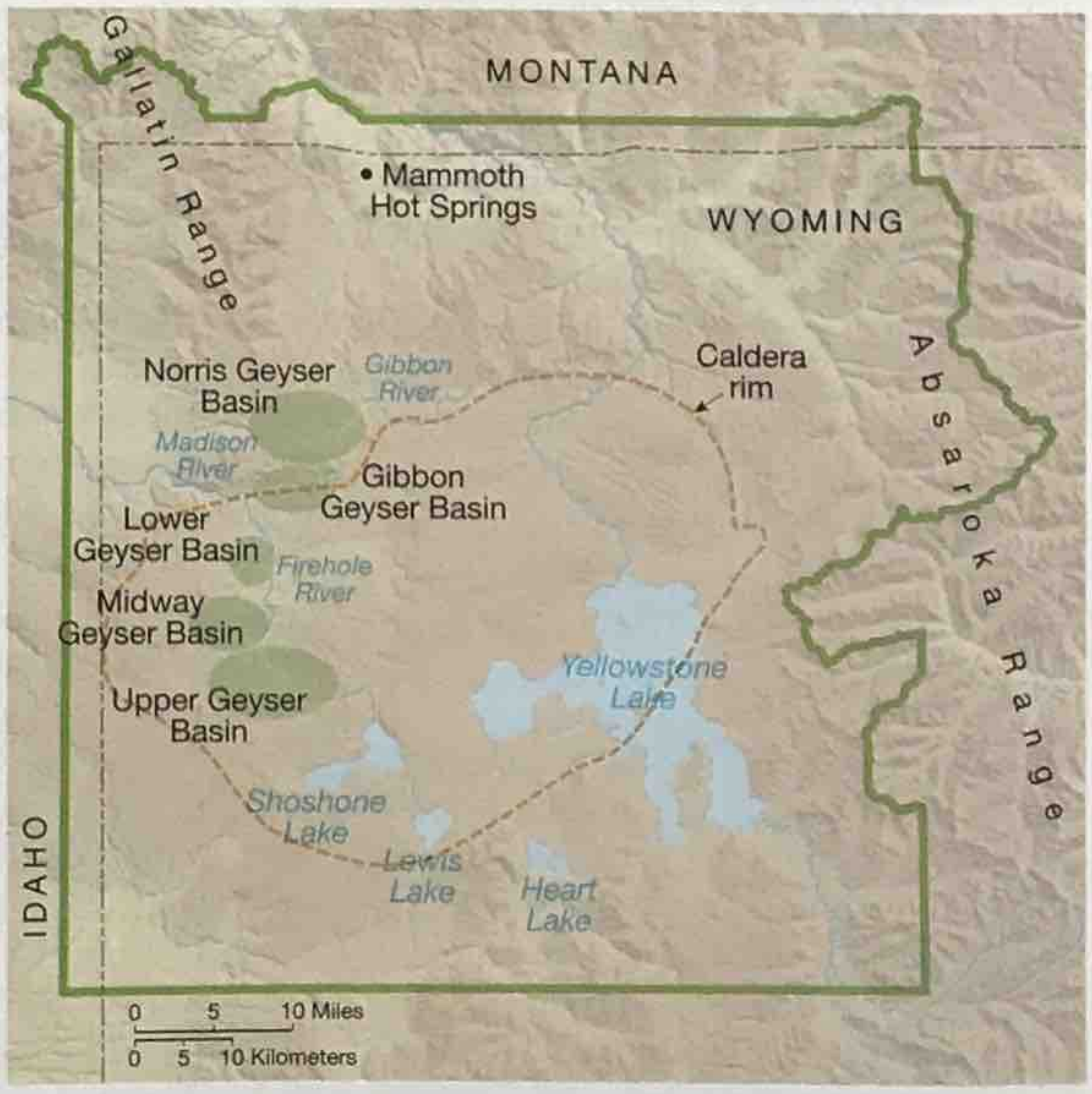
Geyser Basins: The park contains about 225 geysers, more than 3000 hot springs, and 7000 other thermal features (fumaroles, steam vents, hot-water terraces, hot-mud cauldrons, and so forth). There are five major geyser basins, a half dozen minor ones, and an extensive scattering of individual or small groups of thermal features.

The principal geyser basins are all in the same watershed on the western side of the park (Figure 17-16). The Gibbon River from the north and the Firehole River from the south unite to form the Madison River, which flows westward into Montana, eventually to join two other rivers in forming the Missouri (a 1959 earthquake in the Yellowstone area triggered a major landslide in the Madison River valley just to the west of the park). The Gibbon River drains the Norris and Gibbon geyser basins, whereas the Firehole drains the Upper, Midway, and Lower basins. The Firehole River derives its name from the great quantity of hot water fed into it from the hot springs and geysers along its way. Approximately two-thirds of the hydrothermal features of Yellowstone are in the drainage area of the Firehole River.

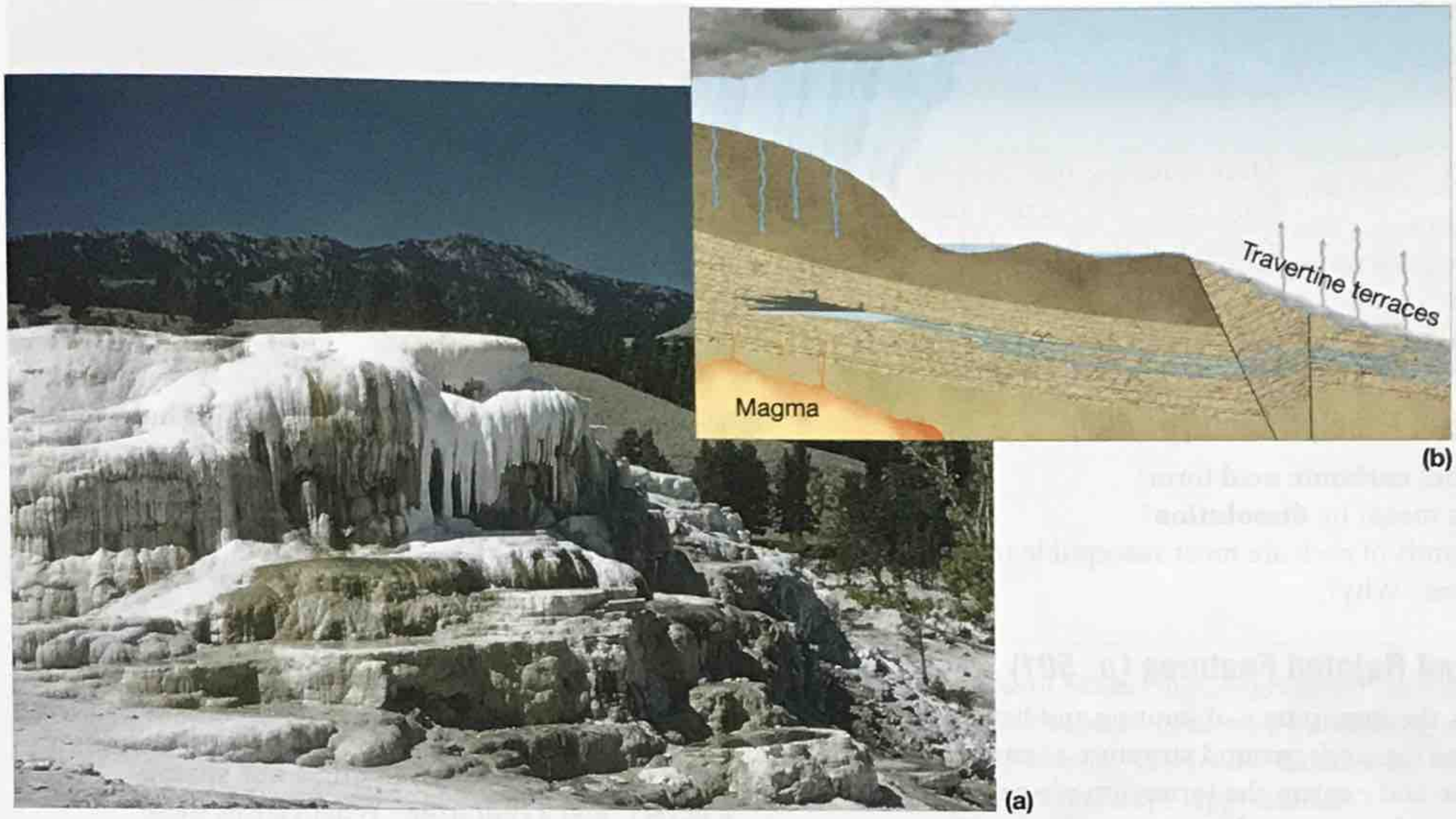
All the major geyser basins consist of gently undulating plains or valleys covered mostly with glacial sediments and large expanses of whitish siliceous material called *geyserite*. Each basin contains from a few to several dozen geysers, some of which are inconspicuous holes in the geyserite, but others of which are built-up cones that rise a few meters above the basin. In addition, each basin contains a number of hot springs and fumaroles.

Yellowstone's geysers exhibit an extraordinary range of behavior. Some erupt continually; others have experienced only a single eruption in all history. Most, however, erupt irregularly several times a day or week. Some shoot their hot water only a few centimeters into the air, but the largest (such as Steamboat and Excelsior) erupt to heights of 100 meters (330 feet), with clouds of steam rising much higher.

Mammoth Hot Springs: In the northwestern portion of the park is the most remarkable aggregation of hot-water terraces in the world—the Mammoth Hot Springs Terraces (Figure 17-17). There, groundwater percolates down from surrounding hills into thick layers of limestone. Hot water, carbon dioxide, and other gases rise from the heated magma to mingle with the groundwater and produce a mild carbonic acid solution that rapidly dissolves great quantities of the limestone. Saturated with dissolved minerals, the temporarily carbonated water seeps downslope until it gushes forth near the base of the hills as the Mammoth Hot Springs (Figure 17-18). The carbon dioxide escapes into the air, and the calcium carbonate is precipitated as massive deposits of travertine in the form of flat-topped, steep-sided terraces.



▲ **Figure 17-16** Yellowstone National Park and its major geyser basins. The approximate outline of the Yellowstone Caldera is shown.



▲ **Figure 17-17** Yellowstone's Mammoth Hot Springs. (a) Although the white material looks like snow or ice, it is actually travertine. (b) Water from rainfall and snowmelt percolates down into the underlying limestone, where it is heated and flows downslope. Hot water issues onto the surface and precipitates travertine deposits when exposed to the air.

◀ **Figure 17-18** Travertine terraces in Mammoth Hot Springs, Yellowstone National Park.

Chapter 17 LEARNING REVIEW

After studying this chapter, you should be able to answer the following questions. Key terms from each text section are shown in **bold type**. Definitions for key terms are also found in the glossary at the back of the book.

KEY TERMS AND CONCEPTS

Solution and Precipitation (*p. 499*)

1. How does **carbonic acid** form?
2. What is meant by **dissolution**?
3. What kinds of rock are most susceptible to solution processes? Why?

Caverns and Related Features (*p. 501*)

4. What is the importance of jointing and bedding planes to the underground structure of **caverns**?
5. Describe and explain the formation of **speleothems** such as **stalactites**, **stalagmites**, and columns.

Karst Topography (*p. 502*)

6. In what kinds of rocks does **karst** topography usually develop?
7. Explain how a **sinkhole** is formed.
8. Describe the formation of a **collapse sinkhole** and an **uvala**.
9. Describe the characteristics of **tower karst**.
10. What is a **swallow hole**? A **disappearing stream**?
11. Why is there a scarcity of surface drainage in karst areas?

Hydrothermal Features (*p. 505*)

12. What is **hydrothermal activity**?
13. What are the differences among a **hot spring**, a **geyser**, and a **fumarole**? What causes these differences?
14. Briefly explain the eruption sequence of a typical geyser.

STUDY QUESTIONS

1. Which is more important for the weathering action of underground water, mechanical or chemical weathering? Why?
2. How does the underground structure of the bedrock influence the dissolution process?
3. How is it possible for percolating groundwater to both remove mineral material and deposit it?
4. How can groundwater pumping by people lead to sinkhole formation?
5. What three conditions are necessary for hydrothermal features to develop?
6. What is the importance of jointing and bedding planes to the development of hot springs and geysers?
7. Why don't most geysers erupt at regular intervals?
8. The 1912 eruption of Mount Katmai in Alaska buried a nearby river valley beneath a thick layer of volcanic ash. Today the area is called "The Valley of 10,000 Smokes." What do you think this name refers to? Explain.

EXERCISES

1. If a "soda straw" speleothem in a cavern grows at an average rate of 1.7 mm per year, how long does it take to form a soda straw 18 centimeters long?
2. During the morning of August 14, 2011, Old Faithful Geyser in Yellowstone National Park erupted at the following times (to the nearest minute): 12:07 A.M., 1:42 A.M., 3:05 A.M., 4:41 A.M., 6:07 A.M., 7:37 A.M., 9:08 A.M., and 10:34 A.M. What was the average interval between eruptions on this morning? _____ minutes