13 Groundwater Systems

The movement of water in the pore spaces of rocks beneath Earth's surface is a geologic process that is not easily observed and therefore not readily appreciated; however, groundwater is an integral part of the hydrologic system and a vital natural resource. Groundwater is not rare or unusual. It is distributed everywhere beneath the surface of Earth. It occurs not only in humid areas, but also beneath desert regions, under the frozen polar regions, and in high mountain ranges. In many areas, the amount of water seeping into the ground equals or exceeds the surface runoff.

In many ways, groundwater systems are like river systems. For each there is a collecting system, transporting system, and a dispersal or discharge system. For groundwater, the collection area is the zone of recharge where surface water enters the subsurface. The path followed by the slowly moving groundwater is controlled by permeability and porosity of the

rocks in an aquifer. Along the flow path, groundwater, like river water, picks up materials and transports them. In groundwater systems, most of the transported materials are carried away as ions dissolved in water. Finally, like a river, a groundwater system has a discharge zone where the water comes back to the surface or enters a lake, river, or ocean. This photograph shows such a discharge zone on the walls of the Grand Canyon in Arizona. Even though this is an arid region, where only a few tens of centimeters of rain fall each year, there is enough recharge that a spring has formed on the steep canyon wall and feeds luxuriant vegetation around it. See Figure 13.13 for a cross-section through the formation which gives rise to this spring.

In this chapter we will study groundwater systems: how water moves through various types of pore spaces in the rock and how it forms karst topography, caves, and cave deposits. You will see that groundwater is related to surface drainage and how it erodes and deposits material to change loose sand into sandstone and fallen tree trunks into petrified wood. We will then consider how we use groundwater, this most precious natural resource, and how we attempt to cope with the environmental problems that result when we modify and manipulate this part of the hydrologic system.

MAJOR CONCEPTS

1. Groundwater is an integral part of the hydrologic system, and it is intimately related to surface water drainage.
2. The movement of groundwater is controlled largely by the porosity and permeability of the rocks through which it flows.
3. The water table is the upper surface of the zone of saturation.
4. Groundwater moves slowly through the pore spaces in rock.
5. The natural discharge of groundwater is generally into springs, streams, marshes, and lakes.
6. Aquifers are saturated permeable rocks; they may be confined between impermeable layers or unconfined and open to the surface.
7. Erosion by groundwater produces karst topography, which is characterized by caves, sinkholes, solution valleys, and disappearing streams. Precipitation of minerals from groundwater creates deposits in caves and along fractures and cements many kinds of clastic sedimentary rocks.
8. Alteration of the groundwater can produce many unforeseen problems, such as pollution, subsidence, collapse, and disruption of ecosystems.

GROUNDWATER SYSTEMS

Two physical properties of a rock largely control the amount and movement of groundwater. One is porosity, the percentage of the total volume of the rock consisting of voids. The other is permeability, the capacity of a rock to transmit fluids.

Groundwater is not stagnant and motionless. Rather, it is a dynamic part of the hydrologic system, in constant motion, and is intimately related to surface drainage. Gravity is the principal driving force for the flow of groundwater. Moreover, like other parts of the hydrologic system (rivers and glaciers), the groundwater system is an open system. Water enters the system when surface water infiltrates the ground (**recharge**); water moves through the system by percolating through the pore spaces of rock and ultimately leaves the system by seeping into streams, springs or lakes (**discharge**). Along this flow path, groundwater does geologic work—mostly as a result of solution or precipitation of rock. The characteristics of the material through which the water moves are fundamental controls on the groundwater system.

Porosity

Permeable Flow

Water can infiltrate the subsurface because solid bedrock—as well as loose soil, sand, and gravel—contains **pore spaces.** There are four main types of pore spaces, or voids, in rocks (Figure 13.1): (1) spaces between mineral grains, (2) fractures, (3) solution cavities, and (4) vesicles. In sand and gravel deposits, pore space can constitute from 12% to 45% of the total volume. If several grain sizes are abundant and the smaller grains fill the space between larger grains, or if a significant amount of cementing material fills the spaces between grains, the **porosity** is greatly reduced. All rocks are cut by fractures, and in some dense rocks (such as granite), fractures are the only significant pore spaces (Figure 13.1). Solution activity, especially in limestone, commonly removes soluble material, forming pits and holes. Some limestones thus have high porosity. As water moves along joints and bedding planes in limestone, solution activity enlarges fractures in the rock and develops passageways that may grow to become caves. In basalts and other volcanic rocks, vesicles formed

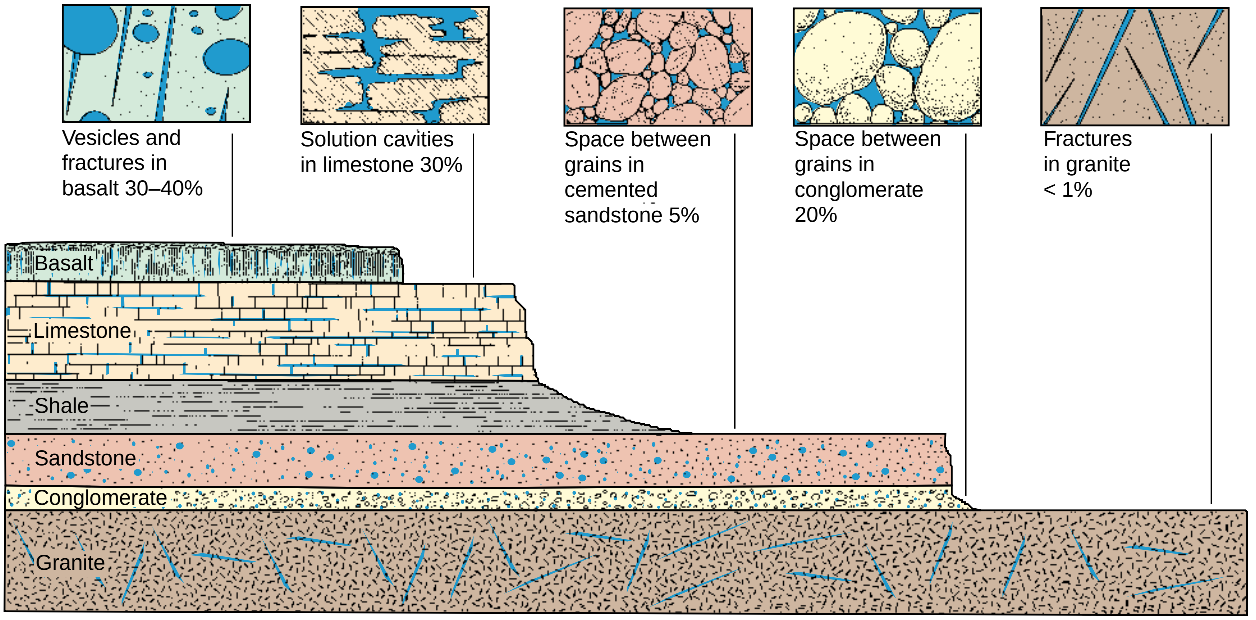


FIGURE 13.1 **Various types of pore spaces** in rocks permit the flow of groundwater.

by trapped gas bubbles significantly affect porosity. Vesicles commonly are concentrated near the top of a lava flow and form zones of very high porosity; these zones can be interconnected by columnar joints or through the voids in cinders and rubble at the top and base of the flow.

Permeability

Permeability, the capacity of a rock to transmit a fluid, varies with the fluid's viscosity, **hydrostatic pressure,** the size of openings, and particularly the degree to which the openings are interconnected. If the pore spaces are very small, a rock can have high porosity but low permeability because it is difficult for water to move through small openings.

How can a rock be highly porous and still have low permeability?

Rocks that commonly have high permeability are conglomerates, sandstones, basalt, and certain limestones. Permeability in sandstones and conglomerates is high because of the relatively large, interconnected pore spaces between the grains. Basalt is permeable because it is often extensively fractured by columnar jointing and because the tops of most flows are vesicular. Fractured limestones are also permeable, as are limestones in which solution activity has created many small cavities. Rocks that have low permeability are shale, unfractured granite, quartzite, and other dense, crystalline metamorphic rocks.

Water moves through the available pore spaces following a tortuous path as the flow twists and turns through the tiny voids. Whatever the permeability of the rock, groundwater flows slowly and the flow is laminar. Thus, the flow of groundwater contrasts sharply with the turbulent flow of rivers. Whereas the flow velocity of water in rivers is measured in kilometers per hour, the flow velocity of groundwater commonly ranges from 1 m/day to 1 m/yr. The rate of percolation in exceptionally permeable material is only 250 m/day. Some water takes more than a million years to move from recharge to discharge zone. Only in special cases, such as the flow of water in caves, does the movement of groundwater even approach the velocity of slow-moving surface streams.

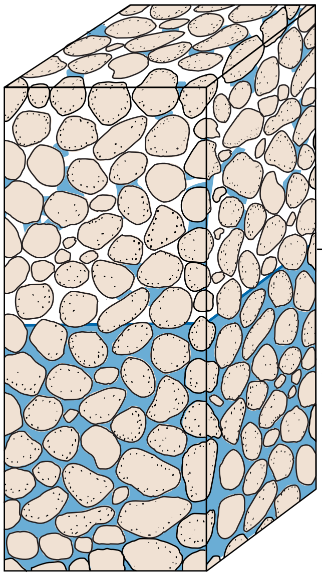


FIGURE 13.2 **The water table** is the upper surface of the zone of saturation. Water seeps into the ground through pore spaces in rock and soil. It passes first through the zone of aeration, in which the pore spaces are occupied by both air and water, and then into the zone of saturation, in which all of the pore spaces are filled with water. The depth of the water table varies with climate and amount of precipitation.

What is the general configuration of the water table?

THE WATER TABLE AND AQUIFERS

The water table is the upper surface of the zone of saturation. Aquifers are saturated permeable rocks; they may be open or confined.

As water seeps into the ground, gravity pulls it downward through two zones of soil and rock. In the upper zone, the pore spaces in the rocks are only partly filled with water, and the water forms thin films, clinging to grains by surface tension. This zone, in which pore space is filled partly with air and partly with water, is the **zone of aeration.** Below a certain level, all of the openings in the rock are completely filled with water (Figure 13.2). This area is called the **zone of saturation.** The **water table,** which is the upper surface of the zone of saturation, is an important element in the groundwater system. It may be only a meter or so deep in humid regions, but it might be hundreds or even thousands of meters below the surface in deserts. In swamps and lakes, the water table is essentially at the land surface (Figure 13.3). Although the water table cannot be observed directly, it has been studied and mapped with data collected from wells, springs, and surface drainage. In addition, the movement of groundwater has been studied by means of radioactive isotopes, dyes, and other tracers, so extensive knowledge of this invisible body of water has been acquired.

A permeable zone or formation that is saturated with water is known as an **aquifer** (Figure 13.4). Aquifers are filled, or recharged, as surface water seeps downward through the zone of aeration. An **unconfined aquifer** is connected to the surface by open pore spaces through which it can be recharged, as shown in Figure 13.3. In an unconfined aquifer, the amount of water is indicated by the height of the water table. Saturated zones in surficial deposits of sand and gravel are commonly unconfined aquifers. They can easily be contaminated by fluids at the surface. At considerable depths, all pore spaces in the rocks are closed by high pressure, and there is no free water. This is the lower limit, or base, of a groundwater system (Figure 13.5). Several important generalizations can be made about the water table and its relation to surface topography and surface drainage (Figure 13.3). In general, the water table tends to mimic the surface topography. In flat country, the water table is flat. In areas of rolling hills, it rises and falls with the surface of the land. The reason is that groundwater moves very slowly, so the water table rises in the areas beneath the hills during periods of greater precipitation but takes a long time to flatten out during droughts.

In humid areas, the water table is at the surface in lakes, swamps, and most streams, and water moves in the subsurface toward these areas, following the general paths shown in Figure 13.3. In arid regions, however, most streams lie above the water table, so they lose much of their water through seepage. Where impermeable layers (such as shale) occur within the zone of aeration, the groundwater is trapped above the general water table, forming a local **perched water table.** If a perched water table extends to the side of a valley, springs and seeps occur.

Confined aquifers are permeable rock units enclosed within impermeable strata such as shales (see Figure 13.9). Confined aquifers typically lie deep below the surface but are recharged in highlands where the permeable rocks are exposed. A sandstone aquifer that extends under much of the upper midwestern states of Iowa and Missouri is recharged hundreds of kilometers to the north in Wisconsin, where the permeable rocks outcrop at the surface. The water pressure in a confined aquifer can reach high levels. Water does not leak readily into a confined aquifer directly downward from the surface.

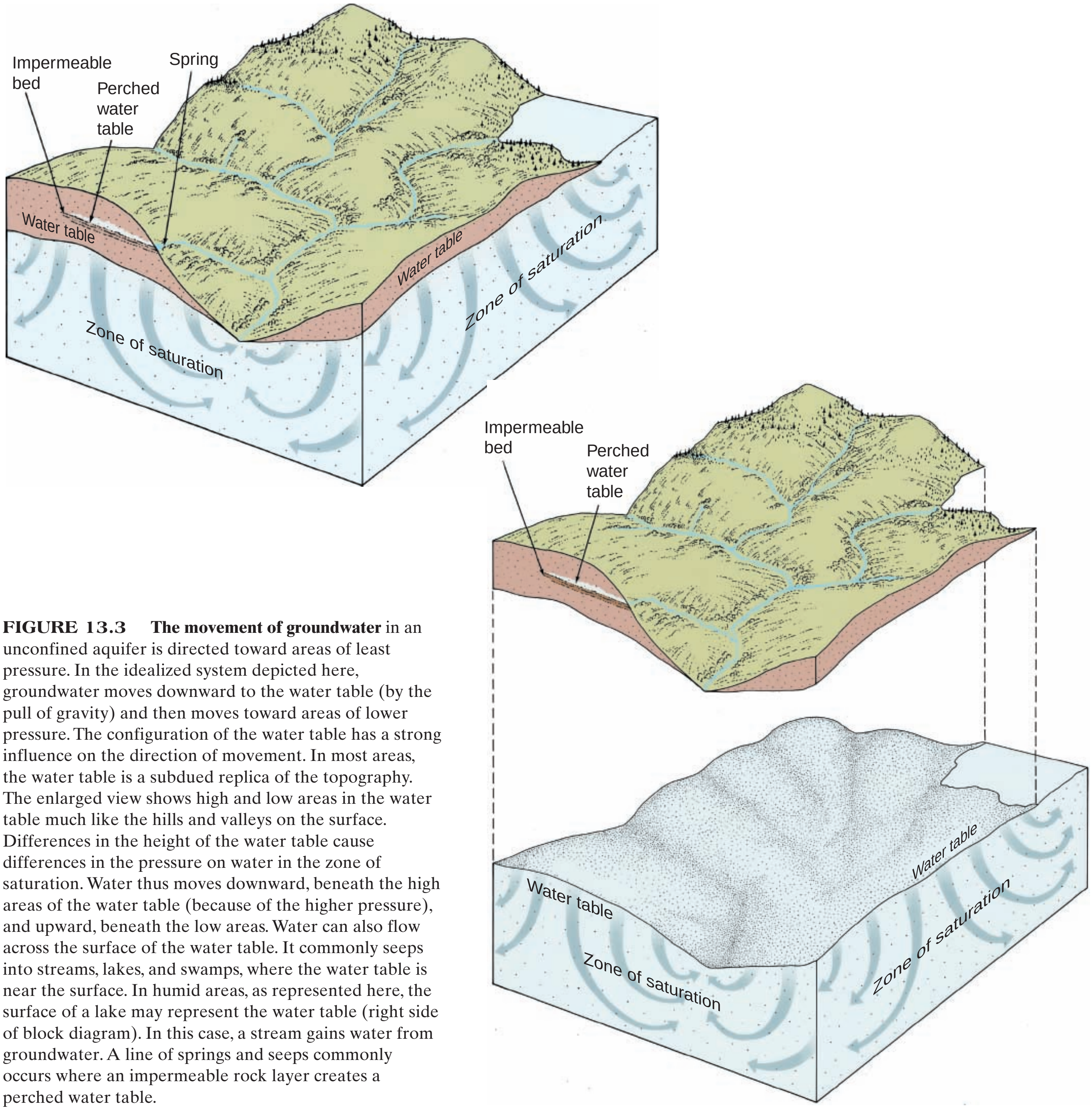


FIGURE 13.3 **The movement of groundwater** in an unconfined aquifer is directed toward areas of least pressure. In the idealized system depicted here, groundwater moves downward to the water table (by the pull of gravity) and then moves toward areas of lower pressure. The configuration of the water table has a strong influence on the direction of movement. In most areas, the water table is a subdued replica of the topography. The enlarged view shows high and low areas in the water table much like the hills and valleys on the surface. Differences in the height of the water table cause differences in the pressure on water in the zone of saturation. Water thus moves downward, beneath the high areas of the water table (because of the higher pressure), and upward, beneath the low areas. Water can also flow across the surface of the water table. It commonly seeps into streams, lakes, and swamps, where the water table is near the surface. In humid areas, as represented here, the surface of a lake may represent the water table (right side of block diagram). In this case, a stream gains water from groundwater. A line of springs and seeps commonly occurs where an impermeable rock layer creates a perched water table.

THE MOVEMENT OF GROUNDWATER

Groundwater moves from zones of high pressure to zones of lower pressure.

In an unconfined aquifer, the difference in elevation between parts of the water table is known as the **hydraulic head.** These pressure differences cause the water in the aquifer to follow the paths illustrated in Figure 13.3. If we could trace the path of a particle of water, we would find that gravity slowly pulls it through the zone of aeration to the water table. When a particle encounters the water table, it

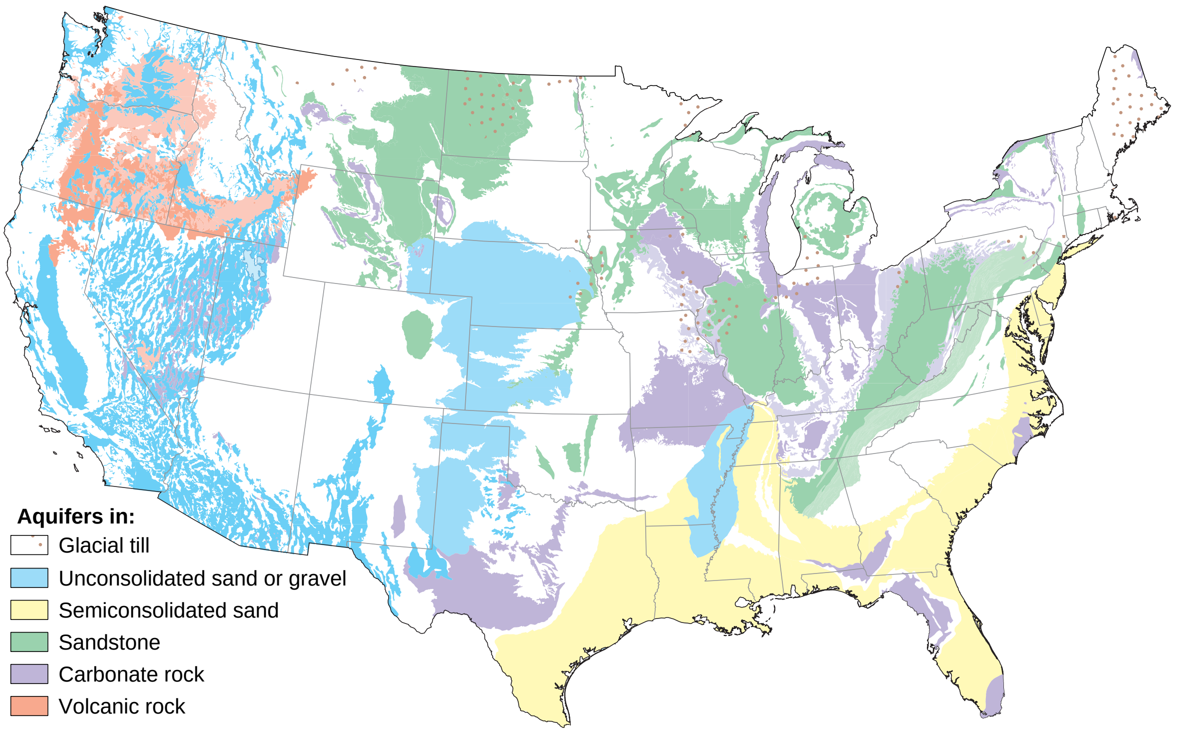


FIGURE 13.4 **The major aquifers** of the United States are shown on this map. Each aquifer consists of permeable rocks. Much of the country's drinking water and water for irrigation is extracted from these reservoirs. For some aquifers, extraction is faster than recharge. *(Modified after U.S. Geological Survey)*

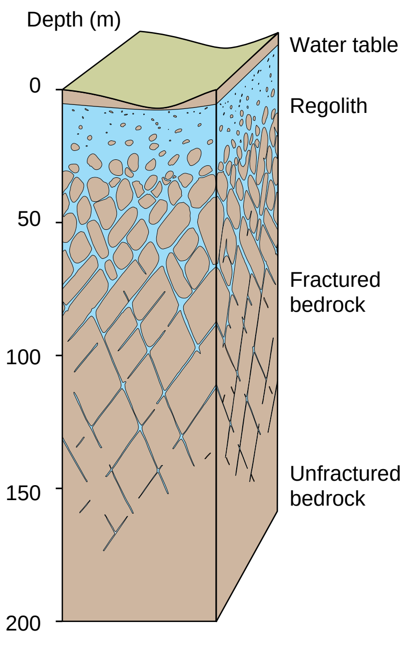


FIGURE 13.5 **The base of an unconfined groundwater reservoir** is not an abrupt surface like the water table. Most of the groundwater reservoir is in porous regolith and bedrock. Different rock types have substantially different porosities and permeabilities. Open pores gradually close with depth, so the base of the reservoir varies from place to place.

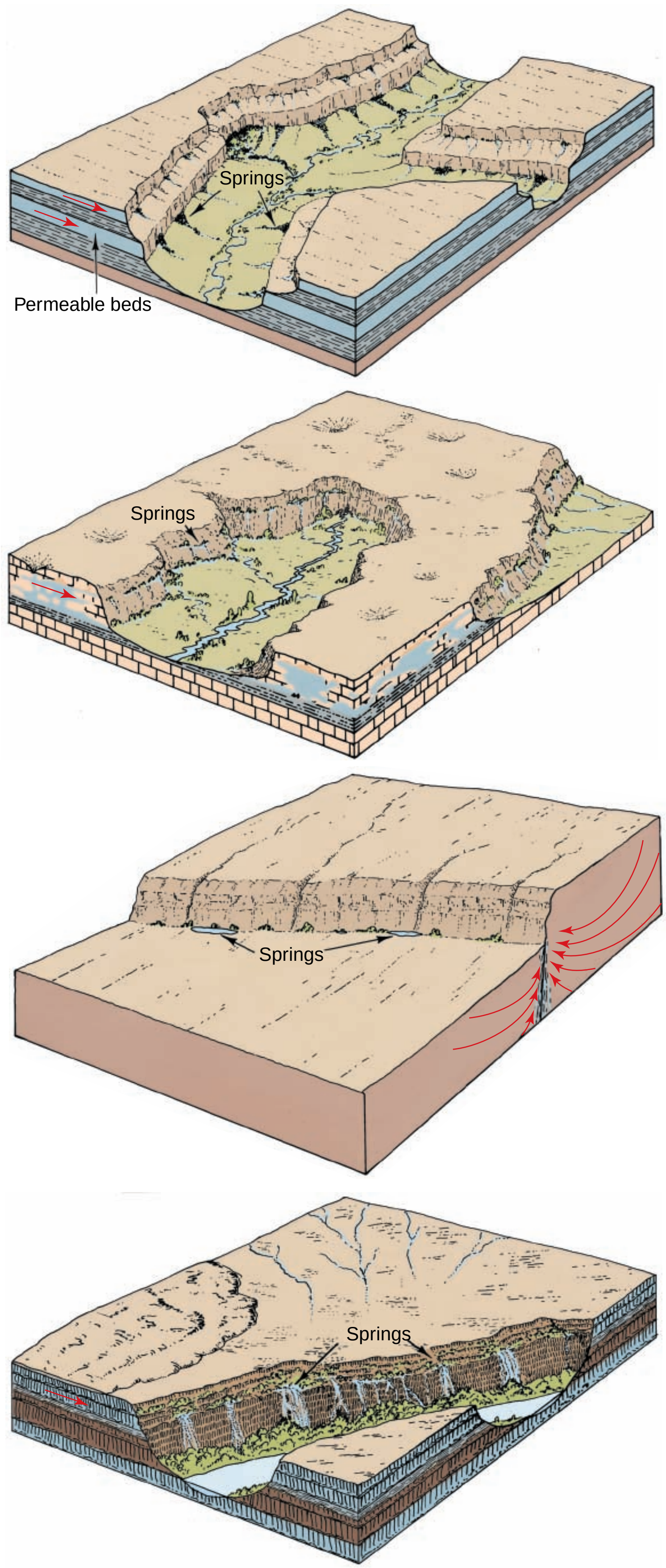
continues to move downward, by the pull of gravity, along curved paths from areas where the water table is high toward areas where it is low (lakes, streams, and swamps). The explanation for this seemingly indirect flow is that the water table is not a solid surface like the ground surface. Water at any given point below the water table beneath a hill is under greater pressure than water at the same elevation below the lower water table in a valley. Groundwater therefore moves downward and toward points of less pressure.

Although these paths of groundwater movement may seem indirect, they conform to the laws of fluid physics and have been mapped in many areas by tracing the movement of dye injected into the system. The movement of the dye reveals a continuous, slow circulation of groundwater, from infiltration at the surface to seepage into streams, rivers, and lakes.

NATURAL AND ARTIFICIAL DISCHARGE

> Natural discharge of the groundwater reservoir occurs wherever the water table intersects the surface of the ground. In general, such places are inconspicuous, typically occurring in the channels of streams and on the floors and banks of marshes and lakes. This discharge is the major link between groundwater reservoirs and other parts of the hydrologic system.

The natural discharge of groundwater into streams, lakes, and marshes is the major link between groundwater reservoirs and other parts of the hydrologic system (Figure 13.6). If it were not for groundwater discharge, many permanent streams would be dry during parts of the year. Most natural discharge is into streams and lakes and, therefore, usually goes unnoticed. It is detected and measured directly by comparing the volume of precipitation with the volume of surface runoff.



(A) A line of springs develops on valley walls where impermeable beds cause groundwater in permeable layers to migrate laterally and eventually to seep out at the surface. They are commonly marked by an abnormal growth of vegetation.

(B) Springs form along valley slopes where cavernous limestone permits the free flow of groundwater to the surface.

(C) Many faults displace rocks so that impermeable beds are placed next to permeable beds. A spring line commonly results as groundwater migrates upward along a fault.

(D) Surface water readily seeps into vesicular and jointed basalt flows. It then migrates laterally and forms springs where basalt units are exposed in canyon walls.

FIGURE 13.6 **Springs** can be produced under a variety of geologic conditions, some of which are illustrated in the block diagrams here. They are natural discharges of the groundwater reservoir and introduce a significant volume of water to surface runoff.

Artificial discharge results from the extraction of water from wells, which are made by simply digging or drilling holes into the zone of saturation. Many thousands of wells have been drilled, so in some areas artificial discharge has modified the groundwater system. Indeed, in some areas, more water is removed from the groundwater system by artificial discharge than is added by natural recharge, and the level of the water table drops.

Natural Discharge

What geologic conditions produce natural springs?

Several geologic conditions that produce natural discharge in the form of **seeps** and **springs** are shown in Figure 13.6. If permeable beds alternate with impermeable layers (Figure 13.6A), the groundwater is forced to move laterally to the outcrop of the permeable bed. Conditions such as this usually are found in mesas and plateaus where permeable sandstones are interbedded with impermeable shales. The spring line commonly is marked by a line of vegetation. Figure 13.6B shows a limestone terrain in which springs occur where the base of the cavernous limestone outcrops. Kentucky's Mammoth Cave area is a good example. Figure 13.6C shows springs along a fault that produces an avenue of greater permeability. Faults frequently displace strata for significant distances; thus, impermeable beds, which block the flow of groundwater, may be displaced along a fault so that they are positioned against permeable rocks. The water then moves up along the fault plane and forms springs along the fault line. Many of the great spas of Europe depend upon springs originating on faults. Figure 13.6D shows lava formations that outcrop along the sides of a canyon. Springs develop because groundwater migrates readily through the layers of vesicular and jointed basalt. Note that surface drainage disappears as the water flows over the lava plain.

An excellent example of this last type of discharge is found in the Thousand Springs area of southern Idaho, where numerous springs occur along the sides of the Snake River Canyon (Figure 13.7). This region is a vast lava plain extending across the entire southern part of the state. It was built up by innumerable flows

(A) Drainage in the tributaries to the Snake River is influenced by the high porosity and permeability of the basaltic bedrock (gray).

(B) The springs issue from the north wall of the canyon and are fed by water that flowed underground.

FIGURE 13.7 **Thousand Springs** along the Snake River Canyon, Idaho, are fed by water that seeps into the basaltic lava plain about 200 km to the northeast. The major tributaries coming from the north lose their entire volume of water by seepage into the subsurface, and the rivers simply end. Much of the groundwater reappears to form the spectacular Thousand Springs.

of basaltic lava, with some interbedded sand and gravel deposited in streams and lakes that occupied the region during the intervals between volcanic eruptions. The porosity and permeability of these basaltic rocks are remarkably high. Porosity is produced by columnar joints and vesicular texture in the basalt and by pore space in zones of rubble at the tops and bottoms of the basalt flows. In addition, porosity is naturally high in lava tubes and in layers of unconsolidated coarse sand and gravel between some flows. In terms of permeability, the rock sequence is almost like a sieve. The Snake River lies near the southern margin of the lava-covered plain, so tributary streams coming from the mountains to the north are forced to flow across the plain before they can join the Snake (Figure 13.7A). Only one river actually completes the short journey. The rest end after flowing a short distance across the plain; they lose their entire volume of water by seepage into the subsurface. Two of the main would-be tributaries are known as Big Lost and Little Lost Rivers. The groundwater returns to the surface in a series of spectacular springs approximately 200 km downstream. The largest and best known are the Thousand Springs just west of Twin Falls, Idaho (Figure 13.7B). These springs clearly show the tremendous movement of groundwater as they discharge about 1500 m^3/sec (nearly 37,000 gal/sec). The visible springs issue from a layer of vesicular basalt 50 m above the river. However, the volume of water that seeps into the Snake River in a less-spectacular fashion below the banks is no doubt many times as great. So much water comes from the Thousand Springs area that an electric power plant has been built on the site to use the energy.

Wells—Artificial Discharge

Ordinary wells are made simply by digging or drilling holes through the zone of aeration into the zone of saturation, as shown in Figure 13.8. Water then flows out of the pores into the well, filling it to the level of the water table. When a well is pumped, the water table is drawn down around the well in the shape of a cone, known as the **cone of depression**. If water is withdrawn faster than it can be replenished, the cone of depression continues to grow, and the well ultimately goes dry. The cone of depression around large wells, such as those used by cities and industrial plants, can be many hundreds of meters in diameter. All wells within the cone of depression are affected (Figure 13.8). This undesirable condition has been the cause of "water wars," fought physically and in the courts. Because groundwater is not fixed in one place, as mineral deposits are, it is difficult to determine who owns it. Many disputes are now being arbitrated using comput-

What is the cone of depression in the water table? How is it produced?

Drawdown

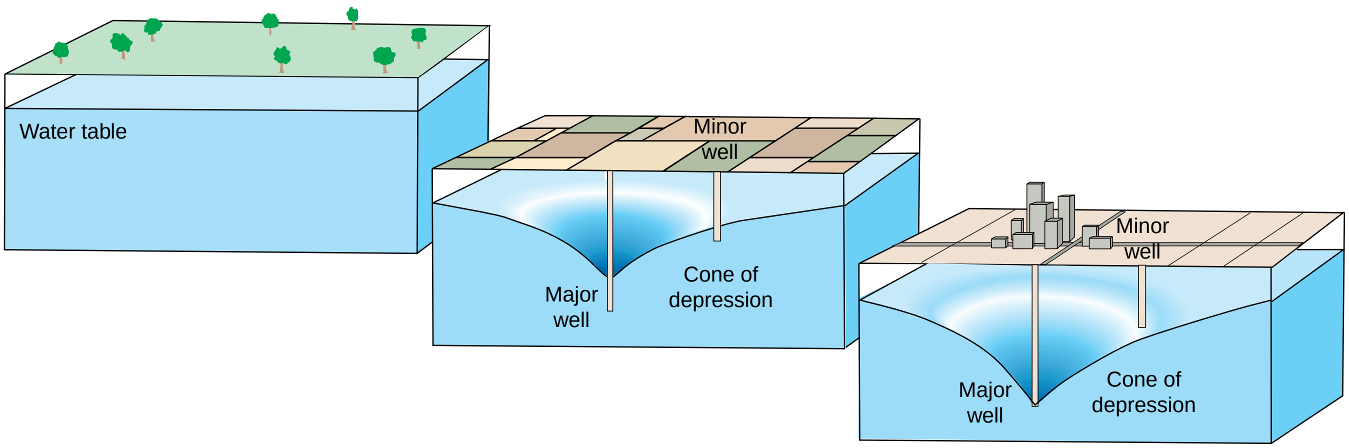


FIGURE 13.8 **A cone of depression** in a water table results if water is withdrawn from a well faster than it can be replenished. The cone can extend for hundreds of meters around large, deep wells and effectively lower the water table over a large area. Shallow wells nearby then run dry because they lie above the lowered water table.

er models that simulate subsurface conditions such as permeability, direction of flow, and level of the water table. The models predict what changes will occur in the groundwater system if given amounts of water are drawn out of a well over specified times.

Extensive pumping can lower the general surface of the water table. This effect has had serious consequences in some metropolitan areas in the southwestern United States, such as Phoenix, Arizona, where the water table has fallen hundreds of meters. The supply of groundwater is limited. Although the groundwater reservoir is being continually replenished by precipitation, the migration of groundwater is so slow that it can take hundreds of years to raise a water table to its former position of balance with the hydrologic system.

CONFINED AQUIFERS

Water in a confined aquifer lies between impermeable beds and is under pressure, like water in a pipe. Where a well or fracture intersects the aquifer, water rises in the opening to reach the potentiometric surface and may produce a flowing (or artesian) well.

A very important type of groundwater occurs in a confined aquifer where a permeable rock body confined between impermeable beds, where it is under pressure. A well drilled into such an aquifer will commonly allow water to rise and flow freely without pumping. The name **artesian** was originally applied to flowing wells in a French province along the English Channel, where this condition is common. The necessary geologic conditions for artesian water, illustrated in Figure 13.9, include the following:

1. The rock sequence must contain interbedded permeable and impermeable strata to create a confined aquifer. This sequence occurs commonly in nature as interbedded sandstone and shale. Permeable beds form the aquifers.
2. The rocks must be tilted and exposed in an elevated area where water can infiltrate into the aquifer.
3. Sufficient precipitation and surface drainage must occur in the outcrop area to keep the aquifer filled.

The water confined in an aquifer behaves much as water does in a pipe. Hydrostatic pressure builds up, so where a well or fracture intersects the bed, water rises in

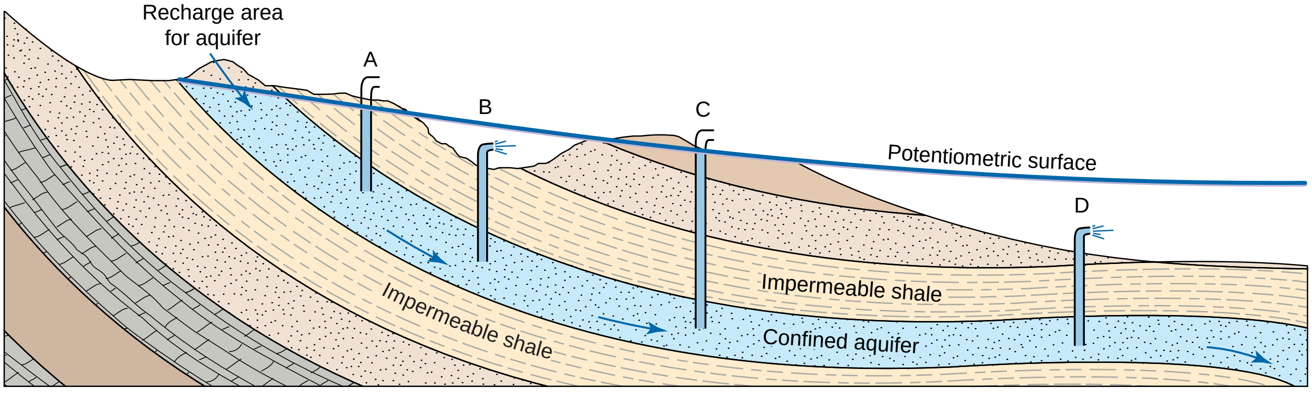


FIGURE 13.9 The necessary geologic conditions for a flowing well include (1) a permeable bed (aquifer, blue) confined between impermeable layers, (2) rocks tilted so the aquifer can receive infiltration from surface waters, and (3) adequate infiltration to fill the aquifer and create hydrostatic pressure. Consequently, water rises in all of the wells (A, B, C, D) to a level called the potentiometric surface. Flowing (or artesian) wells occur only when the top of the well is below the potentiometric surface and require no pumping.

the opening. The height to which water in a confined aquifer rises is shown by the colored line in Figure 13.9. The imaginary surface defined by this level is called the **potentiometric surface**. You might expect it to be a horizontal surface, but actually, a potentiometric surface slopes away from the recharge area. The mineral grains in the aquifer provide resistance to flow, lowering the water pressure. Some pressure is also lost through minor leaks in the underground plumbing system. If a well were drilled at location A or C in Figure 13.9, water would rise in the well, but it would not flow to the surface because the potentiometric surface is below the ground surface. Water in a well at location B or D, where the potentiometric surface is above the ground, would flow to the surface. Nonetheless, the water in all of these wells is under pressure and rises above the top of the aquifer.

What produces flowing wells?

Confined aquifers are common in most areas underlain by sedimentary rocks because the necessary geologic conditions are present in various ways. One of the better-known confined aquifers underlies the Great Plains states (Figure 13.10A). The sequence of interbedded sandstones, shales, and limestones is nearly horizontal throughout most of Kansas, Nebraska, and the Dakotas, but it is upwarped along the eastern front of the Rockies and the margins of the Black Hills. Several sandstone formations are important aquifers. Water is confined in them under hydrostatic pressure. The recharge area is along the foothills of the Rockies.

Figure 13.10B illustrates another type of confined aquifer in the inclined strata of the Atlantic and Gulf Coast plains of North America. The rock sequence consists of permeable sandstone and limestone beds, alternating with impermeable clay. Surface water, flowing toward the coast, seeps into the beds where they are exposed at the surface. It then moves slowly down the dip of the permeable strata.

A third example is from the western United States, where the arid climate makes confined aquifers an important resource (Figure 13.10C). In this region, the subsurface rocks in an intermontane basin consist of sand and gravel deposited in ancient alluvial fans. Farther into the basin, these deposits are interbedded with layers of clay and silt deposited in playa lakes. These fine-grained strata act as confining layers bounding permeable layers of sand and gravel. Water seeping into the fan deposits becomes confined as it moves away from the mountain front.

Confined aquifers also underlie some of the world's great desert regions. Natural discharge from them is largely responsible for oases. Part of the Sahara system is shown in Figure 13.10D. Oases occur where water from a confined aquifer is brought to the surface by fractures or folds or where the desert floor is eroded down to the top of the aquifer.

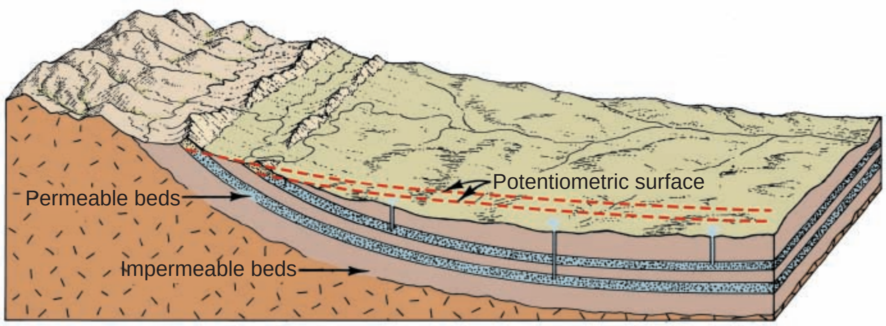
Note that each example shown in Figure 13.10 has the basic geologic conditions necessary for artesian water: (1) There is a sequence of interbedded permeable and impermeable strata, and (2) the sequence of strata is tilted so that the strata are exposed in an elevated area, enabling surface water to infiltrate into the aquifer. The main difference in each area is in the details of the rock structure and sequence of strata.

THERMAL SPRINGS AND GEYSERS

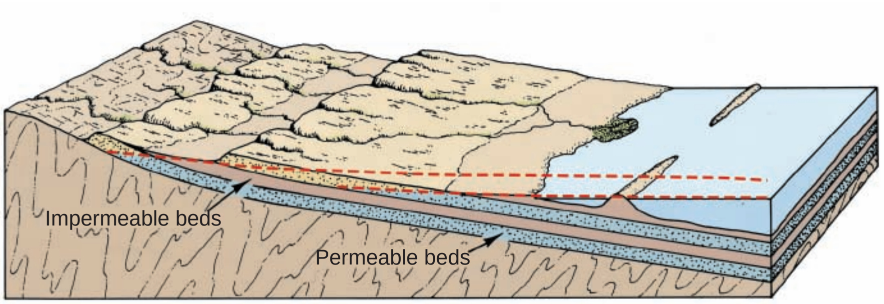
In areas of recent igneous activity, rocks associated with old magma chambers can remain hot for hundreds of thousands of years. Groundwater migrating through these areas of hot rocks becomes heated and, when discharged to the surface, produces thermal springs and geysers.

The most spectacular manifestation of groundwater is in the areas of thermal springs and geysers, where scalding water and steam commonly erupt high into the air. Geysers and thermal springs are usually the results of groundwater migrating through areas of hot, but not molten, igneous rocks.

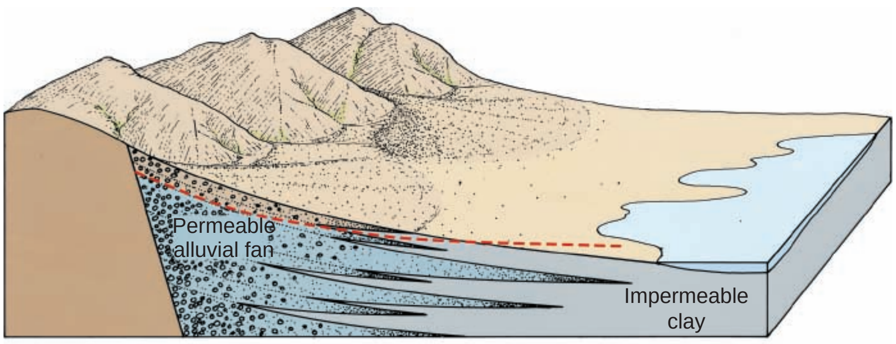
(A) The Great Plains states are underlain by permeable Cretaceous sandstones that are warped up along the front of the Rocky Mountains, where they receive infiltration. This structure forms a widespread confined aquifer in Kansas, Nebraska, and the Dakotas.



(B) Under the Atlantic and Gulf Coast states Tertiary and Cretaceous rocks dip uniformly toward the ocean. Water enters permeable beds where they are exposed and becomes confined down the dip to form a large confined aquifer.



(C) The intermontane basins in the western United States contain permeable sand and gravel (deposited in alluvial fans) interfingered with impermeable clay deposits (deposited in playa lakes). Water seeps into the lenses of buried fan deposits and is confined by the clay to form a confined system.



(D) The Sahara Desert of North Africa is underlain mostly by gently warped permeable beds that receive water where they are exposed at the base of the Atlas Mountains. Oases form when water from the confined aquifer discharges through fractures or where the aquifer is exposed by erosion.

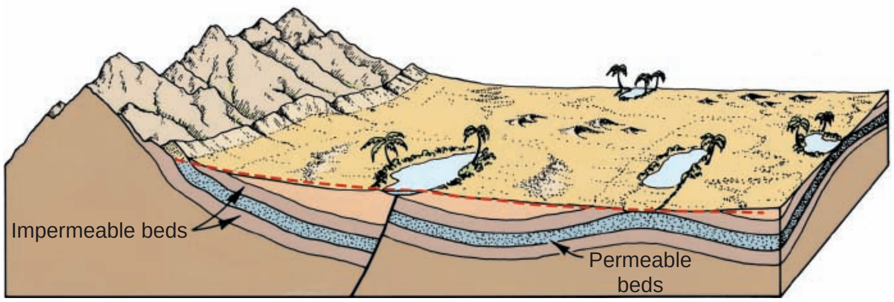


FIGURE 13.10 **Confined aquifers** develop under a variety of geologic conditions, some of which are illustrated in these block diagrams. The main difference is in the geometry of the rock structures in each area. The potentiometric surface is shown with a dashed red line.

The three most famous regions of hot springs and **geysers** (a hot spring that intermittently erupts jets of hot water and steam) are Yellowstone National Park of Wyoming, Iceland, and New Zealand. All are regions of recent volcanic activity, so the rock temperatures just below the surface are quite high. Although no two geysers are alike, all require certain conditions for their development:

1. A body of hot rocks must lie relatively close to the surface.
2. A system of fractures must extend downward from the surface.
3. A relatively large supply of groundwater must be present.

Eruptions of Geysers

Geyser eruptions occur when groundwater pressure in fractures, caverns, or porous rock builds to a critical point at which the temperature-pressure balance is such that a small change will cause the water to convert instantly into steam (Figure 13.11). Because the water at the base of the fracture is under greater pressure than the water above, the deeper water must be heated to a higher temperature before it boils. Eventually, a slight increase in temperature or a decrease in pressure (resulting from the liberation of dissolved gases) causes the deeper water to boil. The expanding steam throws water from the underground chambers high into the air. After the pressure is released, the caverns refill with water and the process is repeated.

Why do geysers erupt in cycles?

This process accounts for the periodic eruption of many geysers. The interval between eruptions is the amount of time required for water to percolate into the fracture and be heated to the critical temperature. Geysers such as Old Faithful in Yellowstone National Park erupt at definite intervals because the rocks are permeable and the "plumbing system" refills rapidly. Other geysers, which require more time for water to percolate into the chambers, erupt at irregular intervals because the water supply over a longer period of time can fluctuate.

Hot water migrates upward through the surrounding rock without losing much heat or energy and emerges at the surface as thermal springs, sometimes at boiling temperatures. These waters are loaded with chemicals dissolved from the rocks through which they flow. Where they reach the surface, they quickly cool and precipitate various minerals in beautiful splashes of color (Figure 13.12).

Geothermal Energy

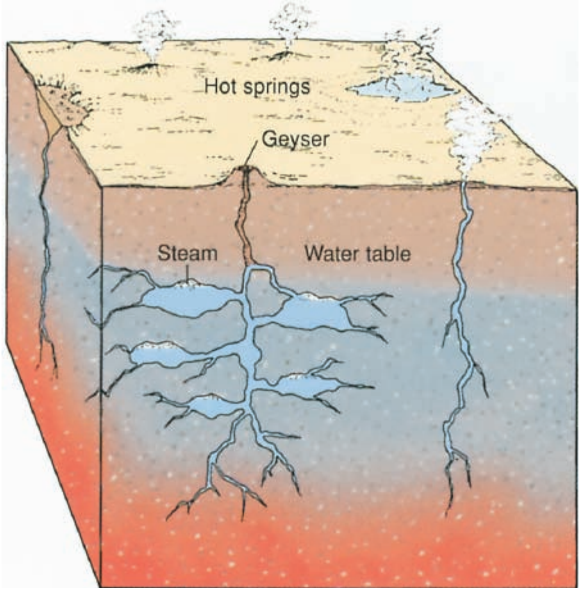
The thermal energy of groundwater, or **geothermal energy,** offers an attractive source of energy for human use. At present, it is used in various ways in areas of the United States, Mexico, Italy, Japan, and Iceland.

In Iceland, geothermal energy has been used successfully since 1928. Wells are drilled in geothermal areas, and the steam and hot water are piped to storage tanks and then pumped to homes and municipal buildings for heating and hot water. The cost of this direct heating is only about 60% of that of fuel-oil heating and about 75% of the cost of the cheapest method of electrical heating. Steam from geothermal energy is also used to run electric generators, producing an easily transported form of energy.

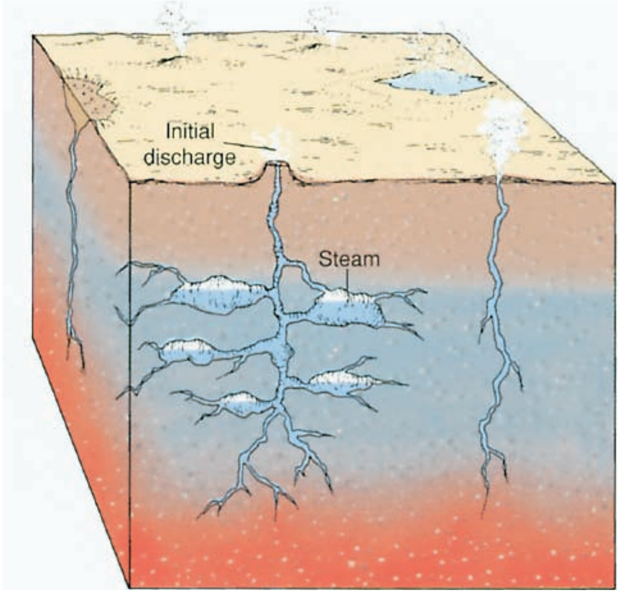
EROSION BY GROUNDWATER

> Slow-moving groundwater can dissolve huge quantities of soluble rock and carry it away in solution. In some areas, it is the dominant agent of erosion and produces karst topography, which is characterized by sinkholes, solution valleys, and disappearing streams.

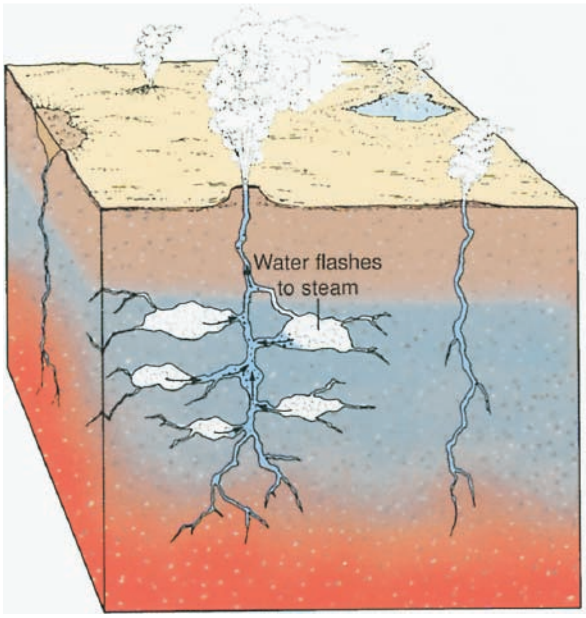
Groundwater can accomplish erosion on an enormous scale, but unlike streams, groundwater erodes only by dissolving soluble rocks such as limestone, dolostone,



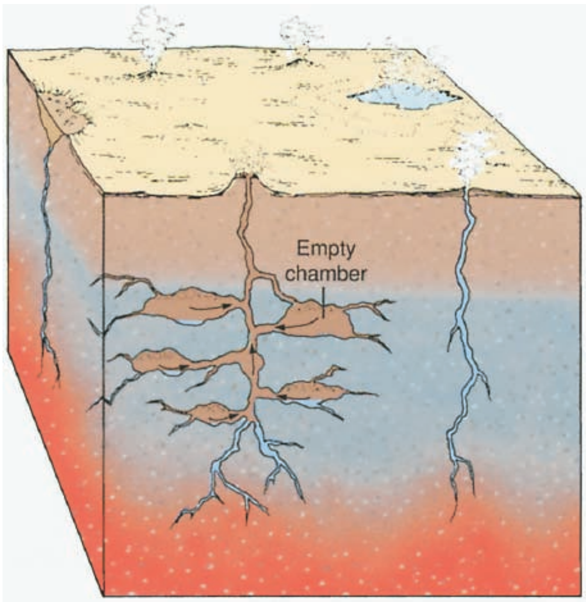
(A) Groundwater circulating through hot rocks in an area of recent volcanic activity collects in caverns and fractures. As temperature rises the water boils and steam bubbles rise, grow in size and number, and may accumulate in restricted parts of the geyser tube.



(B) The expanding steam forces water upward until it is discharged at the surface vent. The deeper part of the geyser system becomes ready for the major eruption.



(C) The preliminary discharge of water reduces the pressure on the water lower down. Consequently, water from the side chambers and pore spaces begins to flash into steam, forcing the water in the geyser system to erupt.



(D) Eruption ceases when the pressure from the steam is spent and the geyser tubes are empty. The system then begins to fill with groundwater again, and the eruption cycle starts anew.

FIGURE 13.11 **The origin of geysers** is depicted in this series of diagrams. A geyser can develop only if (1) a body of hot rock lies relatively close to the surface, (2) a system of irregular fractures extends down from the surface, and (3) there is a constant supply of groundwater. Hot springs and mud pots develop where groundwater has freer access to the surface.

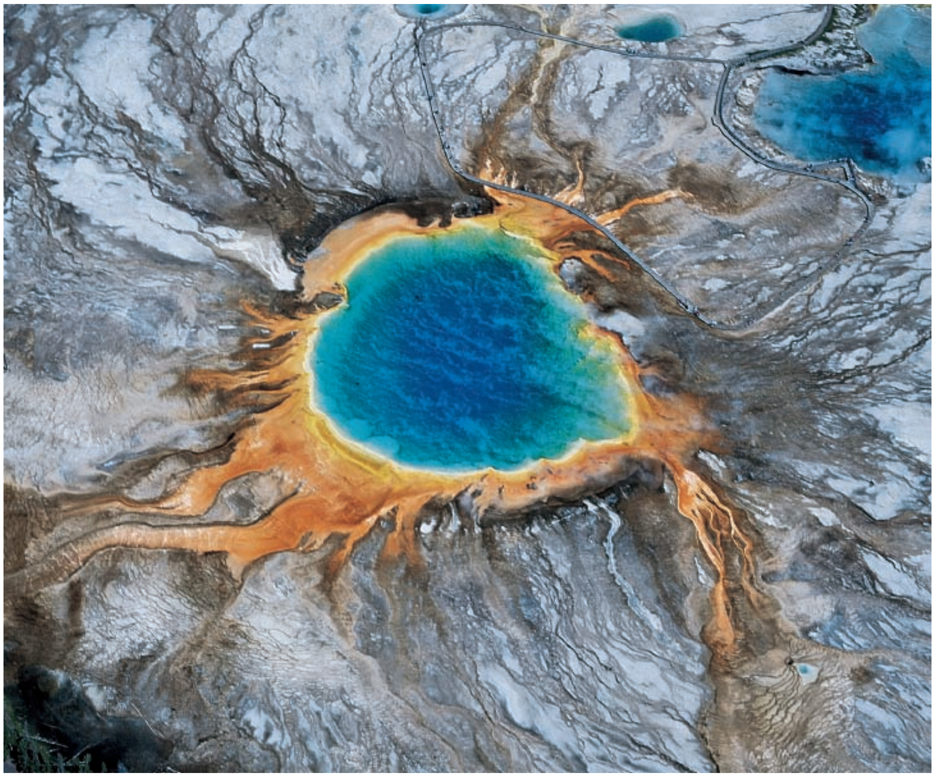


FIGURE 13.12 **Hot springs** such as Prismatic Springs in Yellowstone National Park are common where groundwater is heated in regions with young volcanism or deep faulting. The brilliantly colored water is a result of chemical reactions between the wall rocks and the hot groundwater. Orange hues show where overflows carry the alteration products. A walkway in the upper right part of the photo shows the scale.

rock salt, and gypsum. It then transports the dissolved mineral matter and either discharges it into other parts of the hydrologic system or deposits it in the pore spaces within the rock. Groundwater erosion starts with water percolating through joints, faults, and bedding planes and dissolving the soluble rock (Figure 13.13). In time, the fractures enlarge to form a subterranean network of caves that can extend for many kilometers. The caves grow larger until ultimately the roof collapses, and a craterlike depression, or **sinkhole,** is produced. Solution activity then enlarges the sinkhole to form a solution valley, which continues to grow until the soluble rock is removed completely.

As we saw in Chapter 10, the most important acid in groundwater is carbonic acid (H_2CO_3). This acid forms readily as carbon dioxide in the atmosphere and soil dissolves in water. Most of the carbon dioxide comes from gases in the soil, where plants have enriched carbon dioxide to as much as 10%; in the atmosphere, carbon dioxide makes up only 0.03%. Sulfuric acid—formed from sulfur compounds abundant in organic sediments such as coal, peat, and liquid petroleum—is also commonly present in groundwater. Together with various more-complex organic acids generated in the soil, these dilute acids react with the minerals in rocks and remove them in solutions. These processes of acid production and mineral dissolution can be represented by two chemical reactions:

$$\underset{\text{(water)}}{H_2O} + \underset{\text{(carbon dioxide gas)}}{CO_2} = \underset{\text{(carbonic acid)}}{H_2CO_3}$$

and

$$\underset{\text{(acid)}}{H_2CO_3} + \underset{\text{(calcite)}}{2CaCO_3} = \underset{\text{(calcium bicarbonate)}}{2Ca^{2+} + 2HCO_3^-}$$

The rate of erosion of limestone terrains by the chemical action of groundwater can be measured in several different ways. One is to measure precisely the weight of small limestone tablets and place them in different climatic conditions. Once the weight loss of the limestone during a specific period of time is known, the average rate at which limestone terrains are being lowered, by chemical

FIGURE 13.13 **The importance of fractures in the evolution of a cave system** is revealed in this photograph of the Redwall Limestone. Dissolution was enhanced along vertical fractures and on nearly horizontal bedding planes.

processes alone, can be calculated. Other methods include measuring the amount of mineral matter in water dripping through caves and the dissolved mineral matter carried by a river system in limestone regions. Recently, precise measurements of dissolution rates have been obtained with a microerosion meter, an instrument capable of measuring the erosion of a rock surface to the nearest 0.005 mm. The results of these measurements indicate that in temperate regions the landscape is being lowered at an average rate of 10 mm/1000 yr. In areas of greater rainfall, rates may be as high as 300 mm/1000 yr. These averages may seem small, but they indicate that in some areas erosion by groundwater can be greater than the average erosion of a surface by running water. It is clear from these measurements, and from the characteristics of limestone terrains, that groundwater accomplishes erosion on a grand scale.

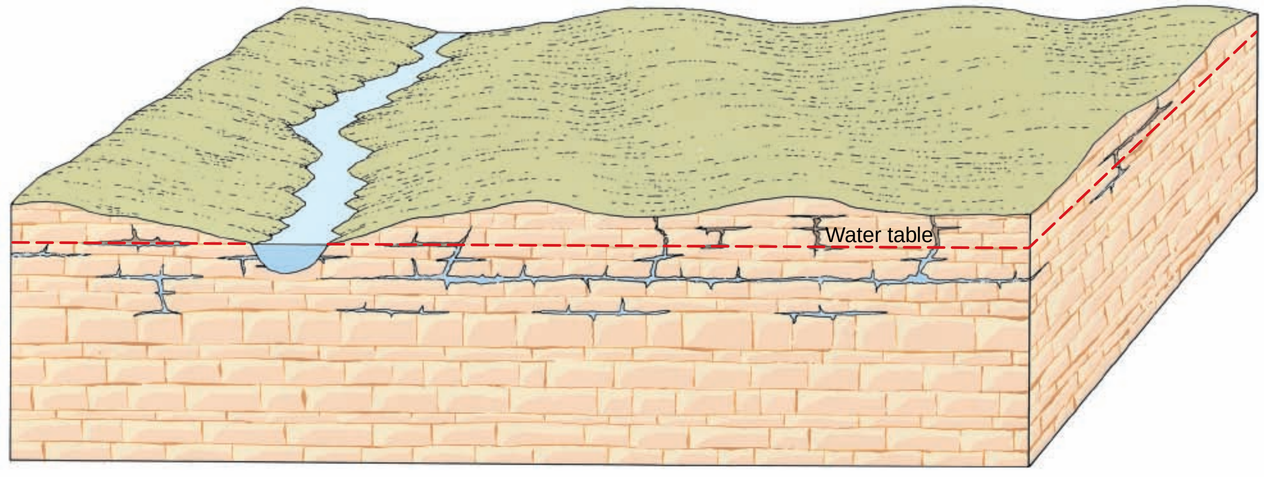
Groundwater Erosion

The permeability and porosity created by dissolution of limestone can create important reservoirs for oil and natural gas accumulation. In fact, about 50% of all petroleum comes from carbonate rocks.

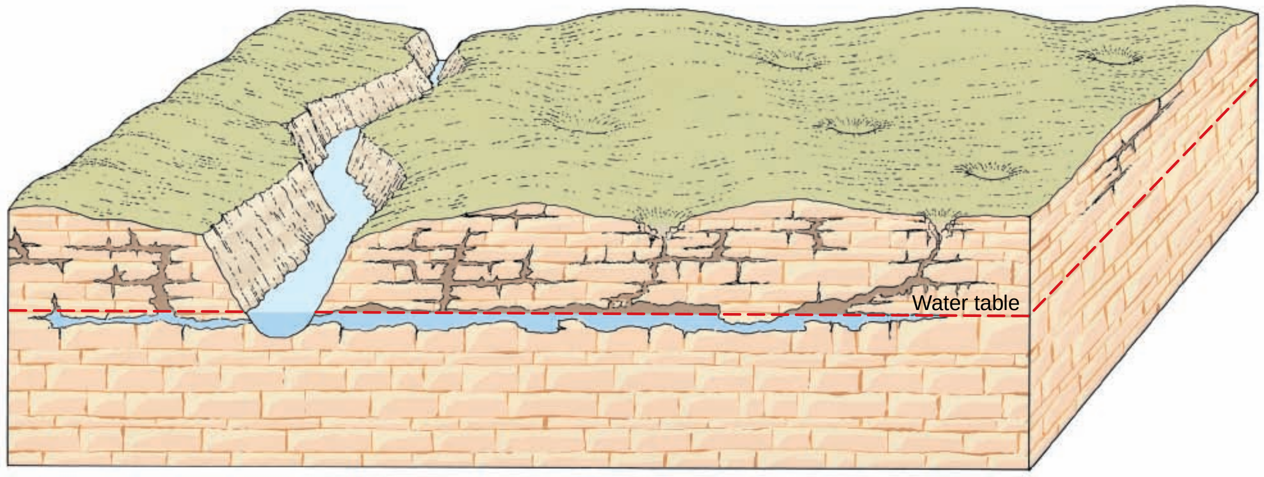
Rock salt and gypsum, the most soluble rocks, are eroded rapidly by solution activity and can cause overlying layers to collapse. They are relatively rare, however, and are not widely distributed on any of the continents.

Caves

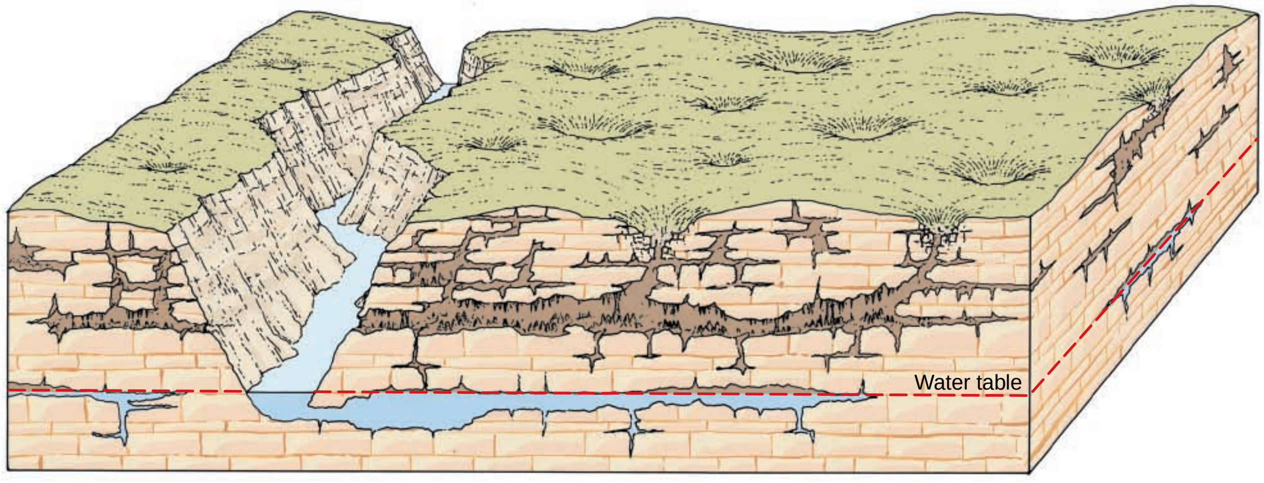
Perhaps the best way to appreciate the significance of solution activity is to consider the nature of a cave system and the amount of rock removed by solution. Shallow groundwater dissolves carbon dioxide and forms a weak acid. The slightly acidic water then percolates through the fractures and bedding planes, slowly dissolving the limestone and enlarging the openings (Figure 13.14). In the zone of aeration, the general direction of groundwater motion is downward, toward the water table. The water then moves toward a natural outlet, such as a river system, and as it moves, it dissolves the limestone. In time, a main subterranean channel is developed that transports the solution to the main streams. If the water table drops (usually by downcutting of the river), water in the main subterranean channel begins once again to seep downward to a new level. Eventually, the old horizontal



(A) In the early stages, water seeps through the fractures and bedding planes in limestone. The groundwater seeps downward to the water table and then moves toward the surface streams. Soluble minerals are dissolved and the flow paths become enlarged.



(B) As the surface streams erode the valley floor, the water table drops. The surface water seeping through the zone of aeration enlarges the existing joints and caves. Movement of water toward the surface stream develops a main system of horizontal caverns.



(C) As the river erodes a deeper valley, the water in the main underground channel seeks a new path to the lower river level. A new, lower system of horizontal caverns develops. The older, higher caverns may continue to enlarge and ultimately collapse to form sinkholes, or they may fill with fallen rubble or cave deposits.

FIGURE 13.14 **The evolution of a cave system** is shown schematically in these diagrams. (*Modified from* Underground Worlds, *Planet Earth Series, Time-Life Books, 1982)*

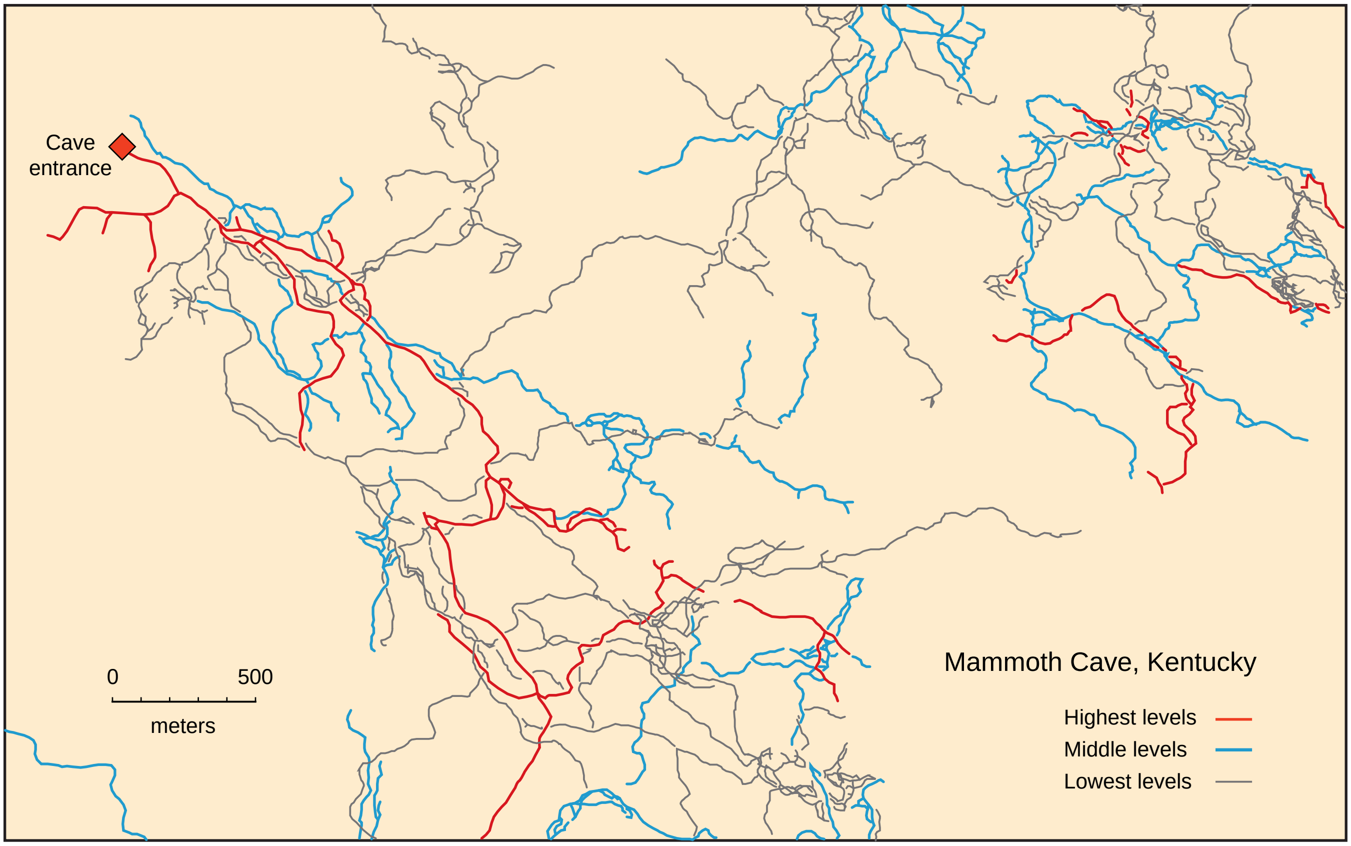


FIGURE 13.15 **A map of Mammoth Cave,** Kentucky, shows the complexity of cavern systems in limestone regions. The major northwest-southeast lineaments show how joints have controlled groundwater erosion. Solution activity along the joints has produced the network of caverns. Various cave systems develop in different layers of limestone. *(After the Cave Research Foundation)*

channel drains, and water dripping from the old channel ceiling begins to deposit calcite, in time creating major deposits in the open cave. The origin and evolution of **caves** are shown in Figure 13.14.

As caves grow larger, they become unstable and tend to collapse. The fallen rubble occupies about one-third more volume than it did as intact rock on the cave ceiling. Consequently, small caves may completely fill because of debris falling from the ceiling, but larger caverns tend to migrate upward as their roofs collapse and bury their floors. Larger or shallower caves ultimately break through to the surface to become sinkholes. A map of a cave system may show long, winding corridors, with branched openings that enlarge into chambers, or a maze of interlacing passageways and channels, controlled by intersecting joint systems. Where a sequence of limestone formations occurs, several levels of cave networks may exist. Kentucky's Mammoth Cave, for example, has more than 50 km of continuous subterranean passages on several different levels (Figure 13.15).

Karst Topography

Karst topography is a distinctive type of terrain resulting largely from erosion by groundwater (Figure 13.16). *Karst* is a German word for the Kras Plateau in Slovenia where this landscape is common. In contrast to a landscape formed by surface streams, which is characterized by an intricate network of stream valleys, karst topography lacks a well-integrated drainage system. Sinkholes are generally numerous and, in many karst regions, they dominate the landscape. Where sinkholes grow and enlarge, they merge and form elongate or irregular closed depressions known as **solution valleys.** Small streams commonly flow on the surface for only a short distance and then disappear down a sinkhole, becoming **disappearing streams.** There the water moves slowly through a system of caverns and caves,

(A) Sinkhole karst, Kentucky. *(Courtesy of John S. Shelton)*

(B) Sinkhole in a karst terrain in Florida. *(Courtesy of GeoPhoto Publishing Co.)*

(C) In some karst regions, streams disappear into subsurface caverns like this one in China.

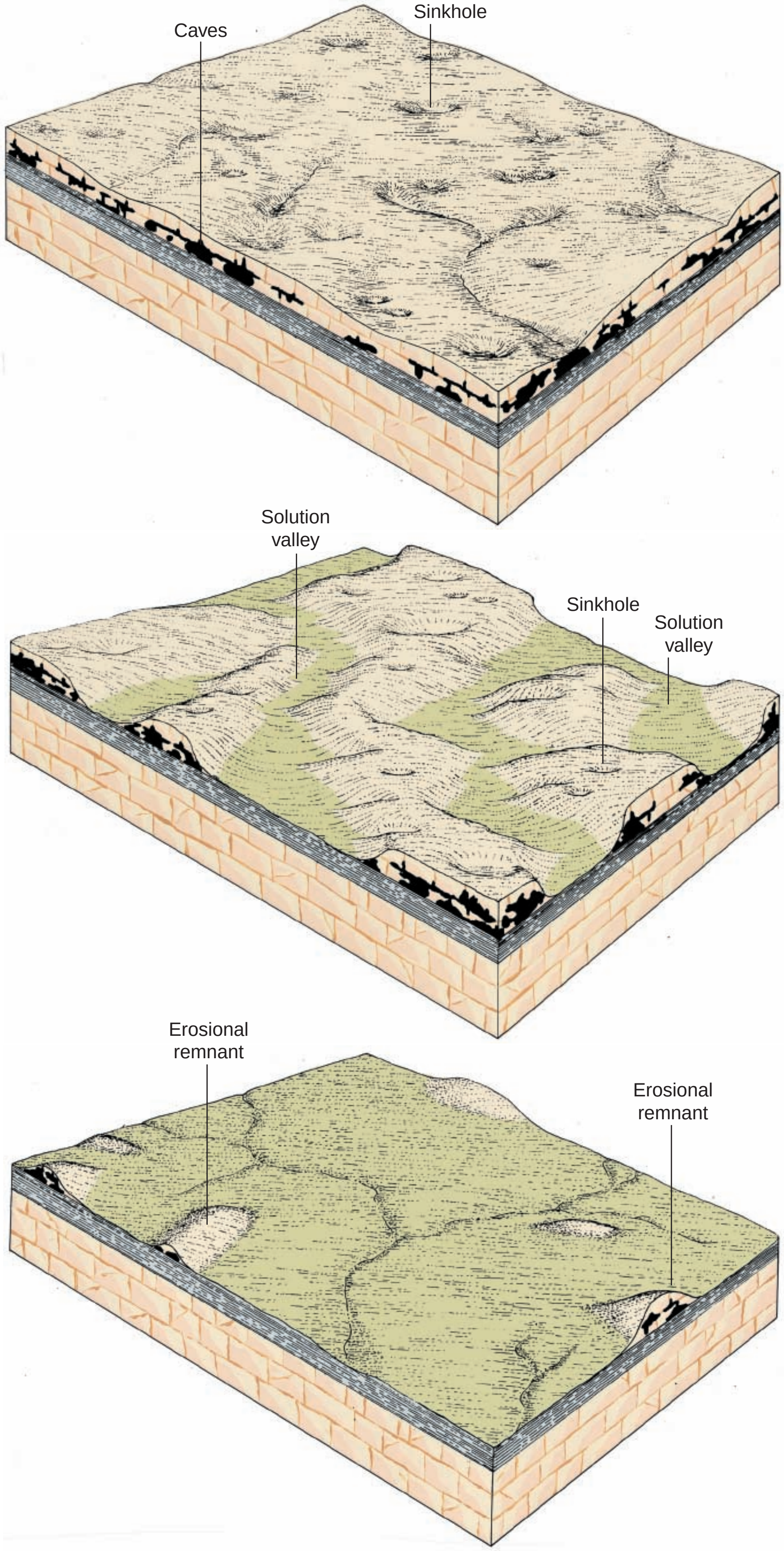
(D) Groundwater solution enlarged these fractures in limestones in New Zealand.

FIGURE 13.16 **Karst topography** includes a wide variety of landforms ranging in size from small solution pits, to sinkholes and caves, to residual towers. These solution features are distinctive and stand out in striking contrast to landscapes formed by running water, glaciers, or the wind.

sometimes as sluggish underground streams. Springs, which are common in karst areas, return water to the surface drainage.

In tropical areas, where dissolution is at a maximum because of the abundance of water from heavy rainfall, a particular type of karst topography, known as **tower karst,** develops. In China, this terrain is called a peak forest. Tower karst is characterized by steep, cone-shaped hills rather than sinkholes and solution valleys (see Figure 13.19 and the frontispiece). The towers are largely residual landforms left after most of the rock has been removed by solution activity along fracture systems, collapse of caverns, and enlargement of solution valleys. They are the remnants of a once-continuous layer of rock that covered the area.

Thus, in detail, karst topography is highly diverse, ranging from fantastic tower landscapes to the low relief of a plane pitted with small depressions. What is common to all karst terrains is that their landforms are caused by the unusually great solubility of certain rock types. Humid climate is a very important factor in developing karst topography. The more water moving through the system, the more solution activity will occur. Karst topography is, therefore, largely restricted to humid and temperate climatic zones. In desert regions, where little rain falls, extensive karst topography will not develop.



(A) Initial stage. Scattered sinkholes dotting the landscape grow in size and number as caverns enlarge and their roofs collapse.

(B) Intermediate stage. Individual sinks enlarge and merge with those in adjacent areas to form solution valleys. Much of the original surface is destroyed. Disappearing streams and springs are common.

(C) Late stage. Solution activity has removed most of the limestone formation. Only isolated knolls remain as remnants of the former surface.

FIGURE 13.17 **The evolution of karst topography** involves these major processes: (1) the enlargement of caves and the development of sinkholes, (2) the enlargement of sinkholes and the development of solution valleys, and (3) the enlargement of solution valleys until the original limestone terrain is completely destroyed.

FIGURE 13.18 **The major areas of karst topography (dark shade) of the world** are restricted to regions where outcrops of limestone occur in humid climatic conditions.

A simplified model of the evolution of karst topography is shown in the block diagrams in Figure 13.17. Initially, water follows surface drainage until a large river cuts a deep valley below the limestone layers. Groundwater then moves through the joints and bedding surfaces in the limestone and emerges at the riverbanks. As time goes on, the passageways become larger and caverns develop. Surface waters disappear into solution depressions. The roofs of caves collapse, so many sinkholes are produced (Figure 13.16B and 13.17A). Springs commonly occur along the margins of major stream valleys. Sinkholes proliferate and grow in size as the limestone formation is dissolved away. The cavernous terrain of central Kentucky, for example, is marked by more than 60,000 holes. As solution processes continue, sinkholes increase in number and size. Some merge to form larger depressions with irregular outlines. This process ultimately develops solution valleys (Figure 13.17B). Most of the original surface is finally dissolved, with only scattered hills remaining (Figure 13.17C). When the soluble bedrock has been removed by groundwater solution, normal surface drainage patterns reappear.

Karst Regions of the World. The development of karst topography is not random but is developed in specific regions where limestone formations are exposed near the surface and where there is adequate precipitation for vigorous chemical reactions to occur. High temperatures are favorable because heat enhances the dissolution process. The map in Figure 13.18 shows the major karst regions of the world, and, although it appears that karst topography is scattered across the globe, close examination of this map will reveal why karst landscapes develop in specific areas and not in others.

Only about 20% of Earth's surface has major limestone sequences exposed at the surface; the development of karst topography is limited to those areas. The continental shields do not favor karst development, nor do terrains dominated by granite, basalt, sandstone, and the like. As can be seen in Figure 13.18, karst topography is not well developed in desert regions, where there is inadequate rainfall, although limestone occurs at the surface. Karst landforms are also rare in regions recently covered by continental glaciers, such as those in Canada and northern Europe.

(A) Residual towers reveal the extent of groundwater solution. Caves are common in such towers.

(B) Surface grooves, pits, and sharp ridges caused by dissolution of limestone in surface waters.

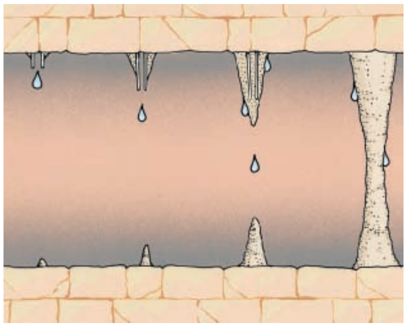
(C) Dissolution is expressed vividly by the abundant cavities so that the limestone formations resemble swiss cheese.

FIGURE 13.19 **Karst features in southern China** are well developed because of the high rainfall and thick layers of limestone exposed at the surface and include large residual towers, as well as small scale features.

The best-developed and most-extensive karst topography is in humid and tropical regions. The Alpine Mountain belt extending through the Pyrenees and southern Europe and across Croatia, Bosnia, Yugoslavia, and Turkey has thick sequences of deformed limestone on which many classic karst landforms have developed. In the United States about 15% of the area is favorable for karst development. The best-known regions are the sinkhole country of Kentucky, Indiana, and Florida. These regions consist of plains pockmarked by innumerable small, isolated depressions (Figure 13.16A). Surface streams of any significant length are extremely rare. The limestone regions of Puerto Rico, Jamaica, Cuba, and Mexico's Yucatan Peninsula have extensive karst regions because of widespread limestone and heavy rainfall. Little-known karst regions in other parts of the world include the large Nullarbor Plain in southern Australia and the karst regions of Southeast Asia, particularly in Malaysia and the Indonesian islands of Sumatra and Java.

The Tower Karst of China. In striking contrast to the sinkhole plains of Indiana and Kentucky, the tower karst topography of southern China presents some of the most spectacular limestone scenery on Earth (see the frontispiece and Figure 13.19). Here, an area of thousands of square kilometers, once covered by thick layers of limestone, is in an advanced stage of dissection by groundwater. The region consists of a "forest" of hills that rise abruptly from the surrounding terrain. These hills are remnants between sinkholes and solution basins and stand like clusters of towers. These strange mountains, shaped like upended loaves of French bread, form an intricate system of precipitous slopes and overhanging cliffs, with caves, arches, and strange landforms made by solution activity.

Classical Chinese art is noted for portraying these bizarre and exotic landforms, which appear unreal to the foreign eye. Western artists believed that the Chinese masters who painted these landforms were impressionists, but anyone fortunate enough to visit the region realizes that the artists were not visionaries; the shapes they painted were nature's own.



(A) Diagram showing, left to right, the evolution of stalactites, stalagmites, and columns.

(B) Long, slender stalactites (soda straws) grow as a drop of water suspended at the end loses carbon dioxide and evaporates. *(Courtesy of David Herron)*

FIGURE 13.20 **Stalactites** originate on the ceilings of caves. Water seeps through a crack and loses carbon dioxide as it partially evaporates. Consequently, a small ring of calcite is deposited around the crack. The ring grows into a tube, which commonly acquires a tapering shape as water seeps from adjacent areas and flows down its outer surface.

The small-scale solution features in this area are almost as impressive as the larger features. Evidence of solution activity is everywhere. Every hill is riddled with caves, caverns, solution pits, and voids that form an intricate network for subterranean drainage. Indeed, most outcrops look like Swiss cheese. This maze of cavities is where the action is, and in a way, it performs the same function as the network of gullies and streams do in surface drainage systems. It collects water and funnels it through the system. As the water moves, it erodes and transports rock material. Thus, the cavities in the towers enlarge and ultimately collapse. Examples of the features in this amazing landscape are shown in Figure 13.19.

DEPOSITION BY GROUNDWATER

The mineral matter dissolved by groundwater can be deposited in a variety of ways. The most spectacular deposits are stalactites and stalagmites, which are found in caves. Less obvious are the deposits in permeable rocks such as sandstone and conglomerates. Here, groundwater commonly deposits mineral matter as a cement between grains.

The chemical processes that cause groundwater to dissolve soluble material are easily reversed, and the minerals are precipitated in the pore spaces, voids, and caves within the rock. The change from solution to precipitation is commonly caused by a lowering of the water table. The main solution processes occur in the zone of saturation; precipitation occurs in the zone of aeration after the caves and pore spaces are drained. This process can be understood by examining what happens in an air-filled cave. Groundwater dripping from a cave's roof contains more CO_2 than the surrounding air. In an attempt to reach equilibrium with the air, CO_2 diffuses out of the water droplet. This diffusion reduces the amount of carbonic acid as well as the amount of calcite that can be dissolved in the water. As a result, the water becomes saturated with $CaCO_3$ and it precipitates. You can visualize this process by examining the chemical reactions shown previously on page 351. Both reactions are driven to the left as a result of the escape of CO_2 from the groundwater.

The deposits formed in caves are some of nature's fancywork; the endless variety of cave deposits is familiar to almost everyone. They originate in a variety of ways and are collectively called **speleothems.** One formative process is shown in Figure 13.20. As water enters a cave (usually from a fracture in the ceiling), carbon dioxide escapes during evaporation, and a small amount of calcium carbonate crystallizes. Each succeeding drop adds more calcium carbonate, so that eventually a cylindrical, or cone-shaped, projection is built downward from the ceiling. Many beautiful and strange forms result, some of which appear in Figures 13.21 and 13.22. Icicle-shaped forms growing down from the ceiling are **stalactites.** These

What features are unique in Lechuguilla Cave?

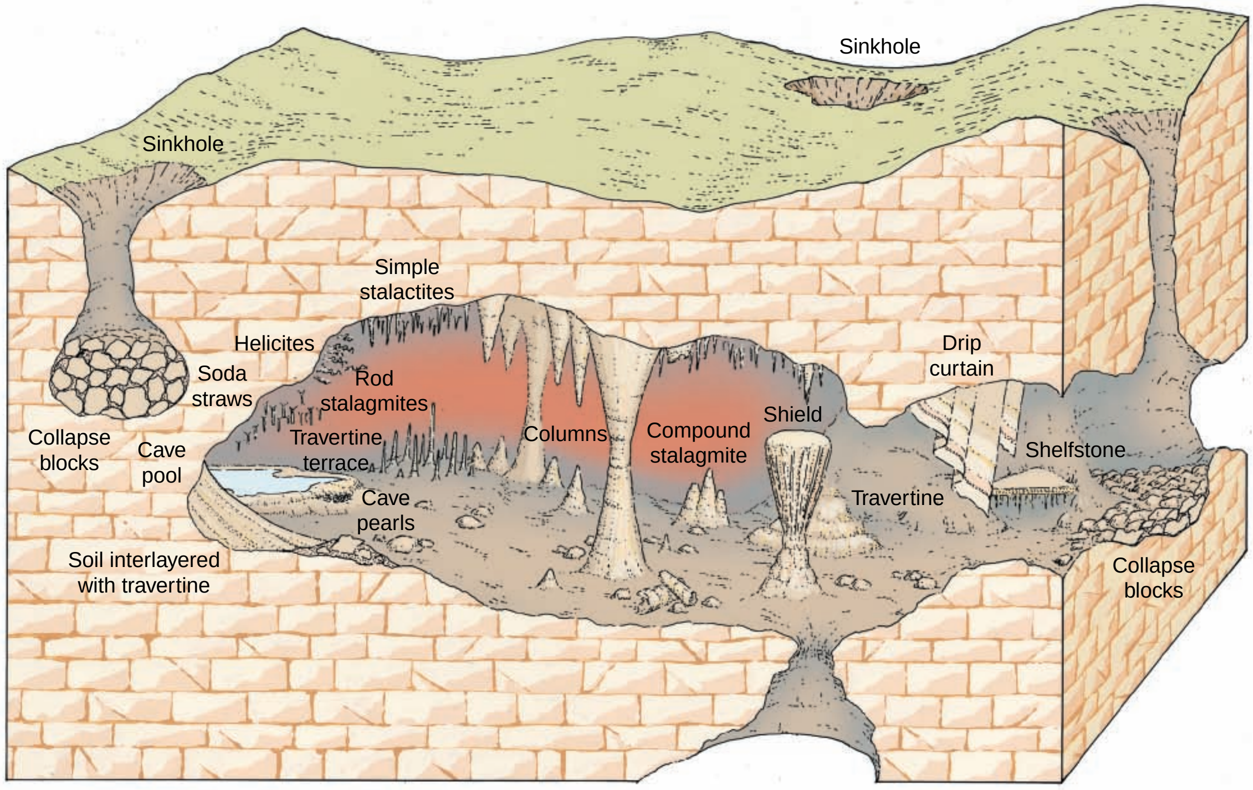


FIGURE 13.21 **Many varieties of cave deposits** are shown in this idealized diagram. Most are composed of calcite deposited by water that seeps into the open cave and then loses carbon dioxide as the water evaporates.

commonly are matched by deposits growing up from the floor, known as **stalagmites,** because the water dripping from a stalactite precipitates additional calcium carbonate onto the floor directly below. Many stalactites and stalagmites eventually unite to form columns. Water percolating from a fracture along a slanting ceiling may form a thin, vertical sheet of rock known as drapery because of its shape. Pools of water on the cave floor flow from one place to another, and as they evaporate, calcium carbonate is deposited on the floor, forming terraces made of travertine—a layered cave or hotspring rock composed of calcium carbonate.

Lechuguilla Cave

One of the best-kept secrets of the National Park Service is Lechuguilla Cave, in the Guadalupe Mountains near Carlsbad, New Mexico. It was first explored in 1986 and was found to be the deepest known cave in the United States, with a vertical range of 475 m. Within this cave are some of the most spectacular cave "formations" in the world. As a result, it is commonly referred to as the "Jewel of the Underground."

Lechuguilla Cave is remarkable, not only for its size and beauty, but also for its strange origin. Most of the world's caves are dissolved from limestone as groundwater with carbonic acid (H_2CO_3) moves downward by the pull of gravity. Lechuguilla developed in an entirely different way. Sulfuric acid (H_2SO_4), rather than carbonic acid, played the dominant role in its formation. Water associated with the vast petroleum deposits of southwestern Texas is rich in hydrogen sulfide(H_2S). This water is under pressure and seeps up, from the trapped oil and gas, through fractures in the rock. Eventually it reaches the shallow groundwater reservoir; there, the hydrogen sulfide combines with oxygen in the fresh groundwater to form sulfuric acid (H_2SO_4). The rising acidic water dissolves the cave system and, in places, excess hydrogen sulfide gas may even dissolve caverns above the water table.

(A) Stalactites and stalagmites formed from calcium carbonate in Lechuguilla Cave.

(B) Gypsum stalactites form coarsely crystalline, clawlike branches. These "chandeliers" are up to 6 m long and are thought to be the world's largest.

FIGURE 13.22 **Deposits in Lechuguilla Cave,** New Mexico. *(Photographs by Norman R. Thompson)*

The unique role played by sulfuric acid in the formation of Lechuguilla Cave has produced an enchanting array of sulfate cave deposits, most notably gypsum ($CaSO_4 \cdot 2H_2O$). Some blocks are as large as houses; elsewhere, crystals are as fine as hair. The hallmarks of Lechuguilla are dozens of unique stalactites hanging from the ceiling like monstrous, grotesque chandeliers (Figure 13.22). Some are more than 6 m long, with downward-twisting trunks ending in branching, clawlike arms of transparent crystals. But the gypsum deposits of Lechuguilla come in many other strange forms. Long, slender, glasslike needles, some as much as 6 m long, extend downward from the ceiling. Other exotic cave deposits, both large and small, occur in great profusion and display, in a most spectacular way—the results of fluid and gases migrating beneath the surface.

Although cave deposits are spectacular expressions of deposition by groundwater, they are trivial compared with the amount of material deposited in the pore spaces of rock. In sandstones and conglomerates, precipitation of silica and calcium carbonate cement the loose grains into a hard, strong rock body. In some formations, the cementing minerals deposited by groundwater may exceed 20% of the volume of the original rock (Figure 13.23).

Mineral precipitation by groundwater action is a slow process, in some cases involving the slow removal—one at a time—of atoms or molecules of organic matter and their simultaneous replacement by other mineral ions carried by the groundwater. One example of this process is petrified wood. Perhaps the best-known deposit of petrified wood is the Petrified Forest National Park in eastern Arizona. Here, great accumulations of petrified logs, buried in ancient river sediments, are now being uncovered by weathering and erosion (Figure 13.24). The Petrified Forest is not really a forest at all but a great collection of driftwood. This driftwood washed down from adjacent highlands about 230 million years ago and accumulated as logjams in ancient river bars and floodplains. It was subsequently covered with hundreds of meters of younger sediments. While the driftwood was covered with sediment, groundwater percolating through the strata replaced the

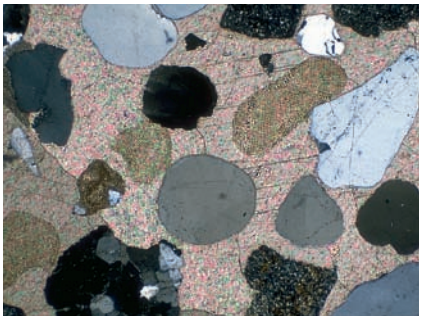


FIGURE 13.23 **Calcite deposited by groundwater** cements the rounded quartz sand grains together, as shown in this thin section of sandstone. The quartz grains are various shades of gray and the calcite is pink and green speckles. The area shown is 3 mm across.

cellular structure of the wood with silica. This process transformed the wood to agate, a variety of silicon dioxide (SiO_2).

Geodes are another common example of the result of the action of groundwater deposition. A geode is a roughly spherical, hollow rock mass with its central cavity lined with mineral crystals. Geodes are common in limestones, but they also occur in preexisting voids in shales and in silica-rich volcanic rocks. The formation of geodes can be explained as a two-stage development. First, a cavity is formed in the rock by groundwater solution activity. Then, under different conditions, the mineral matter carried by groundwater is precipitated on the walls of the rock cavity. Quartz, calcite, and fluorite are the most common minerals precipitated. They accumulate very slowly and form perfect crystals, pointing toward the center of the cavity. Subsequent erosion removes the material around the geode cavity, but the mineral-lined walls of the cavity are resistant, so geodes remain; they are found as boulderlike remnants, left from the weathering of the parent rock material. In a sense, a geode is a fossil cavity.

Another expression of deposition by groundwater is the mineral deposit formed around springs. Mammoth Hot Springs in Yellowstone National Park is one of the most spectacular examples (Figure 13.25).

GROUNDWATER RESOURCES

> Groundwater is a valuable resource that is being exploited at an ever-increasing rate. Ancient groundwater systems have also produced valuable mineral resources.

Groundwater is of major importance to civilization because it is the largest reserve of drinkable water in many regions. This probably constitutes the most important use of groundwater in our modern society for both urban and rural peoples in arid and semiarid regions. Many cities in the western United States derive a substantial portion of their municipal water from wells. Another major use of groundwater is in agricultural irrigation. Although most irrigation water is derived by diverting rivers, increasingly irrigation water in the United States is derived directly from groundwater reserves. Increased use of drinking and irrigation water has caused the water levels in many aquifers to drop. In developing countries, groundwater resources are often the controlling factor for development.

In addition, some important metallic ore deposits are formed by groundwater processes. Groundwater can carry dissolved metals from one place to another, concentrating it in specific areas. Some groundwaters are heated by deep circulation

FIGURE 13.24 **Petrified trees** litter the area, piled like giant jackstraws about a rolling landscape on the Petrified Forest Member of the Chinle Formation, Arizona.

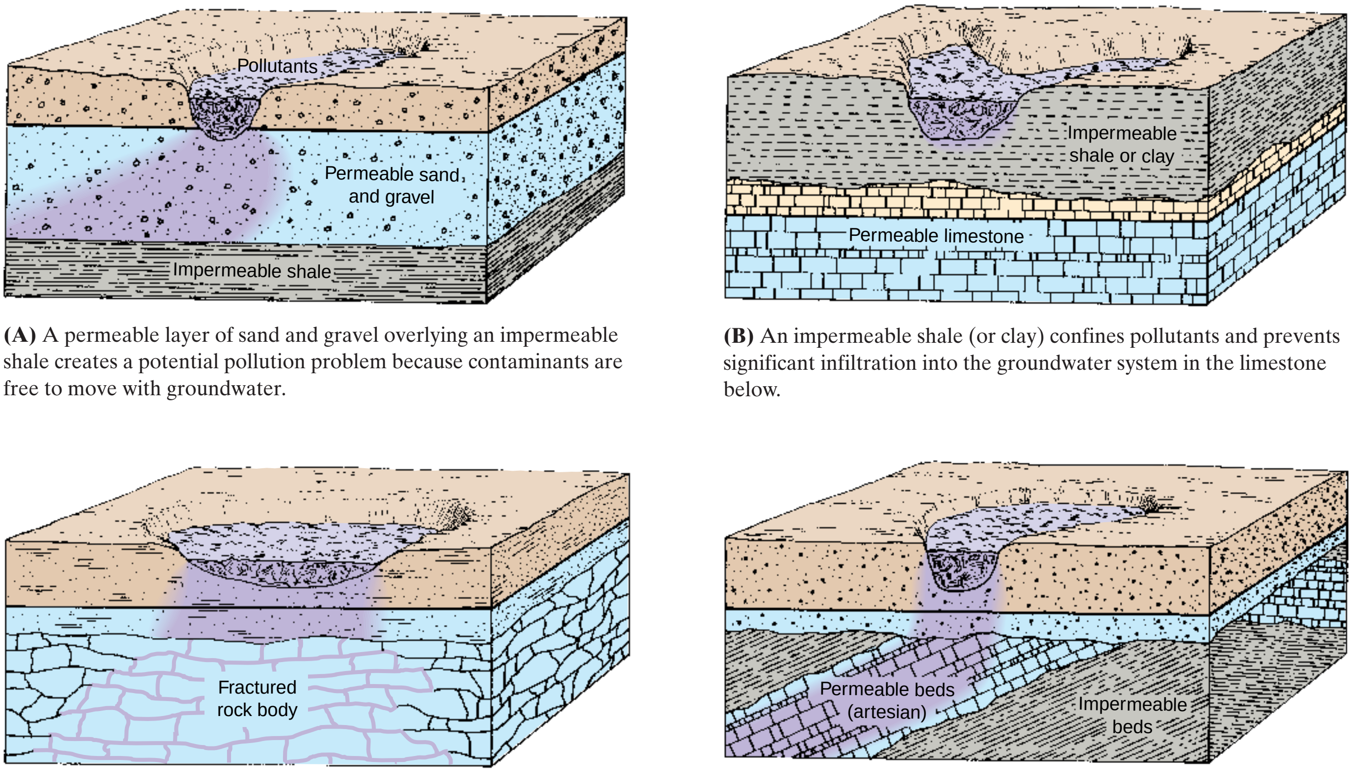
FIGURE 13.25 **Mammoth Hot Springs,** Yellowstone National Park, was formed by the deposition of travertine ($CaCO_3$) as the warm spring water evaporated and lost carbon dioxide.

or igneous intrusions; the heating usually increases their ability to carry dissolved ions. For example, deposits of fluorite, lead, and zinc in the upper Mississippi Valley formed as groundwater carried dissolved metals to shallow levels and concentrated them in deposits of sulfide minerals. Deposits of uranium, vanadium, and copper in sedimentary rocks are also formed by the movement of groundwater. Many nonmetallic resources are also controlled by groundwater systems. Oil is sometimes trapped in paleokarst deposits formed in ancient limestones. The Yates field of western Texas is developed in a buried karst terrain and contains the highest-yielding wells in the United States because of the high permeability and porosity of such partially dissolved rock units. We have already mentioned the use of heated groundwaters to produce electricity and space heating. Even many building stones are derived from groundwater deposits. These include travertine and onyx marble. Many valuable gemstones form from groundwaters: for example, opal, agate, and onyx (forms of amorphous or cryptocrystalline silica) and emerald.

ALTERATION OF GROUNDWATER SYSTEMS

A variety of problems resulting from human activities alter the groundwater system. Important problems are (1) changes in the chemical composition of groundwater (pollution), (2) saltwater encroachment, (3) changes in the position of the water table, and (4) subsidence.

Groundwater is an integral part of the hydrologic system and is intimately related to other parts of the system. As we have seen in this chapter, its source is precipitation and infiltration from surface runoff. Its natural discharge is into streams and lakes and, ultimately, the sea. With time, a balance, or equilibrium, among precipitation, surface runoff, infiltration, and discharge is established. These in turn approach an equilibrium with surface conditions, such as slope angles, soil cover, and vegetation. When any one of these interrelated factors is changed or modified, the others respond to reestablish equilibrium.



(A) A permeable layer of sand and gravel overlying an impermeable shale creates a potential pollution problem because contaminants are free to move with groundwater.

(B) An impermeable shale (or clay) confines pollutants and prevents significant infiltration into the groundwater system in the limestone below.

(C) A fractured rock body provides a zone where pollutants can move readily in the general direction of groundwater flow.

(D) An inclined, permeable aquifer below a disposal site permits pollutants to enter a confined aquifer and move down the dip of the beds, so that they contaminate the system.

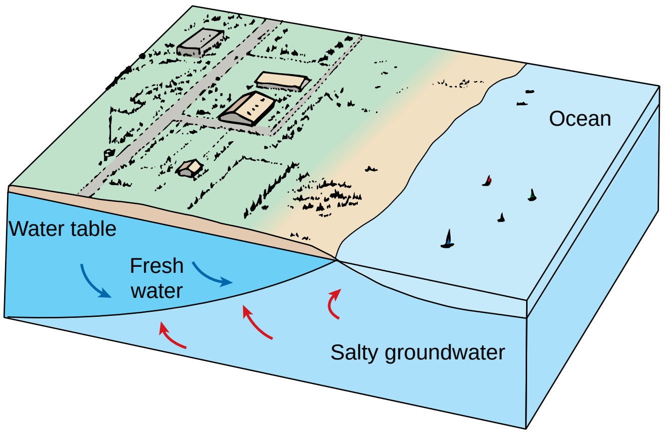
FIGURE 13.26 **The effects of waste disposal or leaking storage tanks on a groundwater system** depend on the geologic setting. In many cases, water seeping through the disposal site enters and pollutes the groundwater system. *(After W. J. Schneider, U.S. Geological Survey)*

Changes in Composition

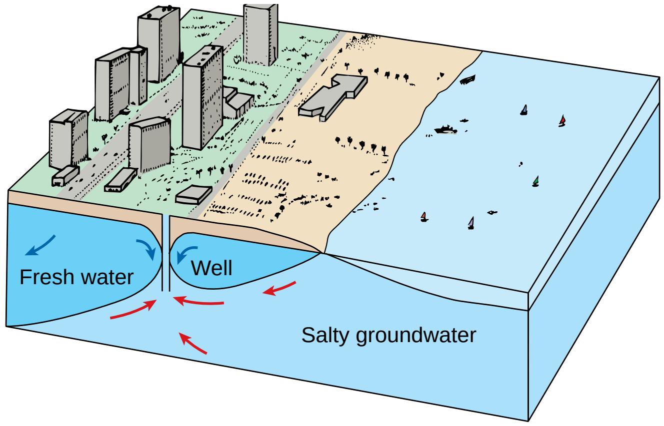
The composition of groundwater can be changed by increases in the concentration of dissolved solids in surface water. The soil is like a filtration system through which groundwater moves. Obviously, any concentration of chemicals or waste creates local pockets that potentially can contaminate the groundwater reservoir. Material that is **leached** (dissolved by percolating groundwater) from waste disposal sites, for example, includes both chemical and biological contaminants. Upon entering the groundwater flow system, the contaminants move according to the hydraulics of that system. The character and concentration of the pollutants depend partly on the length of time the infiltrated water is in contact with the waste deposit, partly on the volume of infiltrated water, and partly on the solubility of waste involved. In humid areas, where the water table is shallow and in constant contact with refuse, leaching continually produces maximum potential for pollution.

How does human activity alter the groundwater system?

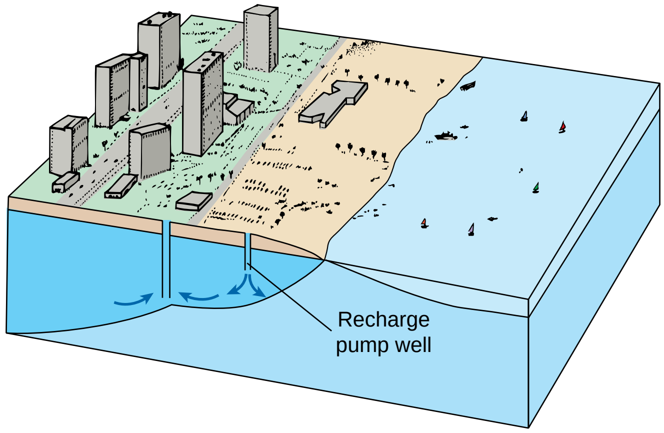
Figure 13.26 illustrates four geologic environments in which waste disposal affects the groundwater system. In the environment shown in Figure 13.26A, the near-surface material is permeable and essentially homogeneous. Dissolved pollutants percolate downward through the zone of aeration and, upon reaching the water table, enter the groundwater flow system. The flowing pollutants ultimately become part of the surface drainage system. As shown in Figure 13.26B, an impermeable layer of shale confines pollutants and prevents their free movement in the groundwater system. As a result, the pollutants are restricted and inhibited from moving freely through the groundwater system. Figure 13.26C illustrates a disposal site above a fractured rock body. Upon reaching the fractured rock, the contaminants can move more readily in the general direction of the groundwater flow.



(A) A lens of fresh groundwater beneath the land is buoyed up by denser saltwater below.



(B) Excessive pumping causes a cone of depression in the water table on top of the freshwater lens and a cone of saltwater encroachment at the base of the freshwater lens.



(C) Fresh water pumped down an adjacent well can raise the water table around the well and lower the interface between the fresh water and the saltwater.

FIGURE 13.27 The relationship between fresh water and saltwater on an island or a peninsula is affected by the withdrawal of water from wells. Excessive pumping causes a cone of saltwater encroachment, which limits the usefulness of the well.

Dispersion of the contaminants is limited, however, because of the restriction of flow to the fractures. Figure 13.26D illustrates a critical condition in which a waste disposal site was constructed in highly permeable sand and gravel, above an inclined aquifer. Here, pollutants move down past the water table and enter the aquifer as recharge. If the waste disposal site is directly above the aquifer, as shown in the diagram, most of the pollutants will enter the aquifer and contaminate the groundwater system.

Saltwater Encroachment

On an island or a peninsula, where permeable rocks are in contact with the ocean, a lens-shaped body of fresh groundwater is buoyed up by the denser saltwater below, as is illustrated in Figure 13.27A. The fresh water literally floats on the saltwater and is in a state of balance with it. If excessive pumping develops a large cone of depression in the water table, the pressure of the fresh water, on the saltwater directly below the well, is decreased, and a large cone of **saltwater encroachment** develops below the well, as is shown in Figure 13.27B. Continued excessive pumping causes the cone of saltwater to extend up the well and contaminate the fresh water. It is then necessary to stop pumping for a long time to allow the water table to rise to its former position and depress the cone of saltwater. Restoration of the balance between the freshwater lens and the underlying saltwater can be hastened if fresh water is pumped down an adjacent well (Figure 13.27C).

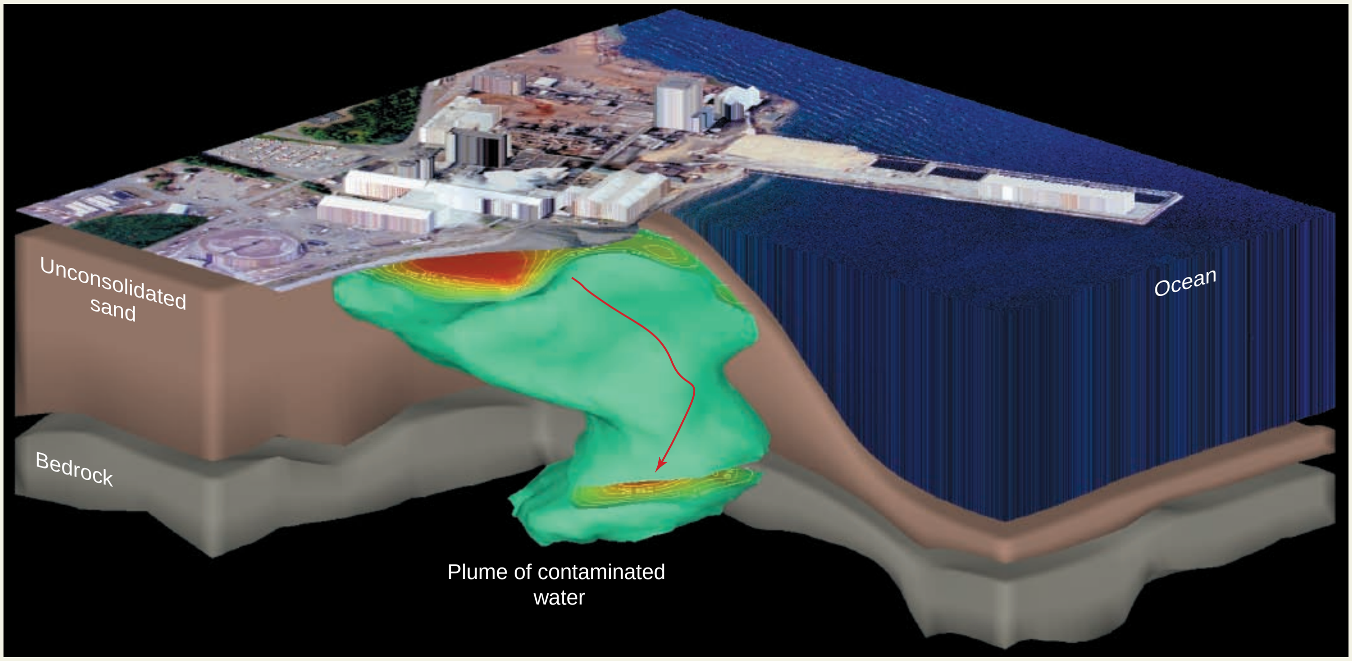
STATE OF THE ART — *Computer Models of Flowing Groundwater*

Deep below your feet, groundwater is probably inching its way through a permeable aquifer. We are largely unaware of this vast resource, but groundwater is used extensively for city water supplies and for irrigating croplands. Although we rely on this water supply to be pure, groundwater invariably carries dissolved ions—in most cases of little consequence to people. However, in some places groundwater has become contaminated with bacteria, arsenic, gasoline, and a host of other pollutants. If such contaminated groundwaters are pumped out of wells and enter municipal water supplies, they could have serious consequences.

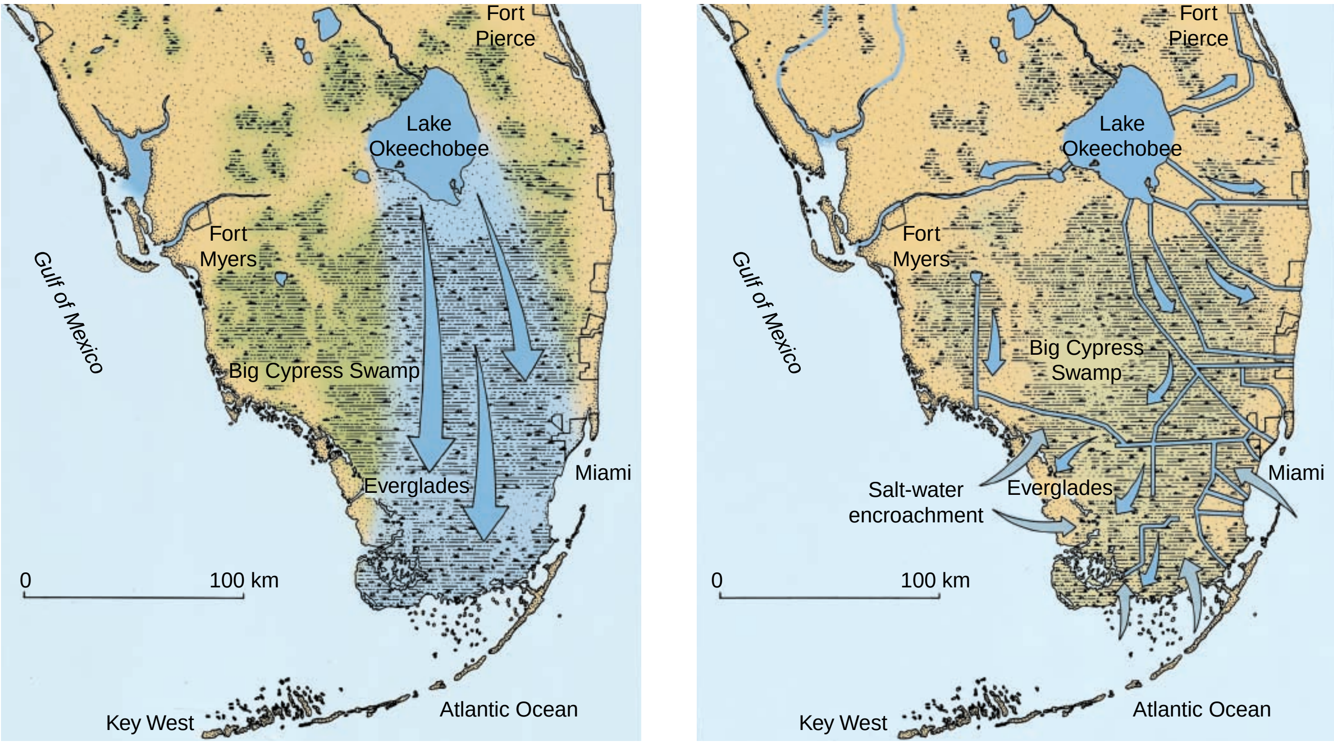
Short of eliminating the use of groundwater altogether, what can be done to protect humans from pollutants moving invisibly in groundwater? Contaminated groundwater does not simply diffuse outward away from the source of pollution. Instead, it follows a path determined by the permeability and structure of the aquifer (Figure 13.26). Around some waste sites, monitor wells are drilled to see where the contaminated water is flowing. Drilling is costly and time-consuming. An alternative is to create a computer model of the flow path of the contaminated groundwater. If such models were accurate, precise predictions about the direction, depth, or rate of flow could be made quickly and inexpensively and the risk of pumping water from contaminated wells avoided.

However, any computer calculation depends heavily on the quality of the starting conditions used in the model. What would you need to know to construct such a model? Of prime importance is a thorough understanding of the geologic and hydrogeologic characteristics of the rocks through which the water is flowing. How deep is the water table? What is its slope? What is the hydraulic head? Are the rocks permeable or impermeable? Do they have fractures or bedding planes along which fluids flow? What is the subsurface configuration of the pressure gradients? How much precipitation is there and how is the aquifer recharged? Are the wastes soluble in water? Will they react with minerals along the flow path and become neutralized? And so on.

Given the complexity of natural rocks, many of these questions can only be approximately answered. Within these limitations, however, reasonable models of groundwater flow can be constructed. In the three-dimensional figure below, you can see a colored plume of contaminated groundwater emanating from an industrial facility that leaked chlorinated hydrocarbons. The contaminant is soluble in water and has leaked into the groundwater system. The contaminated water then moved down through the aquifer. The colored bands show the concentration in the contaminated plume. You can see that the core of the plume, near its source, is more polluted than the rest. Such a computer model would allow city planners to avoid the plume and help environmental geologists devise ways to shut off continued contamination, pump the contaminated water out, or otherwise mitigate the damage.



(Image created by Environmental Visualization System, courtesy of C Tech Development Corp. www.ctech.com)



(A) Natural drainage of southern Florida in 1871 spread southward from Lake Okeechobee in a broad sheet only a few centimeters deep. This sheet maintained swampy conditions in the Everglades and established a water table very close to the surface.

(B) Canals diverted the natural flow of surface water across the Everglades. The water table was lowered, the swamp was destroyed in some areas, and saltwater encroached in wells along the coast.

FIGURE 13.28 **Modification of the natural drainage system** of southern Florida. *(After F. Ward,* National Geographic*)*

Changes in the Position of the Water Table

The water table is intimately related to surface runoff, the configuration of the landscape, and the ecological conditions at the surface. The balance between the water table and surface conditions, established over thousands or millions of years, can be completely upset by changes in the position of the water table. Two examples illustrate some of the many potential ecological problems.

In southern Florida, fresh water from Lake Okeechobee has flowed for the past 5000 years as an almost imperceptible "river" only a few centimeters deep and 64 km wide. This sheet of shallow water created the swampy Everglades. The movement of the water was not confined to channels. It flowed as a sheet, in a great curving swath for more than 160 km (Figure 13.28). The surface of the Everglades slopes southward only 2 cm/km, but this gradient was enough to keep the water moving slowly to the coast and to prevent saltwater from invading the Everglades and the subsurface aquifers along the coast. In effect, the water table in the swamp was at the surface, and the ecology of the Everglades was in balance with the water table.

Today, many canals have been constructed to drain swamp areas for farmland, to help control flooding, and to supply fresh water to the coastal megalopolis (Figure 13.28). The canals diverted the natural flow of water across the swamp, in effect lowering the water table, in some places as much as 0.5 m below sea level. This change in position of the water table produced many unforeseen and often unfortunate results. As the water table was lowered, saltwater encroachment occurred in wells all along the coast. Some cities had to move their wells far inland to obtain fresh water.

FIGURE 13.29 Subsidence of buildings in Mexico City resulted from compaction after groundwater was pumped from unconsolidated sediment beneath the city. Subsidence has caused this building to tilt and sink more than 2 m.

The most visible effects, however, involve the ecology of the swamp. In the past, the high water table could maintain a marsh during periods of natural drought. Now the surface is dry during droughts. Forest fires ignite the dry organic muck, which burns like peat, smoldering long after the surface fires die out. This effectively destroys the ecology of the swamp. The lowering of the water table also caused the muck to compact, so that it subsided as much as 2 m in places. In addition, muck exposed to the air oxidizes and disappears at a rate of about 2.5 cm/yr. Once the muck is gone from the swamp, only nature can replace it.

Raising the water table can also modify many surface processes. An example is found in the environmental changes caused by irrigation in Washington's Pasco Basin. This area, which lies in the rain shadow of the Cascade Mountains, receives only 15 to 25 cm of precipitation a year. In recent years, extensive irrigation has caused the water table to rise, introducing many changes in the surface conditions. Today, from 100 to 150 cm of water is applied each year to the ground by irrigation, which simulates the effect of a large climatic change. The higher water table has rapidly developed large springs along the sides of river valleys. The springs are now permanent, reflecting saturation of much of the ground. Erosion is accelerated, and many farms and roads have been damaged severely. Landslides present the most serious problems. Slopes that were stable under arid conditions are now unstable because they are partly saturated from the high water table and from the formation of perched water bodies.

In many areas, it is imperative that we modify the environment by reclaiming land or by irrigation; unless we are careful, however, the detrimental effects of our modifications may outweigh the advantages. Before we modify an environment, we must attempt to understand the many consequences of altering natural systems.

Subsidence

Surface **subsidence** related to groundwater can result from natural Earth processes, such as the development of sinkholes in a karst area or from the artificial withdrawal of fluids. An ever-present hazard in limestone terrains is the collapse of subterranean caverns and the formation of sinkholes (Figure 13.16B). Buildings and roads have frequently been damaged by sudden collapses into previously undiscovered caverns below. In the United States, important karst regions appear in central Tennessee, Kentucky, southern Indiana, Alabama, Florida, and Texas (Figure 13.18). The problem of potential collapse is difficult to solve. Important

FIGURE 13.30 A dam constructed on permeable limestone in western Wyoming never functioned because the surface water seeped into the subsurface. The dam lies at the beginning of the gorge. The light-colored sediment behind the dam marks the fraction of the reservoir that formed before water was lost through seepage.

construction in karst regions should be preceded by test borings to determine whether subterranean cavernous zones are present. Geophysical studies using ground-penetrating radar and seismic investigations can be used to detect some shallow caverns and soil cavities. Wet concrete can be pumped down into caves and solution cavities, but such remedies can be very expensive.

Compaction and subsidence also present serious problems in areas of recently deposited sediments. In New Orleans, for example, large areas of the city are now 4 m below sea level, a drop due largely to the pumping of groundwater. As a result, the Mississippi River flows some 5 m above parts of the city, and rainwater must be pumped out of the city at considerable cost. Also, as the surface subsides, waterlines and sewers are damaged.

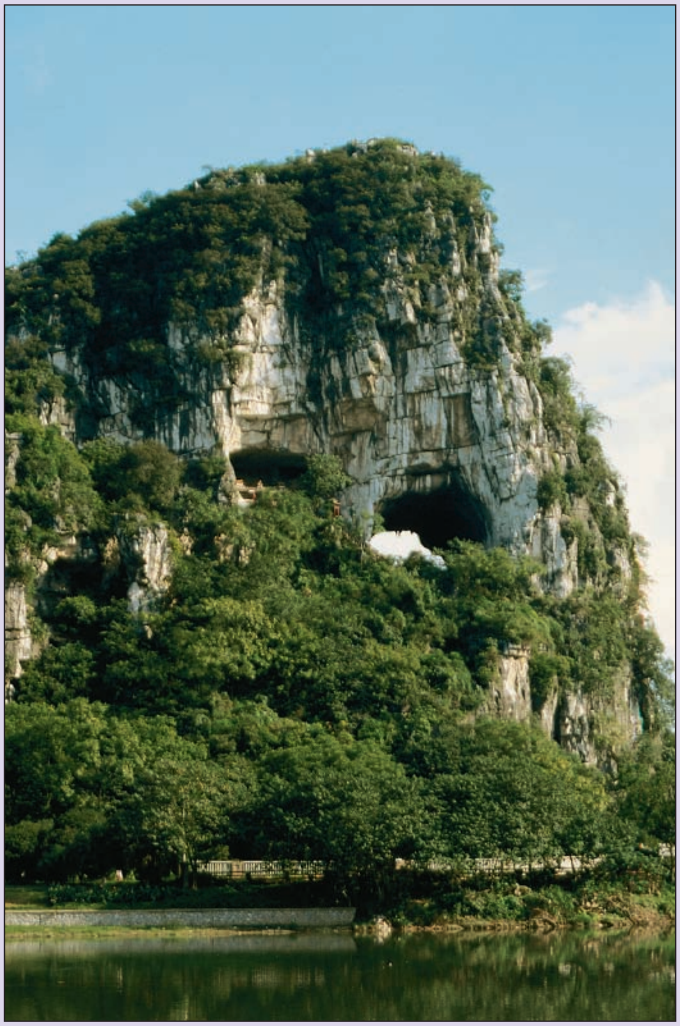
Where groundwater, oil, or gas is withdrawn from the subsurface, significant subsidence can also occur, damaging construction, water supply lines, sewers, and roads. Long Beach, California, has subsided 9 m as the result of 40 years of oil production from the Wilmington oil field. This subsidence resulted in almost $100 million worth of damage to wells, pipelines, transportation facilities, and harbor installations. Parts of Houston, Texas, have subsided as much as 1.5 m as a result of the withdrawal of groundwater.

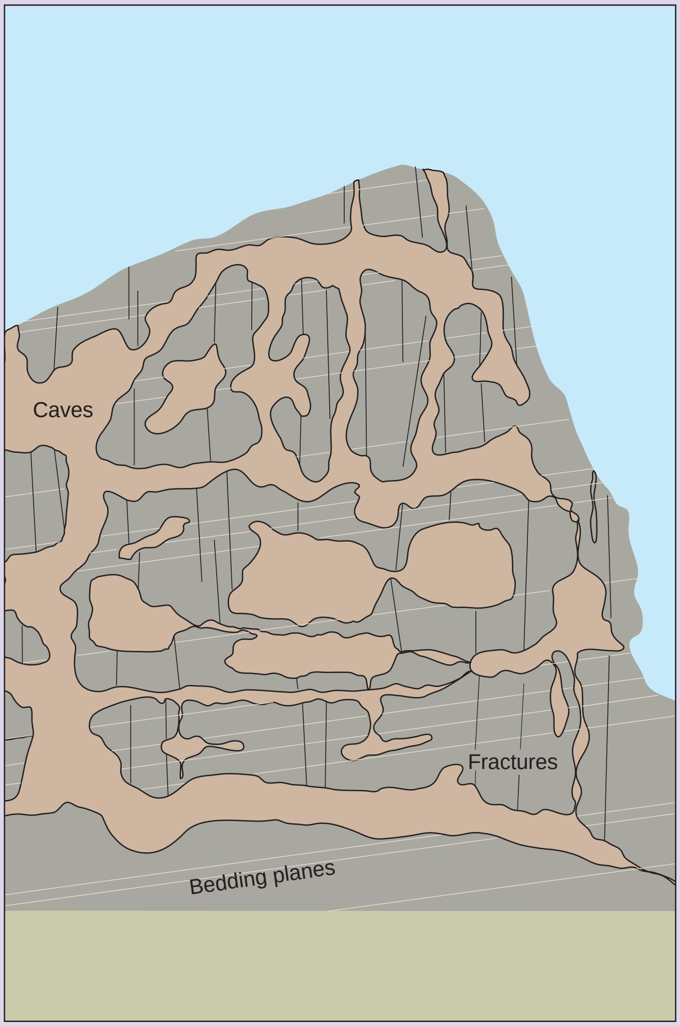
Probably the most spectacular example of subsidence is Mexico City, which is built on a former lake bed. The subsurface formations are water-saturated clay, sand, and volcanic ash. The sediment compacts as groundwater is pumped for domestic and industrial use, and slow subsidence is widespread. The opera house (weighing 54,000 metric tons) has settled more than 3 m, and half of the first floor is now below ground level. Other large structures are noticeably tilted (Figure 13.29).

Another type of groundwater problem is shown in Figure 13.30. In western Wyoming, a dam for storing irrigation water was built in the tilted strata of the Madison Limestone Formation. The limestone, however, was so porous and permeable that all of the water that was supposed to be stored in the reservoir seeped into the subsurface and was lost. The reservoir never filled, and the project was abandoned.

We are using and altering the groundwater system at an ever-increasing rate. Approximately 20% of all water used in the United States is pumped from the subsurface. This amounts to more than 83 billion gallons a day, almost three times as much as in 1950. How much groundwater will be needed in the future? What effect will pumping groundwater have on the environment?

GeoLogic Cave Systems of Guilin, China





One of the most exotic landscapes in the world is the tower karst in southern China. Here, groundwater is a powerful agent of erosion and forms vast cave systems largely hidden from view. Openings to many caves occur on hill sides but they only give a hint to the extent of the cave system within the mountains. What were the major controlling factors in their formation?

Observations

1. Limestone, a soluble rock, is the dominant rock type in this region.
2. The hills are unusual steep-sided, conical mounds.
3. Intersecting sets of fractures cut the rocks and bedding planes are etched into the rocks.
4. The hills are remnants of the once extensive limestone layer.
5. The hillside is riddled with openings to caves—some go through the entire hill.
6. The abundance of water and vegetation show that the climate is humid.

Interpretations

Taken together, these observations lead to the logical conclusion that this landscape was shaped largely by groundwater solution. In this humid climate, surface water seeped into intersecting joints and enlarged them by solution activity. This separated the once continuous limestone layer into numerous conical towers. Caves and smaller openings on the face of the hills indicate extensive cavern systems inside the hills. In many cases, cave exploration has verified this conclusion. The caverns were also dissolved by groundwater percolating along fractures and bedding planes. The diagram illustrates how a geologist might view this area. Without abundant water none of these processes would be possible and the limestone would resist weathering and erosion.

KEY TERMS

aquifer (p. 340)
artesian water (p. 346)
cave (p. 354)
cone of depression (p. 345)
confined aquifer (p. 340)
discharge (p. 338)
disappearing stream (p. 354)
geothermal energy (p. 349)
geyser (p. 349)
groundwater (p. 338)
hydraulic head (p. 341)
hydrostatic pressure (p. 339)
karst topography (p. 354)
leach (p. 364)
perched water table (p. 340)
permeability (p. 339)
pore spaces (p. 338)
porosity (p. 338)
potentiometric surface (p. 347)
recharge (p. 338)
saltwater encroachment (p. 365)
seep (p. 344)
sinkhole (p. 351)
solution valley (p. 354)
speleothem (p. 359)
spring (p. 344)
stalactite (p. 359)
stalagmite (p. 360)
subsidence (p. 368)
tower karst (p. 355)
unconfined aquifer (p. 340)
water table (p. 340)
zone of aeration (p. 340)
zone of saturation (p. 340)

REVIEW QUESTIONS

1. Define porosity and permeability.
2. Describe and illustrate the major types of pores, or voids, in rocks.
3. What rock types are generally impermeable or nearly impermeable?
4. Describe the major zones of subsurface water, and explain how water moves through each zone.
5. Contrast the geologic conditions that form confined and unconfined aquifers.
6. What is a potentiometric surface? How does it control the movement of water in confined aquifers?
7. Explain some ways in which springs originate.
8. What effects are produced in the water table by excessive and rapid pumping?
9. Explain how a flowing well develops.
10. Explain the origin of geysers.
11. What is the source of heat for hot springs and geysers?
12. Describe the evolution of a landscape in which groundwater is the dominant agent of erosion.
13. Explain how stalagmites and stalactites originate.
14. What important resources are related to groundwater systems?
15. Describe the forms and processes of groundwater pollution.
16. Describe the relationship between salty groundwater and fresh groundwater beneath an island or a peninsula.
17. What undesirable effects can result from withdrawing an excessive amount of groundwater from wells close to the ocean?
18. Explain how the alteration of the natural drainage system in southern Florida has affected the Everglades.
19. How can subsidence of the land result from the withdrawal of groundwater? Give examples.

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MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Review) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of the effects of overpumping a well and of how water flows through pore spaces
- Slide shows with examples of groundwater erosion
- A direct link to the Companion Website