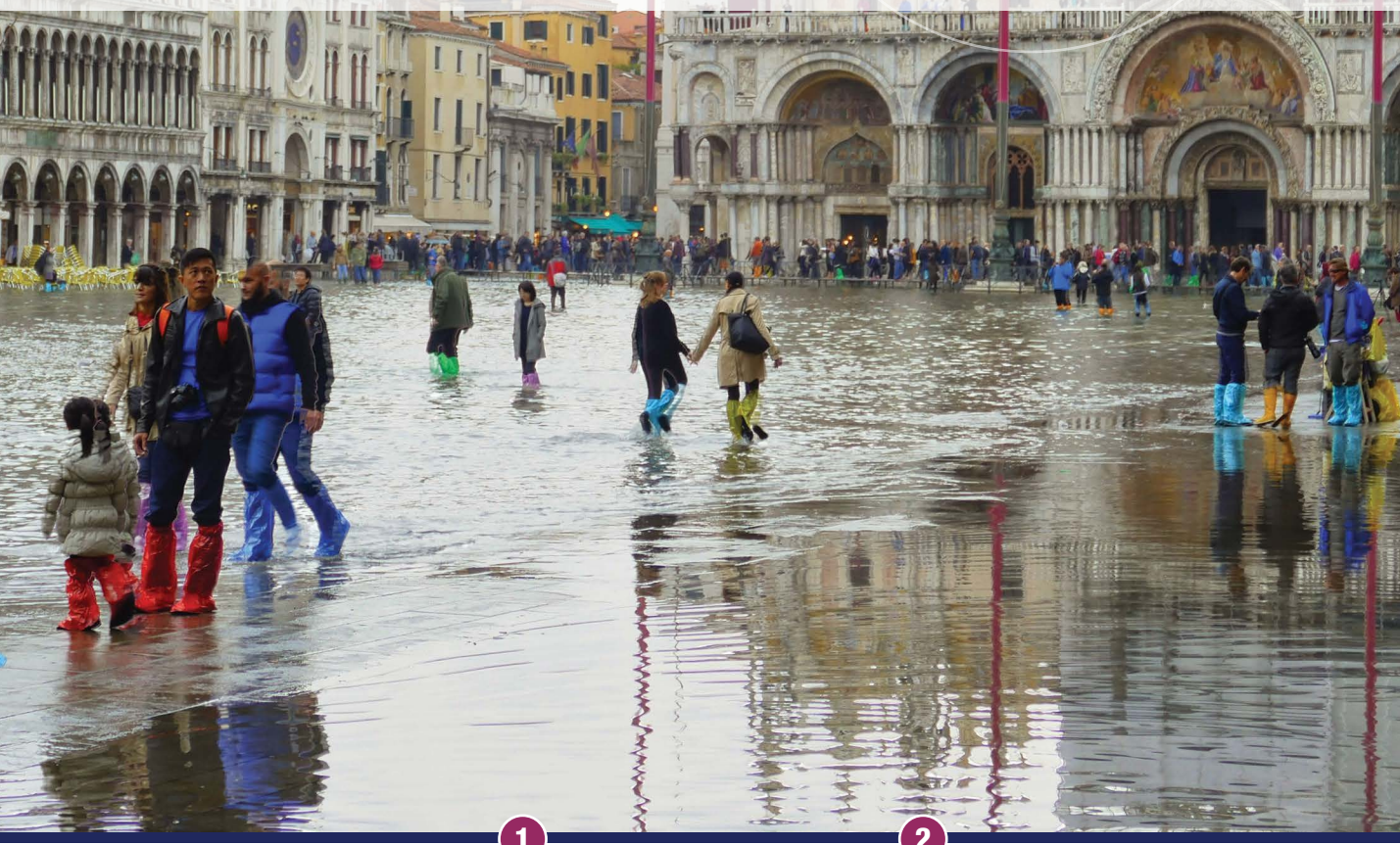
# Natural and human-induced processes are contributing to the subsidence of Venice

8



## APPLYING the 5 fundamental concepts Venice is Sinking

1

**Science helps us predict hazards.**

Short-term annual subsidence estimates form satellite data and longer-term estimates from scientific investigation of historical records and anthropological studies provide valuable data from which to understand the causes (natural and human-induced) of subsidence and enable preventative action to be taken.

2

**Knowing hazard risks can help people make decisions.**

Italy has evaluated the subsidence of Venice, as well as the risk of damage to land and property from future subsidence, for many decades. However the city is a global tourist attraction, and residents and tourists consider the risk to be acceptable—for now.

# Subsidence and Soils

## Venice is Sinking

Italy's beautiful and famous city of Venice faces a serious geologic problem; the city is sinking, or subsiding, at more that 1.5 mm (~0.06 in.) per year in some areas.[1] Venice is built on 118 small islands in a coastal lagoon. The islands are separated by waterways and connected by more than 400 bridges. Although its coastal location and numerous canals are part of Venice's attraction as a tourist destination, the presence of so much water surrounding a subsiding city makes Venice extremely prone to flooding. Today the city uses a network of hydrologic stations, capable of predicting high-water incursions 48 hours in advance, linked to sirens (and ringing of church bells) to warn the residents and tourists of impending flood events.

Historic records indicate that Venice has subsided by about 25 cm (~10 in.) since the late 1800s, leaving much of the land on which the city is built only a few centimeters above sea level.[1] Although subsidence (vertical deformation, in this case sinking) has been occurring naturally for millions of years, over pumping of groundwater from the 1930s to the 1960s significantly increased the historic rate of subsidence.[2] This subsidence has resulted in numerous floods from the sea due to such things as minor as high tides (see chapter-opener

**< Flooding in St. Mark's Square, Venice, Italy**
An exceptional high tide (137 cm (~57 in.)) on October 17, 2015, caused the flooding of 80 percent of Venice in northern Italy. Flooding is becoming more common as Venice subsides and sea-level rises. *(Panoramio (grumpylumixuser))*

Subsidence, the sinking of the land, and expansion and contraction of the soil are important geologic processes capable of causing extensive damage in some areas of the world.

After reading this chapter, you should be able to:

**LO:1** Describe what a soil is and the processes that form and maintain soils.

**LO:2** Explain why soil erosion might threaten our society.

**LO:3** Summarize the causes and effects of subsidence and volume changes in the soil.

**LO:4** Locate on a map the geographic regions at risk for subsidence and volume changes in the soil.

**LO:5** Discuss the hazards associated with karst regions.

**LO:6** Summarize the effects of subsidence and soil volume changes.

**LO:7** Identify linkages between subsidence, soil expansion and contraction, and other hazards, as well as natural service functions of karst.

**LO:8** Explain how humans interact with subsidence and soil hazards.

**LO:9** Evaluate what can be done to minimize the hazard from subsidence and volume changes in the soil.

**LEARNING Objectives**

**3**

**Linkages exist between natural hazards.**

Subsidence of Venice is linked to flooding, which is increasing due to global climate change and consequent sea-level rise.

**4**

**Humans can turn disastrous events into catastrophes.**

Ground water pumping during the mid-twentieth century has led to increased total and rates of subsidence over the past 100 years, exacerbating the flood hazard to this densely populated and highy visited city.

**5**

**Consequences of hazards can be minimized.**

When we return to Venice at the end of the chapter you will learn about the city's strategy for minimizing the effects of subsidence-driven flooding caused by high tides and storm surges beyond their early warning system.

photograph). The human response to this flooding has been to raise buildings and streets above the flood level, but the former ground floors of many old houses are uninhabitable. Both natural- and human-induced subsidence is still occurring and together with sea-level rise over the past century the frequency of floods has increased. As recently as February 2013, floodwaters entered historic buildings and shops in Venice, forcing some Venetians to wade in waist-deep water.

# 8.1 Soil and Hazards

**Soil** develops in the upper few meters (~10 ft.) of Earth's surface where rock, water, atmospheric gasses, and life interact for a prolonged period of time. Soil is composed of a mixture of rock and mineral fragments, organic material, liquids, gasses, and innumerable organisms that together support life. The actual definition of soil, however, may be defined in different ways. To geologists, it is rocky earth material that has been altered by physical and chemical processes, and is a medium for water transport and storage. To biologists, it is the top layer of Earth in which rooted plants grow, and serves as a habitat for thousands of species. To civil engineers, on the other hand, soil is any solid earth material that can be manipulated or removed without blasting. Each of these definitions highlight different soil properties, all of which are important to understanding soil-related earth processes as hazards.

Understanding soil development, in addition to being fundamental to soil-hazard science, is useful for evaluating other natural hazards, such as floods, landslides, earthquakes, and climate change. For example, the study of soils has been a powerful tool in establishing the local age of Earth's surface deformed by both faulting and landsliding, which has led to better site calculations of event frequency and thus assist in minimizing future impacts. Soil is also intimately involved in all components of the geologic cycles (see Section 1.3), and as Earth's largest terrestrial carbon reservoir, global soils are intergral to the planet's global climate system and may be instrumental in efforts to slow the rapid rise of atmospheric $CO_2$.

The development of a soil from inorganic and organic materials is a slow and complex process. The first step in this process is the physical breakdown and/or chemical decomposition of rock and mineral material into *sediment*—a process known as **weathering**. In addition to liberating precious nutrients nessessary for life, chemical weathering creates clay minerals which are intimately involved in many soil hazards (see Section 8.2). Further weathering of sediment and soil is enhanced by the activity of organisms that reside in the soil, as well as reactions with gasses and liquids trapped in or passed through the pore spaces (the spaces between soil particles).

A soil can be considered an open system that interacts with all components of the geologic cycle. Although the more insoluble weathered material may remain in place, some weathered material will be transported by water, wind, or glaciers and deposited far away from the rock source from which it was weathered. Different soil characteristics and properties are the result of local environmental factors, including: *climate* (temperature, precipitation), *topography* (slope, elevation), *parent material* (composition of the rock), *age* (time to develop), and *biota* (organisms) where the soils form.

## SOIL HORIZONS

Vertical and horizontal movements of material in a soil system over time creates a *soil profile*—a collection of distinct soil layers parallel to the surface. The layers are called zones or **soil horizons**, and can be distinguished based on soil color, texture and composition. Our discussion of soil profiles will mention only the horizons most commonly present in soils. Additional information is available from detailed soils texts.[3,4]

Figure 8.1a shows the common master (prominent) soil horizons. The O horizon and A horizon contain highly concentrated organic material; the differences between these two layers reflect the amount of organic material present. Generally, the O horizon consists entirely of plant litter and other organic material, whereas the underlying A horizon contains a good deal of both organic and mineral material. Below the O or A horizon, some soils have an E horizon, or zone of leaching, a layer that is leached of iron-bearing components and is light in color because it contains less organic material than either the O or A horizon and little inorganic coloring material such as iron oxides.

The B horizon, or zone of accumulation, underlies the O, A, or E horizon and consists of a variety of materials translocated downward from the overlying horizons. Several types of B horizon have been recognized. Probably the most important type is the argillic B, or $B_t$ horizon. A $B_t$ horizon is enriched with clay minerals that have been translocated downward by soil-forming processes. Another type of B horizon of interest to environmental geologists is the $B_k$ horizon, characterized by the accumulation of calcium carbonate which whitens the colors the soil horizon (Figure 8.1b). The carbonate coats individual soil particles in the soils and may fill some pore spaces, but it does not dominate the morphology (structure) of the horizon. A soil horizon that is so impregnated with calcium carbonate that its morphology is dominated by the carbonate is designated a K horizon. Carbonate completely fills the pore

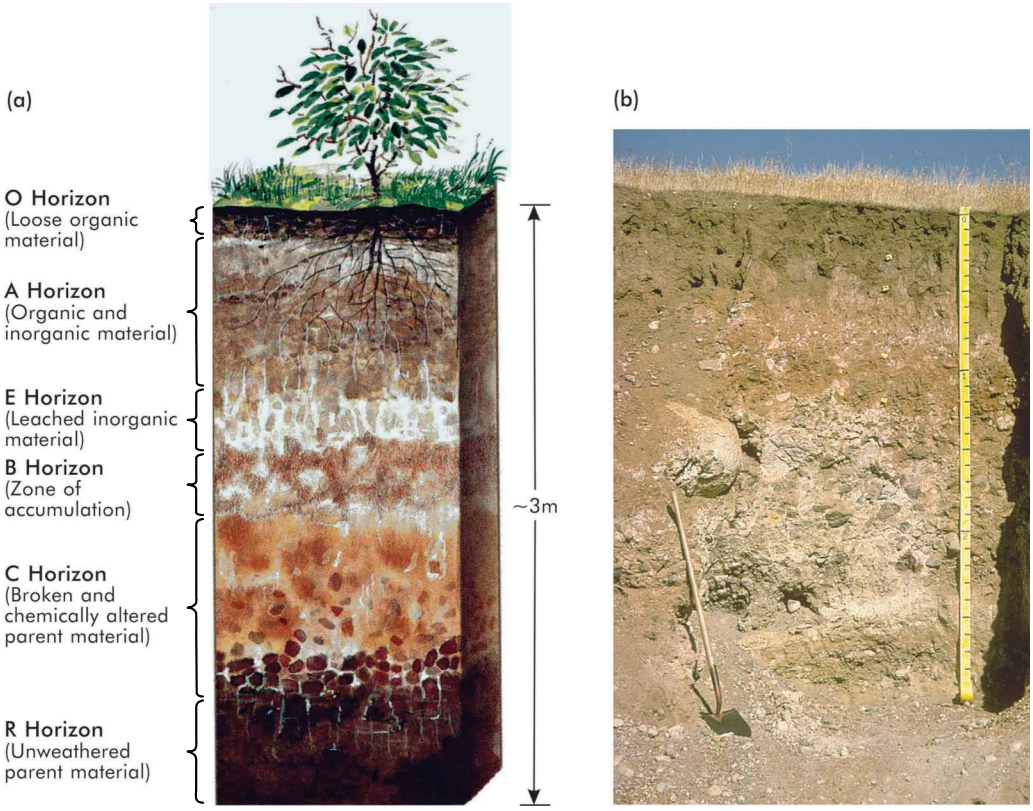



**FIGURE 8.1 Soil Profiles**

(a) Idealized diagram showing a soil profile with soil horizons. (b) Soil profile showing a darker brown A horizon, a light red B horizon, a whitish $B_k$ horizon rich in pedogenic calcium carbonate, and a lighter colored C horizon. For this particular profile the A and E horizons are not differentiated. *(Edward A. Keller)*

spaces in K horizons, and the carbonate often forms in layers parallel to the surface. The term *caliche* is often used for irregular accumulation or layers of calcium carbonate in soils.

The C horizon lies directly over the unaltered parent material and consists of parent material partially altered by weathering processes. The R horizon, or unaltered parent material, is the consolidated bedrock that underlies the soil. However, some of the fractures and other pore spaces in the bedrock may contain clay that has been translocated downward.[3]

The term *hardpan* is often used in the literature to describe a dense soil layer. Hardpans are often composed of compacted clay within the $B_t$ horizon, or a well-cemented carbonate layers in the $B_k$ horizon that are typical of soils in arid and semi-arid landscapes. Hardpan horizons are nearly impermeable and, thus, restrict the downward movement of soil water. Such hardpans, or impermeable soil horizons, lead to increased runoff during heavy rain fall events and, therefore, are linked to downstream and flash flooding events.

## SOIL COLOR

One of the first things we notice about a soil is its color, or the colors of its horizons. The color of a particular horizon is a function, in part, of its chemical and physical composition reflecting different soil processes within the profile (Table 8.1). The O and A horizons tend to be dark because of their abundant organic material. The E horizon, if present, may be almost white due to the leaching of iron and aluminum oxides. The B horizon shows the most dramatic differences in color, varying from yellow-brown to light red-brown to dark red, depending on the presence of clay minerals and iron oxides. The $B_k$ horizons may be light-colored due to their carbonates, but they are sometimes reddish as a result of iron oxide accumulation. If a true K horizon has developed, it may be almost white because of its accumulation of calcium carbonate. Although soil color can be an important diagnostic tool for analyzing a soil profile, one must be cautious about calling a red layer a B horizon. The original parent material, if rich in iron,

**TABLE 8.1 Soil Profile Descriptions by Horizon**

| Soil Horizon | Horizon Description |
|---|---|
| O | Horizon is composed mostly of organic materials, including decomposed or decomposing leaves, twigs, etc. The color of the horizon is often dark brown or black. |
| A | Horizon is composed of both mineral and organic materials. The color is often light black to brown. Leaching, defined as the process of dissolving, washing, or draining earth materials by percolation of groundwater or other liquids, occurs in the A horizon and moves clay and other material such as iron and calcium to the B horizon. |
| E | Horizon is composed of light-colored materials resulting from leaching of clay, calcium, magnesium, and iron to lower horizons. The A and E horizons together comprise the zone of leaching. |
| B | Horizon is enriched in clay, iron oxides, silica, carbonate, or other material leached from overlying horizons. This horizon is known as the zone of accumulation. |
| C | Horizon is composed of partially altered (weathered) parent material; rock is shown in Figure 8.1a but the material could also be alluvial in nature, such as river gravels in other environments. The horizon may be stained red with iron oxides. |
| R | Unweathered (unaltered) parent material. |

may produce a very red soil, even with relatively little soil profile development.

Soil color can be an important indicator of how well drained a soil is. Well-drained soils are well aerated (oxidizing conditions), and iron oxidizes form giving these soils a red color. Poorly drained soils are wet, and iron in it is reduced rather than oxidized. The color of such a soil is often yellow. This distinction is important because poorly drained soils are associated with environmental problems such as lower slope instability. These soils are also a poor choice for siting waste disposal functions such as household sewage systems (septic tanks and leach fields).

## SOIL TEXTURE

The texture of a soil is defined by the relative proportions of sand-, silt-, and clay-sized particles (Figure 8.2). *Clay particles* have a diameter of less than 0.004 mm, *silt particles* have diameters ranging from 0.004 to 0.074 mm, and *sand particles* are 0.074 to 2.0 mm in diameter. Earth materials with particles larger than 2.0 mm in diameter are called *gravel*, *cobbles*, or *boulders*, depending on the particle size. Note that the sizes of particles given here are for engineering classification and are slightly different from those used by the U.S. Department of Agriculture for soil classification.

Soil texture is commonly estimated in the field and then refined in the laboratory by separating the sand, silt, and clay and determining their proportions. A useful field technique for estimating the size of sand-sized or smaller soil particles is as follows: It is sand if you can see individual grains, silt if you can see the grains with a 10× hand lens, and clay if you cannot see grains with such a hand lens. Another method is to feel the soil:

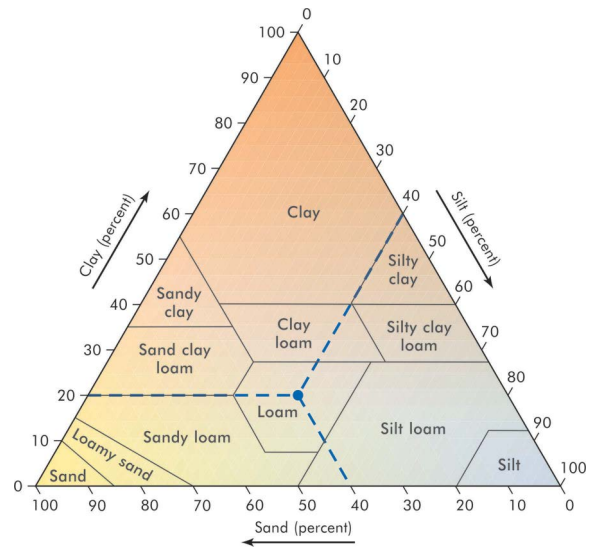



**FIGURE 8.2 Soil Textural Classes**
The classes are defined according to the percentage of clay-, silt-, and sand-sized particles in the soil sample. The point connected by dashed lines represents a soil composed of 40 percent sand, 40 percent silt, and 20 percent clay, which is classified as loam. *(U.S. Department of Agriculture standard textural triangle)*

Sand is gritty (crunches between the teeth), silt feels like baking flour, and clay is cohesive. When mixed with water, smeared on the back of the hand, and allowed to dry, clay cannot be dusted off easily, whereas silt or sand can.

Soil particles often cling together in aggregates, called *peds*, that are classified according to shape into several types. Figure 8.3 shows some of the common structures of peds found in soils. The type of structure

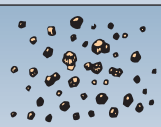
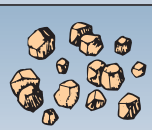
| Soil Structure Type | Typical size range | Horizon usually found in | Comments |
|---|---|---|---|
| Granular  | 1–10 mm | A | Can also be found in B and C horizons |
| Blocky  | 5–50 mm | $B_t$ | Are usually designated as angular or subangular |
| Prismatic  | 10–100 mm | $B_t$ | If columns have rounded tops, structure is called *columnar* |
| Platy  | 1–10 mm | E | May also occur in some B horizons |

**FIGURE 8.3 Chart of Different Soil Structures (Peds)**

present is related to soil-forming processes, but some of these processes are poorly understood.[3] For example, *granular structure* is fairly common in A horizons, whereas *blocky* and *prismatic structures* are most likely to be found in B horizons. Soil structure is an important diagnostic tool in helping to evaluate the development and approximate age of soil profiles. In general, as the profile develops with time, structure becomes more complex and may go from granular to blocky to prismatic as the clay content in the B horizon increases.

## RELATIVE SOIL PROFILE DEVELOPMENT

Most geologists will not need to make detailed soil descriptions and analyses of soil data. However, it is important for geologists to recognize differences among weakly developed, moderately developed, and well-developed soils, that is, to recognize their relative profile development. These distinctions are useful in the preliminary evaluation of soil properties and help determine whether the opinion of a soil scientist is necessary in a particular project:

- *A weakly developed soil profile* is generally characterized by an A horizon directly over a C horizon (there is no B horizon or it is weakly developed). The C horizon may be oxidized. Such soils tend to be only a few hundred years old in most areas, but they may be several thousand years old.
- *A moderately developed soil profile* may consist of an A horizon overlying an argillic $B_t$ horizon that overlies the C horizon. A carbonate $B_k$ horizon may also be present but is not necessary for a soil to be considered moderately developed. These soils have a B horizon with translocated changes, a better-developed texture, and redder colors than those that are weakly developed. Moderately developed soils often date from at least the Pleistocene (more than 10,000 years old).
- *A well-developed soil profile* is characterized by redder colors in the $B_t$ horizon, more translocation of clay to the $B_t$ horizon, and stronger structure. A K horizon may also be present but is not necessary for a soil to be considered strongly developed. Well-developed soils vary widely in age, with typical ranges between 40,000 and several hundred thousand years and older.

A *soil chronosequence* is a series of soils arranged from youngest to oldest on the basis of their relative profile development. Such a sequence is valuable in hazards work because it provides information about the recent history of a landscape, allowing us to evaluate site stability when locating such critical facilities as a waste disposal operation or a large power plant. A chronosequence combined with numerical dating (applying a variety of dating techniques, such as radiocarbon $^{14}C$, to obtain a date for the soil in years before the present time) may provide the data necessary to make such

inferential statements as, "There is no evidence of ground rupture due to earthquakes in the past1000 years," or "The last mudflow was at least 30,000 years ago." It takes a lot of work to establish a chronosequence in soils in a particular area. However, once such a chronosequence is developed and dated, it may be applied to a specific problem.

Consider, for example, the landscape shown in Figure 8.4, an offset alluvial fan along the San Andreas fault in the Indio Hills of Southern California. The fan is offset about 0.6 km, which is equal to 60,000 cm (~0.4 mi.). Soil age estimates from pits excavated in the alluvial fan suggest that it is at least 20,000 years old but younger than 45,000 years. The age was estimated based on correlation with a soil chronosequence in the nearby Mojave Desert, where numerical dates for similar soils are available. Soil development on the offset alluvial fan allowed the age of the fan to be estimated. Thus, the slip rate (the amount of offset of the fan divided by the age of the fan—that is, 60,000 cm divided by 20,000 years) for this part of the San Andreas fault could be estimated at about 3 cm (~1 in.) annually.[5,6] The slip rate for this segment of the fault was not previously known. The rate is significant because it is a necessary ingredient in the eventual estimation of the probability and the recurrence interval of large, damaging earthquakes (see Chapter 3).

More recent work, using a numerical dating technique known as exposure dating, suggests the age of 35,000 +/– 2,500 years and a total displacement of about 570 m. (~1870 ft.). This new and more accurate estimation of age provides a maximum slip rate of about 1.7 cm (~0.7 in.) per year. Thus, the earlier soil date has been improved by more recent technology. As numerical dating has improved, the use of soil development as a dating tool has decreased.

## WATER IN SOILS

If you analyze a block of soil, you will find it is composed of bits of solid inorganic and organic matter with pore spaces between particles. The pore spaces are filled with gases (mostly air) or liquids (mostly water). If all the pore spaces in a block of soil are completely filled with water, the soil is said to be in a *saturated condition*; otherwise, it is said to be *unsaturated*. Soils in swampy areas may be saturated year-round, whereas soils in arid regions may be saturated only occasionally (Figure 8.5).

The amount of water in a soil, called its *water content* or its *moisture content*, can be important in determining engineering properties such as the strength of a soil and its potential to shrink and swell. If you have ever built a sand castle at the beach, you know that dry sand is impossible to work with but that moist sand will stand vertically, producing walls for your castle. Differences between wet and dry soils are also apparent to anyone who lives in or has visited areas with dirt

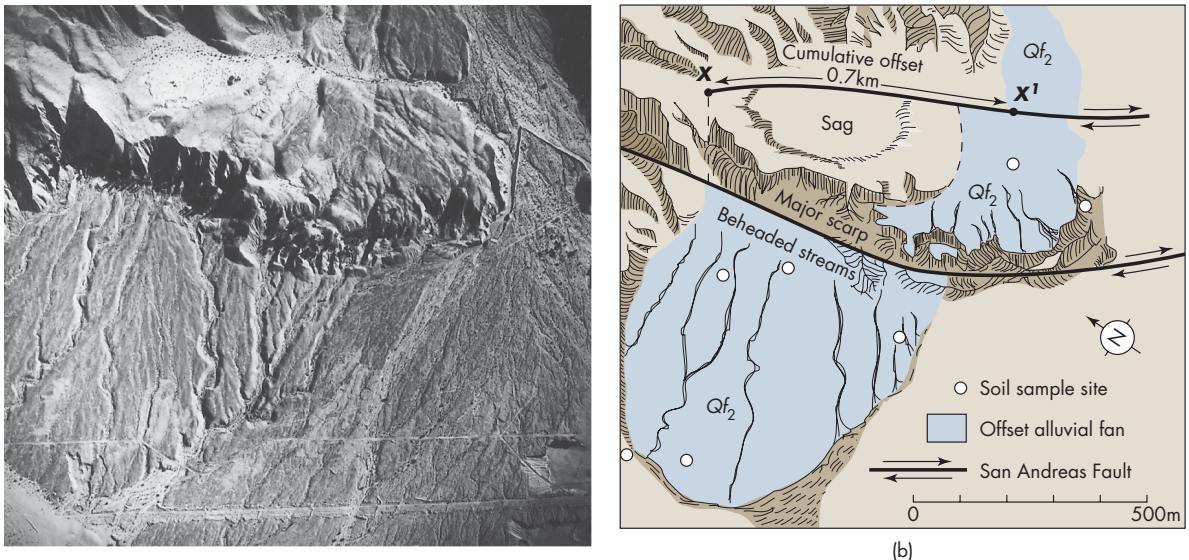
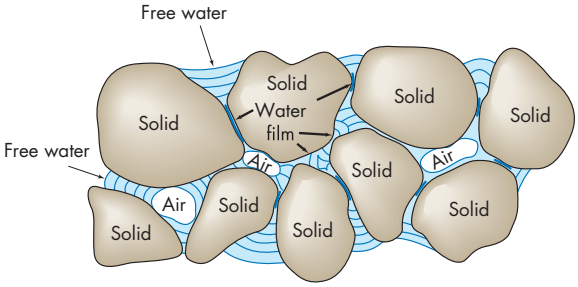



**FIGURE 8.4 Offset Alluvial Fan Along the San Andreas Fault Near Indio, California**
(a) Aerial photograph of an alluvial fan offset across the San Andreas fault and (b) sketch map of the important tectonic features used to estimate offset. *(Woodward-Clyde Consultants)*




**▲ FIGURE 8.5 Partly Saturated Soil Showing Particle–Water–Air Relationships**

Particle size is greatly magnified. Attraction between the water and soil particles (surface tension) develops a stress that holds the grains together. This apparent cohesion is destroyed if the soil dries out or becomes completely saturated. *(Based on R. Pestrong,* Slope Stability. *American Geological Institute, 1974)*

roads that cross clay-rich soils. When the soil is dry, driving conditions are excellent but, following a rain storm, the same roads become mud pits and are nearly impassable.[7]

Water in soils may flow laterally or vertically through soil pores, which are the void spaces between grains, or in fractures produced as a result of soil structure. The flow is termed *saturated flow* if all the pores are filled with water and *unsaturated flow* when, as is more common, only part of the pores are filled with water.

In unsaturated flow, movement of water is related to processes such as thinning or thickening of films of water in pores and on the surrounding soil grains.[8] The water molecules closest to the surface of a soil particle are held most tightly, and as the films thicken, the water content increases and the outer layers of water may begin to move. Flow is, therefore, fastest in the center of pores and slowest near the edges.

Soil moisture relations and movement of water and other liquids in soils, along with ways to monitor movement of liquids, are important research topics. Water in the soil is related to many processes, including slope stability and subsidence of earth materials.

## CLASSIFYING SOILS

Both the terminology and the classification of soils present a problem in environmental studies because we are often interested in both soil processes and the human use of soil. A *taxonomy* (classification system) that includes engineering as well as physical and chemical properties would be most appropriate, but none exists. We must, therefore, be familiar with two separate systems of soil classification: *soil taxonomy*, used by soil scientists, and the *engineering classification*, which groups soils by material types and engineering properties.

Soil scientists have developed a comprehensive and systematic classification of soils known as *soil taxonomy*, which emphasizes the physical and chemical properties of the soil profile. This classification is a sixfold hierarchy that groups soils into several levels: Orders, Suborders, Great Groups, Subgroups, Families, and Series. The eleven Orders (Table 8.2) are mostly based on gross soil morphology (number and types of horizons present), nutrient status, organic content (plant debris, etc.), color (red, yellow, brown, white, etc.), and general climatic considerations (amount of precipitation, average temperature, etc.). With each step down the hierarchy, more information about a specific soil becomes known.

Soil taxonomy is especially useful for agricultural and related land-use purposes. It has been criticized for being too complex and for lacking sufficient textural and engineering information to be of optimal use in site evaluation for engineering purposes. Nevertheless, the serious earth scientist must know and understand this classification because it is commonly used by soil scientists and Quaternary geologists who study earth materials and the processes of recent earth history (past 1.8 million years).

The *unified soil classification system*, widely used in engineering practice, along with the evaluation of hazards is shown in Table 8.3. Because all natural soils are mixtures of coarse particles (gravel and sand), fine particles (silt and clay), and organic material, the major divisions of this system are *coarse-grained soils*, *fine-grained soils*, and *organic soils.* Each group is based on the predominant particle size or the abundance of organic material. Coarse soils are those in which more than 50 percent of the particles (by weight) are larger than 0.074 mm in diameter. In fine soils, less than 50 percent of the particles are greater than 0.074 mm in diameter.[7] Organic soils have a high organic content and are identified by their black or gray color and sometimes by an odor of hydrogen sulfide, which smells like rotten eggs.

## SOIL EROSION AS A HAZARD

A big question with soil as it relates to our society and our future prosperity is whether the agricultural systems that we depend on to feed a growing human population can maintain and improve soil fertility while minimizing soil erosion.[9] It appears that many of our agricultural practices are mining the soil; that is, soils are being eroded faster than they are being produced by soil-forming processes (Figure 8.6). Eventually,

**TABLE 8.2 General Properties of Soil Order Used with Soil Taxonomy by Soil Scientists**

| Order | General Properties |
|---|---|
| Entisols | No horizon development; many are recent alluvium; synthetic soils are included; often young soils. |
| Vertisols | Include swelling clays (greater than 35 percent) that expand and contract with changing moisture content. Generally form in regions with pronounced wet and dry seasons. |
| Inceptisols | One or more horizons have developed quickly; horizons are often difficult to differentiate; most often found in young but not recent land surfaces; have appreciable accumulation of organic material. Most common in humid climates but range from the Arctic to the tropics; native vegetation is most often forest. |
| Aridisols | Desert soils; soils of dry places; low organic accumulation; have subsoil horizon where gypsum, caliche (calcium carbonate), salt, or other materials may accumulate. |
| Mollisols | Soils characterized by black, organic-rich A horizon (prairie soils); surface horizons are also rich in bases. Commonly found in semiarid or subhumid regions. |
| Andisols | Soils derived primarily from volcanic materials; relatively rich in chemically active minerals that rapidly take up important biologic elements such as carbon and phosphorus. |
| Spodosols | Soils characterized by ash-colored sands over subsoil, accumulations of amorphous iron-aluminum sesquioxides and humus. They are acid soils that commonly form in sandy parent materials; found principally under forests in humid regions. |
| Alfisols | Soils characterized by a brown or gray-brown surface horizon and an argillic (clay-rich) subsoil accumulation with an intermediate to high base saturation (greater than 35 percent as measured by the sum of cations, such as calcium, sodium, magnesium, etc.). Commonly form under forests in humid regions of the midlatitudes. |
| Ulfisols | Soils characterized by an argillic horizon with low base saturation (less than 35 percent as measured by the sum of cations); often have a reddish-yellow or reddish-brown color. Restricted to humid climates and generally form on older landforms or younger, highly weathered parent materials. |
| Oxisols | Relatively featureless, often deep soils, leached of bases, hydrated, containing oxides of iron and aluminum (laterite) as well as kaolinite clay. Primarily restricted to tropical and subtropical regions. |
| Histosols | Organic soils (peat, muck, bog). |

Source: Based on *Soil Survey Staff, Keys to Soil Taxonomy*, 6th ed. Soil Conservation Service, U.S. Department of Agriculture, 1994.

**TABLE 8.3 Unified Soil Classification System Used by Engineers**

| Major Divisions | | | | Group Symbols | Soil Group Names |
|---|---|---|---|---|---|
| COARSE-GRAINED SOILS (Over half of material larger than 0.074 mm) | Gravels | Clean Gravels | Less than 5% fines | GW | Well-graded gravel |
| | | | | GP | Poorly-graded gravel |
| | | | | GM | Silty gravel |
| | | Dirty Gravels | More than 12% fines | GC | Clayey gravel |
| | Sands | | | SW | Well-graded sand |
| | | Clean Sands | Less than 5% fines | SP | Poorly-graded sand |
| | | | | SM | Silty sand |
| | | Dirty Sands | More than 12% fines | SC | Clayey sand |
| FINE-GRAINED SOILS (Over half of material smaller than 0.074 mm) | Silts Non-plastic | | | ML | Silt |
| | | | | MH | Micaceous silt |
| | | | | OL | Organic silt |
| | Clays Plastic | | | CL | Silty clay |
| | | | | CH | High plastic clay |
| | | | | OH | Organic clay |
| | | Predominantly Organics | | PT | Peat and muck |



**FIGURE 8.6 Soil Erosion in Eastern Washington State**
An example of serious soil erosion, with development of shallow gullies, in a wheat field. *(Jack Dykinga/USDA Forest Service)*

agricultural soil loss could erode the foundation of our civilization, as has happened to other civilizations throughout history.

**Soil erosion** may be defined in three ways: (1) the grain-by-grain removal of mineral and organic material in a soil by wind and/or water; (2) removal of soil material at an unacceptable rate; and (3) removal of soil material at a rate faster than it is being produced. Soil erosion has multiple effects, including loss of soil resources as well as degradation of the quality of the water due to sedimentation. Soil erosion is a problem in urban environments, where vegetation is often removed prior to development. Although we have many safeguards in effect to minimize soil erosion resulting from agriculture and other land-use change, the problem persists in many parts of the United States and is severe in many parts of the world where protection of soil resources may not be a high priority.[9,10]

8.1 CASE study

## Haiti and Soil Erosion

An example of extreme soil erosion comes from the Caribbean. Haiti and the Dominican Republic share the island of Hispaniola, but the two countries are very different. In Haiti, the median age of the population is 18, compared to 24 for the Dominican Republic. Life expectancy for Haitians is 60 years, compared to 72 for Dominicans. Haiti's per capita income is a fraction of that of the Dominican Republic. Another significant difference is the amount of forest cover: 3.8 percent in Haiti compared to 28.4 percent in the Dominican Republic (Figure 8.7). The percentage of forest cover is much lower for Haiti compared to the other Caribbean islands as well. Haiti is distinguished by its extensive deforestation, accompanied by a serious soil erosion problem, both of which are linked to an inadequate and unsafe water supply for the population (Figure 8.7).[11,12]

Historians and other scientists have studied the differences between Haiti and the Dominican Republic. There is general agreement that many of these differences result from their different colonial histories. The people of Haiti went through a difficult, violent revolution, gaining their freedom from France in 1804. During French rule, Haiti was prosperous with a high population density. Following the revolution, the Haitian people mistrusted Europeans to such an extent that trade

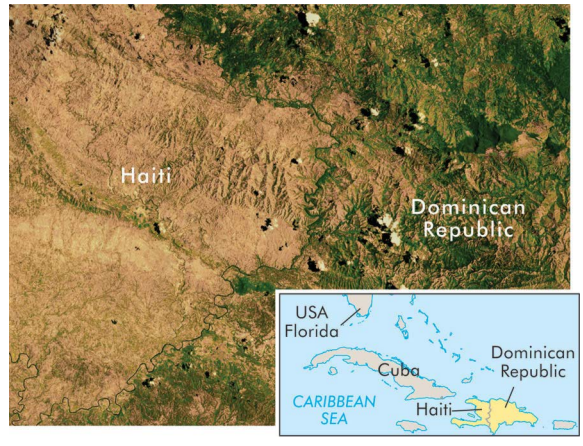



**FIGURE 8.7 Clearly Visible Boundary between Haiti and Dominican Republic**
Deforestation in Haiti has resulted in severe soil erosion, threatening slope stability and water quality and affecting the country's ability to feed its people. The boundary between Haiti and the Dominican Republic is clearly visible by the absence of vegetation in Haiti. *(NASA)*

with other countries was much reduced. Haiti was relatively wealthy following independence and did well for a while until political, social, and economic forces eventually led to a downward spiral that resulted in Haiti becoming the poorest country in the Western Hemisphere. The path to independence was different for the Dominican Republic. Spain was wealthy in terms of her colonies, and the Dominican people were left with the Spanish language, a dominant language of the time,[11] as well as good contacts with Europe, and so were able to effectively develop trade and commerce with the rest of the world.

Later in their respective histories, absolute dictators ruled both countries—but one of the Dominican Republic's dictators was interested in preserving forests for sustainable timber harvesting in order to increase the money in his own accounts. For this and other reasons, the Dominican Republic today has retained much of its forest cover and has a good deal of land in national parks. In Haiti, however, the French began the deforestation process by taking back a lot of timber to Europe and, following independence, deforestation continued at accelerating rates. Trees were unable to regenerate effectively, due to Haiti's lesser amounts of rainfall and the extensive soil erosion that occurred. Today, Haiti is virtually denuded of forests and has a seriously high erosion rate that favors landsliding and other problems related to tropical storms in the Caribbean.[11,12]

The population of Haiti has grown, as has that of the Dominican Republic. However, in Haiti the high density of people living in degraded land areas has led to a situation in which Haitians cannot adequately support themselves on their own land and, as a result, must depend on imported food and other commodities necessary for life. A devastating earthquake in 2010 only worsened Haiti's already precarious economy.

In summary, Haiti is an example of what can happen when environmental degradation linked to high population density, unprotected water and soil resources, and inadequate infrastructure results in extreme poverty.

**Rates of Soil Erosion** The depth of the soil at a particular site represents a balance between weathering of fresh parent material (rock or sediment) beneath the soil and erosion processes that removes soil. We are most concerned with top, organically rich soil that is best for growing crops. It takes about 500 to 1,000 years to form 50 mm (~2 in.) of soil. Although rates are highly variable, depending on climate, topography, and parent material, the rate of soil formation for agricultural land is 0.1 to 0.05 mm (~0.004–0.002 in.) per year. Accelerated erosion due to poor soil conservation can remove centuries of accumulation in less than a decade. Fortunately, agricultural practices such as no-till agriculture that minimize soil disturbance, along with other known conservation measures, can significantly reduce erosion rates.[10]

Rates of soil erosion are measured as a volume, mass, or weight of soil that is removed from a location within a specified time and area, for example, kilograms per year per hectare. Soil erosion rates vary with the engineering properties of the soil, land use, topography, and climate. The natural rate of soil erosion is about 0.5 to 1.0 ton per hectare per year (tons/ha/yr). The erosion rate of 6 tons per hectare will decrease soil depth by about 1 mm. That doesn't sound like much, but the process of soil loss is generally slow and difficult to recognize unless the erosion is concentrated in easily visible gullies. However, soil erosion rates in North, Central, and South America average 10–20 tons/ha/yr, and in Asia, the average is about 30 tons/ha/yr. These rates are many times the natural rate, suggesting that soil erosion in many agricultural regions is excessive and is depleting the soil resource and land productivity along with it.[13,14]

There are several approaches to measuring rates of soil erosion. The most direct method is to make actual measurements on slopes over a period of at least several years and use these values as representative of what is happening over a wider area and longer time span. This approach is rarely used, however, because data from individual slopes and drainage basins are very difficult to obtain. A second approach is to use data obtained from resurveying reservoirs to calculate the change in the reservoirs' storage capacity of water; the depletion of storage capacity is equivalent to the volume of sediment eroded from upstream soils. A third approach is to use an equation to calculate rates of sediment eroded from a particular site. One of the most common is the Universal Soil Loss Equation.[15] This equation uses data on rainfall, runoff, the size and shape of the slope, the soil cover, and erosion control practices to predict the amount of soil moved from its original position.[16]

With this introduction to soils behind us, we will turn to more specific aspects of subsidence.

## 8.1 CHECK your understanding

1. Define soil.
2. Decribe the main soil horizons.
3. What is relative soil profile development, and how is it useful in evaluating hazards?
4. What is the role of water in soils?
5. Explain the two primary ways that soils are classified.
6. Why is soil erosion a serious problem?
7. How are soil erosion rates determined?

## 8.2 Introduction to Subsidence and Soil Volume Change

In contrast to mass wasting (Chapter 7), which originates on slopes, subsidence and changes in the volume of the soil occur on both slopes and flat ground. **Subsidence** is a type of ground failure characterized by nearly vertical deformation, or the downward sinking of earth materials. It often produces circular surface pits, but it may produce linear or irregular patterns of failure. Volume changes in the soil result from various natural processes. These processes include shrinking and swelling caused by changes in the water content of the soil and frost heaving related to the freezing of water in the soil. With volume changes of 5–15 percent, the effects of changes of shrink/swell and freeze/thaw movement in soil are generally not as dramatic as some subsidence—you are unlikely to see a headline "Dozens Die in Denver as Soil Expands." However, volume changes in the soil are one of the most widespread and costliest of natural hazards.

Subsidence is commonly associated with the dissolution of soluble rocks, such as limestone, beneath the surface. The resultant landscape has closed depressions and is known as **karst topography**. Other major causes of subsidence include the thawing of frozen ground and compaction of recently deposited sediment. To a lesser degree, earthquakes and the underground drainage of magma are also responsible for causing subsidence. Human-induced subsidence, discussed in Section 8.7, can result from the withdrawal of underground fluids, from the collapse of soil and rock over underground mines, and from the draining of marshes and swamps.

### KARST FORMATION

Although the term *karst* is not in most people's vocabulary, it is the name given to a common type of landscape in the United States and in many other parts of the world.[17] In this type of topography, subsidence results from chemical weathering—the dissolution of rocks beneath the land surface. Dissolution occurs as surface water or groundwater percolates through rock that is easily dissolved. Four common sedimentary rocks—rock salt and rock gypsum, which are evaporites; limestone and dolostone, which are carbonates—and one common metamorphic rock, marble, are easily dissolved. Rock salt and rock gypsum dissolve rapidly as fresh surface water flows through holes in the rock, whereas limestone, dolostone, and marble will dissolve if the percolating water is acidic. Although rock salt is approximately 7,500 times more soluble and rock gypsum 150 times more soluble than limestone, most karst topography is underlain by limestone because of its greater abundance in near-surface rocks.[18]

Percolating water may become acidic when carbon dioxide is dissolved in it. This acidification generally occurs in the soil where carbon dioxide is produced by bacterial decomposition of dead plants and animals. Most soil bacteria "breathe" like humans; that is, their respiration takes in oxygen and releases carbon dioxide. Dissolving carbon dioxide in water produces carbonic acid, the same weak acid that is present in carbonated soft drinks such as Coke and Pepsi. Where acidified water comes in contact with limestone, it dissolves the bedrock and the land surface is lowered at an average rate of 10 cm (~4 in.) per century.[19] Carbonic acid dissolves limestone more readily than dolostone; thus, land underlain by limestone is more susceptible to dissolution and more likely to become karst topography (Figure 8.8).

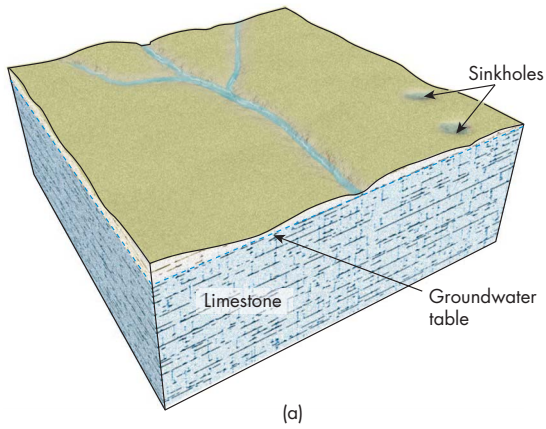
Areas underlain by dense, thin-bedded, fractured, or well-jointed crystalline limestone are especially vulnerable to dissolution. In such areas, surface waters are easily diverted to subterranean routes along irregular fractures or to planar cracks between sedimentary layers. If the percolating surface water has become acidic, it can enlarge these openings in the rock to produce underground holes, or voids, of various shapes and sizes. Where the void space is relatively close to the surface, pits known as **sinkholes** may develop (see Figure 8.8).

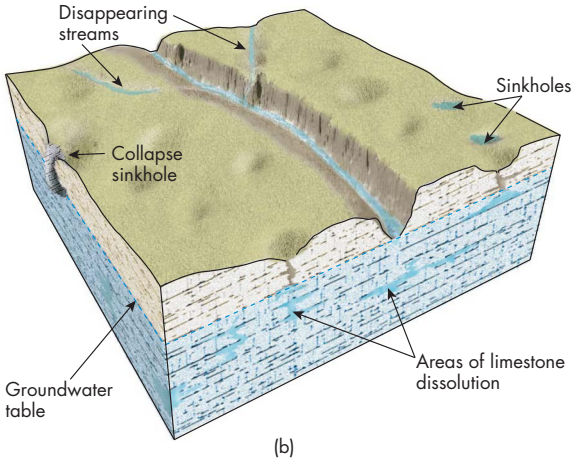
Sinkholes may exist individually or develop in large numbers to form a pockmarked surface known as a *karst plain*. The limestone plateau in southern Indiana and central Kentucky and Tennessee is an example of a karst plain (Figure 8.9).

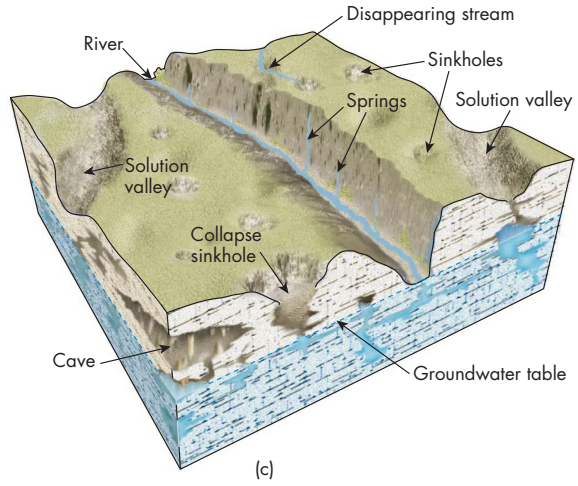
In addition to sinkholes, many karst areas have other features developed by the chemical weathering of bedrock. In humid temperate climates, karst landscapes are characterized by beautiful rolling hills with alternating areas of subsidence and undisturbed land. These areas may be underlain by large natural caves, commonly referred to as *caverns*, if the voids excavated by dissolution are at sufficient depth below the surface (see Figure 8.8). Cave openings can be the site of disappearing streams, where surface water goes underground, or the place where groundwater comes out at the surface to form springs. In humid tropical regions, extensive dissolution removes most of the soluble bedrock, leaving behind a landscape of steep hills known as *tower karst*.

**Sinkholes** In karst areas, sinkholes vary in size from one to several hundred meters in diameter and can open up extremely rapidly. There are two basic types of sinkholes (Figure 8.10):

1. **Solutional sinkholes:** Solutional sinkholes form by dissolution on the top of a buried bedrock surface and are the more common type of




**< FIGURE 8.8 Kart Topography Formation**
(a) In the early stage of karst formation in a limestone terrain, water from the surface seeps through fractures and along layering in the soluble rock. Weak acid in the water then dissolves the rock. (b) As a river erodes more deeply into the land surface, the groundwater table drops. Caves begin to form and collapse to become sinkholes. Some surface streams disappear underground to become groundwater. (c) In later stages of karst development, a downward-eroding river continues to lower the groundwater table. Large caverns and sinkholes develop and eventually merge to form solution valleys that form without surface streams. In humid tropical climates, intense dissolution removes nearly all of the rock, leaving behind pillars of limestone referred to as *karst towers. (Tarbuck, Edward J., Lutgens, Frederick K., and Tasa, Dennis G.,* Earth: An Introduction to Physical Geology, *10th ed. Upper Saddle River, NJ: Pearson, © 2011, p. 484. Reprinted and Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)*

sinkhole. Dissolution occurs where the downward infiltration of acidic groundwater becomes concentrated in holes created by joints and fractures. In the formation of these sinkholes, groundwater is typically drawn into a cone above a hole in the limestone, like water being drawn into a sink drain.

2. **Collapse sinkholes:** Collapse sinkholes develop when surface or near-surface material collapses into an underground cavern. As subsidence features, these sinkholes can develop into spectacular collapse structures (Figure 8.11).

Some sinkholes have openings into subterranean passages that allow water to escape during a rainstorm. Most, however, are filled with rubble that blocks any underground passages. Blocked sinkholes usually fill up with water, forming small lakes. Most of these lakes eventually drain when the water is able to filter through the debris.[20] Similar drainage problems can result when artificial ponds and lakes are constructed over sinkholes (see Case Study 8.2: Survivor Story).

**Cave Systems** As solutional pits enlarge and water moves downward through limestone, a series of caves or larger caverns may be produced. Mammoth Cave, Kentucky, and Carlsbad Caverns, New Mexico, are two of the famous caverns, or **cave systems**, in the United States. The primary mechanism for forming caves is groundwater moving through rock (see Figure 8.10a). Cave systems tend to develop at or near the present groundwater table. With respect to karst, the groundwater table refers to the level of groundwater below which rock fractures and caverns are filled with water (saturated). At and near the groundwater table there is a continuous replenishment of water that is not saturated with the weathering products of the limestone. Many cave systems have passages and




**FIGURE 8.9 Karst Topography**
This rolling landscape in west-central Kentucky is typical of karst topography in a humid temperate climate.
*(Tony Waltham/Robert Harding Picture Library Ltd/Alamy)*

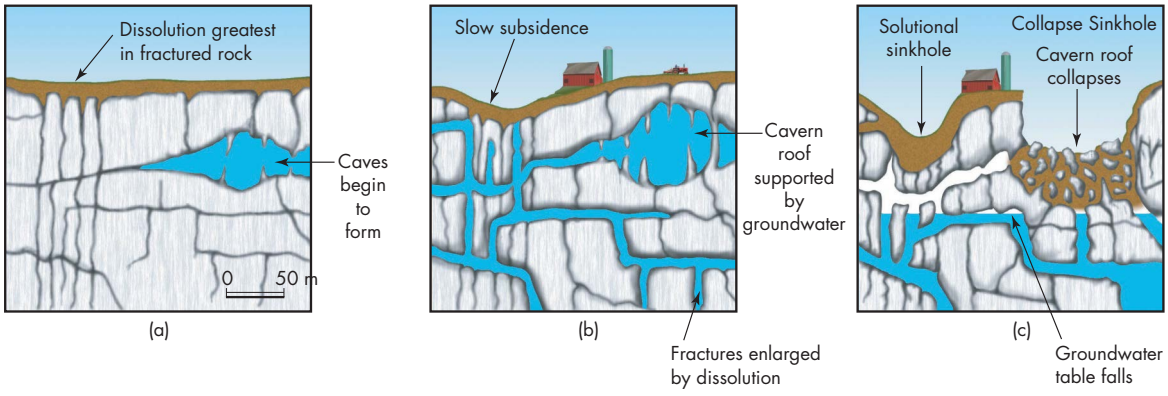



**FIGURE 8.10 Formation of Sinkholes**
(a) Initial dissolution of soluble bedrock takes place along vertical and horizontal fractures, and some fractures become small caves. (b) Over geologic time, dissolution continues to enlarge fractures and some caves become caverns with roofs partly supported by groundwater. (c) Subsequent lowering of the groundwater table removes the cavern roof support, and it falls into the cave to form a *collapse sinkhole.* Collapse may occur only a few years after the groundwater table has lowered. The heavily fractured area of bedrock is dissolved to create a *solutional sinkhole.*



**FIGURE 8.11 Giant Sinkhole**
Swallowing a 3-story building, this 18 m (60 ft.) diameter, 100 m (300 ft.) deep sinkhole opened in Guatemala City in 2010. Although the sinkhole was triggered by torrential rain during tropical storm Agatha, it appears a broken sewer pipe helped hollow out the subsurface cavity.

underground rooms on a number of levels. In these systems, each level may represent cave formation at different times that are in response to a fluctuating groundwater table. Fundamentally, caves are enlarged as groundwater moves through limestone along fractures or along planes between sedimentary layers, eventually forming a cavern. Later, if the groundwater table moves to a lower level, water seeping into the cave from above will deposit calcium carbonate on the sides, floor, and ceiling. These deposits form beautiful cave formations such as *flowstone*, *stalagmites*, and *stalactites* (Figure 8.12).

**Tower Karst** Large, steep limestone "towers" rising above the surrounding landscape are known as *tower karst*. Most common in humid tropical regions, karst towers are residual landforms of a highly eroded karst landscape. Cuba and Puerto Rico exhibit tower karst, as does much of Southeast Asia. The most spectacular examples come from Guilin, China, where they have been painted by artists since the first century (Figure 8.13).

**Disappearing Streams** Karst regions are often underlain by a complex groundwater system that occasionally intersects with the land surface. In these areas, surface streams may suddenly disappear into cave openings. Such *disappearing streams* do not actually disappear; rather, they flow directly into the groundwater system and continue along a subterranean route (see Figure 8.8b).

**Springs** Areas where groundwater naturally discharges at the land surface are known as *springs*. Most springs in karst areas are highly productive, especially during rainy periods. Karst springs are an important resource, but many are drying up as a result of overpumping of groundwater.

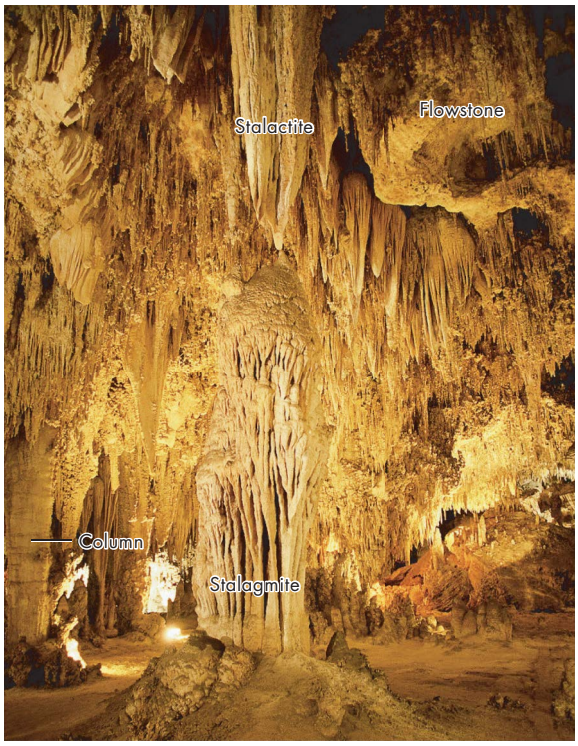



**FIGURE 8.12 Cave Formations**
Carlsbad Caverns, New Mexico, contains stalactites, which hang from the ceiling; stalagmites, which grow up from the cave floor; and flowstone, which forms as water flows slowly down the walls or across an incline. Stalactite hangs "tight" to the ceiling and a stalagmite "might" grow up from the cave floor to meet the stalactite. *(Bruce Roberts/Science Source)*

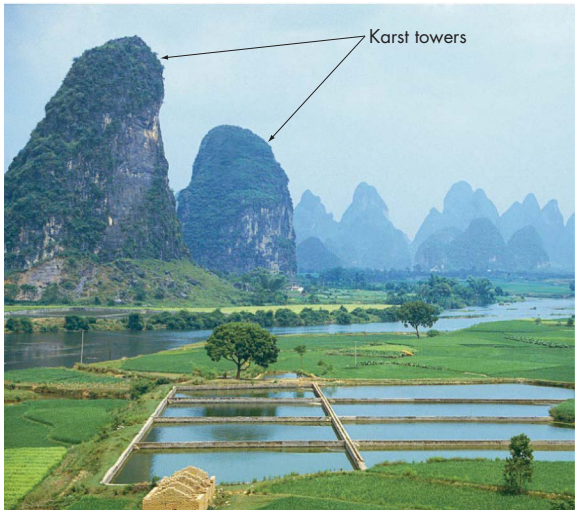



**FIGURE 8.13 Tower Karst**
Tower karst south of Guilin in South China's Guangxi Zhuang Autonomous Region. *(Tony Waltham/Robert Harding)*

## THERMOKARST FORMATION

Some karst terrains develop from processes other than the groundwater dissolution of rock. In polar regions, and at high elevations, much of the soil and underlying sediment remain frozen throughout the year. This natural condition, called **permafrost**, may be continuous throughout the soil or, in slightly warmer climates, may exist as discontinuous patches or thin layers. Permafrost consists of particles of soil or sediment that remain cemented with ice for at least two years. The melting of this frozen earth material can produce subsidence, especially if it contains a large amount of ice. Land subsidence of several meters or more is possible through the melting of permafrost.[21]

If undisturbed by human activity, the thawing of permafrost is generally limited to the upper few meters of earth material. This forms an active layer directly below the land surface, in which the permafrost thaws during summer months and the water in the soil refreezes in the winter. However, more extensive thawing of permafrost can produce an irregular land surface known as *thermokarst*. Climatic warming over the past five decades has thawed large areas of Arctic permafrost and formed thermokarst. In some areas, the uppermost layers of permafrost are thawing at rates of close to 20 cm (~8 in.) per year.[22]

## SEDIMENT AND SOIL COMPACTION

Rapidly deposited fine sediment, soil and sediment cemented with soluble minerals, and organic-rich soil are all susceptible to subsidence. This subsidence may occur as the rapidly deposited sediment compacts; as sediment and soil collapse when the binding material is loosened; or, in organic soils, as water is drained from the soil. Compaction of sediment and soil can occur naturally or as the result of human activities.

**Fine Sediment** Fine sand and mud that have been transported and deposited in a relatively short amount of time contain a great many water-filled spaces between the sediment particles. With time, the amount of water between the particles is reduced, and the sediment compacts. Rapid deposition and compaction are especially common in river deltas. In deltas, natural subsidence has to be balanced by additional sedimentation to keep the land surface of the delta, called the *delta plain*, from sinking below sea level. Episodic events such as floods and earthquakes can cause deltaic sediment to remobilize and subside. Historically, this subsidence has submerged coastal cities, including Eastern Canopus, Herakleion, and part of Alexandria on the Nile Delta in Egypt.[23]

CASE study

# 8.2 Survivor Story

# Sinkhole Drains Lake

The shores of Scott Lake, in central Florida, were a coveted address for residents of the area. Influential executives built multimillion-dollar mansions alongside the 285-acre private waterway. Scott Lake's pristine waters attracted birds, otters, alligators, and people who fished for the teeming populations of largemouth bass, grass carp, bluegill, and catfish.

Then, within the space of a week, virtually the entire lake disappeared.

The story began on June 13, 2006, when the lake received more than 8 inches of rain. But instead of rising, the water level of the lake began dropping. Over the next few hours, the water began to drain in earnest. Residents on the lake's southeastern shore watched the lake's normally placid waters begin to bubble, then whirlpool around a single point. Boathouses collapsed. Docks across the lake were left standing high and dry (Figure 8.2.A).

Dave Curry, who has lived on the lakeshore for more than 30 years, guessed the cause immediately: a sinkhole.

As in most of Florida, the soil around Scott Lake is shallow, just a few tens of feet deep. Beneath the soil is a porous layer of limestone and the water-saturated rock of the great Floridan aquifer. Several seasons of drought had lowered the water level in the aquifer, undermining support for the soil above. With the sudden weight of so much rain, the lake bottom collapsed into a hole more than 1.5 m (~5 ft.) in diameter and 16 m (~52 ft.) deep.

"This happens all the time in Florida," Curry says. He had watched the lake drain once before, in 1969, likely due to a previous sinkhole.

This time, Scott Lake lost more than a billion gallons of water, more than 95 percent of the lake's volume. The event was catastrophic for lake wildlife. "I counted seven alligators down in that one hole. They couldn't get out; they ended up being washed into the Floridan aquifer along with the fish and the turtles," Curry says.

Of the estimated 85,000 pounds of fish in the lake, those not sucked into the sinkhole were left gasping on the muddy bottom. "There were huge dead fish laying all around the banks. But the smell didn't last too long because thousands of buzzards and all kinds of other bird life I'd never seen before came in and cleaned it up in a few days. Otters were catching some of the live fish in distress," Curry says.

On shore, houses nearest the sinkhole fared the worst. The foundations of two houses cracked, windows shattered, and fissures opened up in lawns and swimming pools. The collapse of the soil had steepened the shoreline, causing the houses to slip. "It looked like a California mudslide," Curry says.

Since then, Scott Lake has steadily begun to refill. Mud and other debris seem to have formed a natural plug, and the lake, about one-third of its original size, attracts birds and other wildlife. The lake—and housing values—may recover, at least until Mother Nature strikes again.

— KATHLEEN WONG



**FIGURE 8.2.A Dave Curry Viewing Drop in Lake Level**
Property owner Dave Curry walks out on a boat dock that once served Scott Lake in south-central Florida. The lake level was lowered drastically when a sinkhole opened in the lake bottom. *(Dave Curry/Curry Controls Company)*

The natural tendency for deltas to subside can be amplified if sedimentation on the delta plain is slowed or stopped. Sedimentation has been sharply reduced on both the Mississippi and the Nile Deltas during the past 125 years.[23] On the Mississippi, sedimentation on the delta plain was slowed and stopped by levees built on both sides of the river. These levees have protected communities such as New Orleans from river flooding, but they have also kept riverbanks from eroding and new sediment from being added to the delta plain. In the case of the Nile, construction of the Aswan dams upstream and the diversion of two-thirds of the river water into canals have stopped sediment from reaching much of the delta plain.[24] Part of the subsidence in both the Mississippi and the Nile Deltas is also the result of compaction of organic soils. We will now explore the subsidence of the Mississippi Delta in more detail.

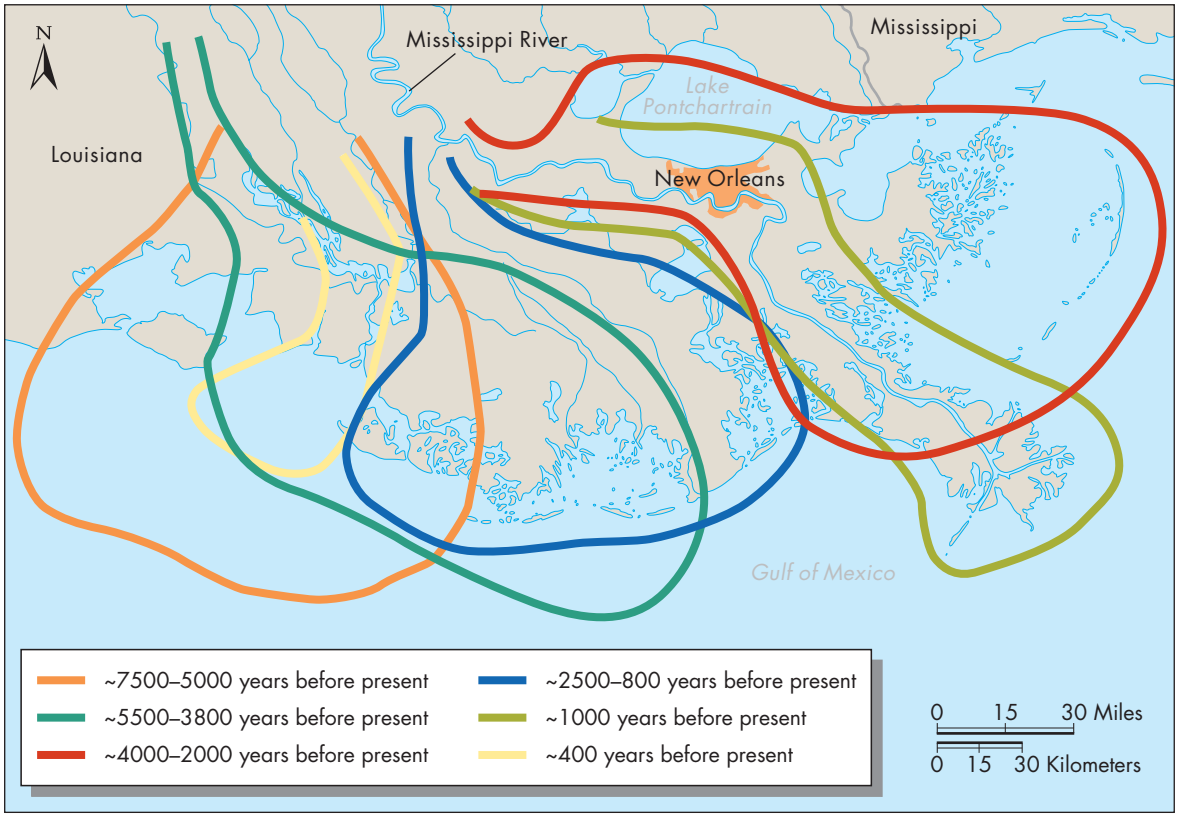
**FIGURE 8.14 Mississippi Delta Built in Stages**
During the past 7,500 years, the Mississippi and Atchafalaya Rivers have built the Mississippi Delta plain in a series of stages. In each stage, the rivers built a complex lobe of sand and mud into the Gulf of Mexico. Each lobe became inactive when the river breeched its levee during a flood and shifted its flow to a shorter channel to the sea. *(Based on Roberts, H. H., "Dynamic Changes of the Holocene Mississippi River Delta Plain: The Delta Cycle,"* Journal of Coastal Research *13(3): 605–27, 1997)*

8.3 CASE study

## Mississippi River Delta Subsidence

Home to nearly 40 percent of the coastal marsh and swamp wetlands in the United States, the Mississippi Delta is the major land feature in southern Louisiana. Geologically young, the present coastline of the delta was built by sedimentation from both the Mississippi and the Atchafalaya Rivers during the past 7,500 years.[25] As these rivers reach the sea, their channels subdivide into multiple distributaries. Actively flowing distributary channels build out a lobe-shaped pile of sand and mud into the ocean. This outbuilding continues until floodwaters break through a channel bank and the river finds a shortcut to the sea. If the break is permanent, then the river abandons its old distributaries and forms a new lobe of deltaic sediment. For the Mississippi Delta, this has occurred, on average, once each millennium (Figure 8.14).

As the river shifts its distributaries, two natural processes keep the land surface—the delta plain—above sea level: the deposition of sand and mud by distributary floodwaters, and the accumulation of organic soil



from dead marsh and swamp vegetation. The resulting sedimentary deposit is loosely packed together and saturated with water, much like a wet sponge. Over time, this deposit naturally compacts, and the land surface will subside unless new sediment is added to the delta plain.

Nearly three centuries ago, French settlers in New Orleans began to alter the natural balance between sedimentation and subsidence with the construction of levees along the Mississippi. By the early twentieth century, the U.S. Army Corps of Engineers had completed levees on both sides of the river and essentially stopped the Mississippi from flooding the delta plain. Without river flooding, the delta plain lost its regular supply of freshwater, nutrients, and sediment, and near-surface subsidence increased.

Starving the delta plain of new sediment and nutrients has not been the only cause of subsidence. Withdrawal of large amounts of groundwater, oil, and natural gas from below the delta surface appears to have significantly contributed to subsidence and a loss of wetlands.[26] Other scientists have hypothesized that tectonic subsidence, the sinking of Earth's crust below the delta, has contributed to lowering the delta surface. Investigations testing this hypothesis have yielded conflicting results, and further study will have to be done.[27,28]

A major consequence of the increased subsidence of the Mississippi Delta plain has been a significant loss of wetlands. Marshes and swamps in coastal Louisiana are disappearing at an average rate of a football-field-sized area every 30 minutes, which translates to the disappearance of 50 to 89 $km^2$ (~20 to 35 $mi.^2$) of land each year.[29] Wetland loss makes the coastline, including New Orleans, even more vulnerable to hurricane storm surges (see Chapter 10) and has resulted in major economic losses for fisheries.

In addition to subsidence, rising sea levels and the construction of numerous navigation and drainage canals have also contributed significantly to the loss of wetlands. The canals, built primarily for oil and gas operations, have exposed the delta plain to erosion and brought in saltwater that has killed wetland plants (Figure 8.15).[30]

An estimated 25 percent of the original coastal wetlands in Louisiana disappeared in the past century




**▲ FIGURE 8.15 Wetland Loss on the Mississippi Delta**

Excavation of numerous canals for oil and gas drilling, such as these near Leesville, Louisiana, have contributed significantly to wetland loss in the Mississippi Delta. Each canal drains the adjacent wetland and exposes organic soil to decomposition and erosion. Loss of this soil causes the land surface to subside. In many areas, the only land remaining is the spoil piles of sediment that were dredged to make the canals. *(Philip Gould/Corbis)*




**< FIGURE 8.16 Cutting a Levee to Restore a Wetland**
The floating dredge *California* in the lower center of the photograph is cutting a channel through the levee along the west bank of the Mississippi River south of New Orleans. The channel, part of the $22 million U.S. Army Corps of Engineers West Bay Sediment Diversion Project, was completed in 2003. This project was designed to divert 1400 $m^3$ (~50,000 $ft.^3$) of river water per second to build a small, deltaic wetland in an adjacent bay. *(U.S. Army Corps of Engineers, New Orleans District)*

through subsidence, vegetation loss, and erosion. What will happen to the remaining 14,000 $km^2$ (~5500 $mi.^2$) of wetlands? In the late 1990s scientists, engineers, government officials, and business leaders in Louisiana determined that a massive wetland and barrier island restoration effort was needed to combat the loss of coastal marshes and swamps (Figure 8.16).[29] Although this effort is projected to cost more than $14 billion over the next 40 to 50 years, it is substantially less than the $135 billion in property damage from Hurricane Katrina (see Chapter 10) and other large consumer and federal expenditures. Dealing with coastal land loss, such as that on the Mississippi Delta, will be one of the major environmental and disaster-planning challenges for the United States in the twenty-first century.

**Collapsible Soils** Some windblown dust deposits, referred to as *loess*, and stream deposits in arid regions are loosely bound with clay particles and water-soluble minerals. These deposits dry out rapidly after they form and may remain essentially dry for a long time. This dry condition can change if water ponds on the surface long enough for it to percolate downward through the entire deposit. The percolating water weakens the bonds of clay particles and dissolves minerals that hold the soil together. The entire deposit can then collapse and lower the land surface, sometimes by more than a meter (~3 ft.).[31] Soil and sediment that are prone to this behavior are referred to as **collapsible soil**.[32]

**Organic Soils** Some wetland soils forming in marshes, bogs, and swamps contain large amounts of organic matter. Called *organic soils*, these earth materials consist of partially decayed leaves, stems, roots, and, in colder regions, moss, which soak up water like a sponge. When water is drained from these soils, they dry out, compact, and are exposed to processes that cause them to disappear.

Bacterial decomposition is the primary process causing subsidence in drained organic soil. This process converts organic carbon compounds to carbon dioxide gas and water. Other destructive processes include water and wind erosion and the combustion of peat in prescribed burns and wildfires. The decomposition, erosion, and burning of organic soils cause the irreversible subsidence of drained wetlands. Part of the subsidence of the city of New Orleans can be attributed to compaction of organic soil.[33]

One of the most dramatic examples of subsidence in organic soils has occurred in the Florida Everglades. Land drainage, primarily for agriculture and urban development, has combined with droughts to cause more than half of the freshwater Everglades to subside from 0.3 to 3 m (~1 to 9 ft.) during the twentieth century.[34,35]

## EARTHQUAKES

Although we commonly think of earthquakes as associated with uplift of the ground surface, they may also cause subsidence. In the Pacific Northwest, the geologic record contains evidence of repeated episodes of subsidence along the coasts of British Columbia, Washington, and Oregon. See Chapter 4 and Figures 4.5 and 4.6 for a discussion of subsidence with earthquakes.

## UNDERGROUND DRAINAGE OF MAGMA

Subsidence can also occur from volcanic activity, related to either the central magma chamber of the volcano or shallow tunnels on the flank of the volcano. As magma moves upward into underground chambers below a volcano, the surface of the volcano may be forced upward. When it erupts, the volume of magma in the underground chamber is reduced and the land initially uplifted by the magma will subside. As mentioned in Chapter 5, cycles of uplift and subsidence are useful in predicting volcanic eruptions.

When basaltic lava flows down the flank of a volcano, the surface of the flow may cool as molten lava continues to move underground through a tunnel called a *lava tube* (see Figure 5.22). Lava eventually drains from the tube, leaving a void near the surface that is susceptible to collapse. Unfortunately, some unsuspecting home buyers on the Big Island of Hawaii have discovered too late that it is not advisable to build on a lava tube.

## EXPANSIVE SOILS

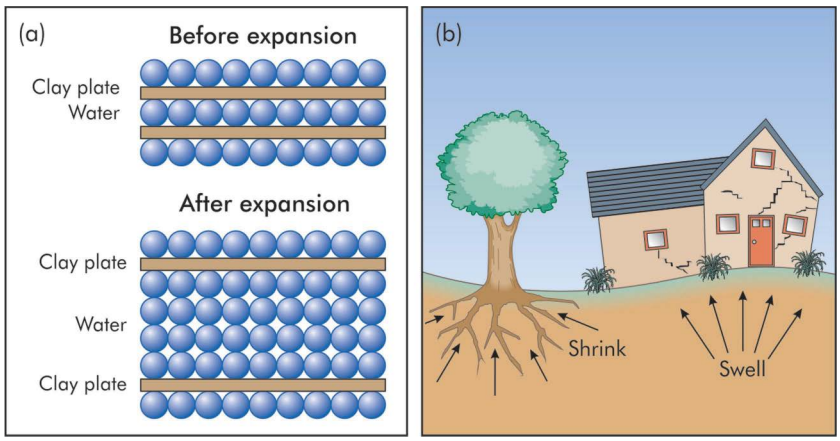
Changes in moisture conditions can produce substantial movement in some clay-rich soils. Referred to as **expansive soils**, these soils shrink significantly during dry periods and expand or swell during wet periods. Most of the swelling is caused by the chemical attraction of water molecules to the surface of very fine particles of clay (Figure 8.17).[36] Swelling can also be caused by the chemical attraction of water molecules to layers within the crystal structure of some clay minerals.

The *smectite* group of clay minerals, including the mineral montmorillonite, typically has the smallest clay crystals and thus, in bulk, has the greatest surface area to attract water molecules. Smectites are abundant in many clay and shale deposits derived from the chemical weathering of volcanic rock, and they are the primary mineral in bentonite, a rock that forms from the alteration of volcanic ash. Clay, shale, and clay-rich soil containing smectite have the greatest potential for shrinking and swelling.

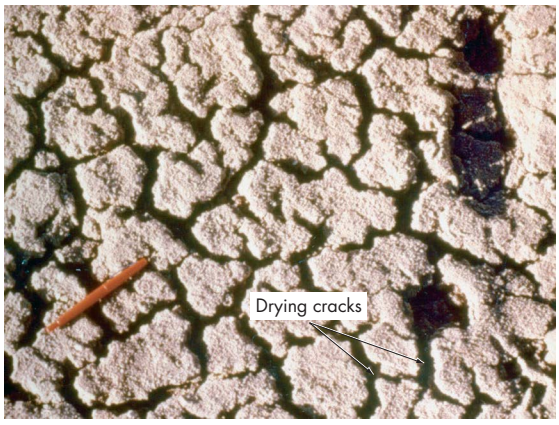
The presence of *shrink-swell clays* such as smectites can often be recognized from features on the land surface. These features include deep cracks produced as these soils dry out (Figure 8.18a), a popcorn-like weathering texture on bare patches of clay, an alternating pattern of small mounds and depressions in the land surface, a series of wavy bumps in asphalt pavement (Figure 8.18b), the tilting and cracking of blocks of concrete and bricks in sidewalks and foundations (Figure 8.18c), and the random tilting of utility poles and gravestones.

Shrinking and swelling of expansive soils cause significant structural damage to building foundations and the shifting and breaking of pavement and utility lines. This decrease or increase in the overall volume of the soil results from changes in its moisture content. Factors that affect the moisture content include climate, vegetation, topography, and drainage.[37] Regions that have a pronounced wet season followed by a dry season often have shrink-swell soils. These regions, such as the southwestern United States, are more likely to experience problems with expansive soils than do regions where precipitation is more evenly distributed throughout the year. Vegetation can also cause changes in the moisture content of a soil. Large trees draw and use a lot of local soil moisture, especially during a dry season. This withdrawal of water may produce soil shrinkage (Figure 8.17b).

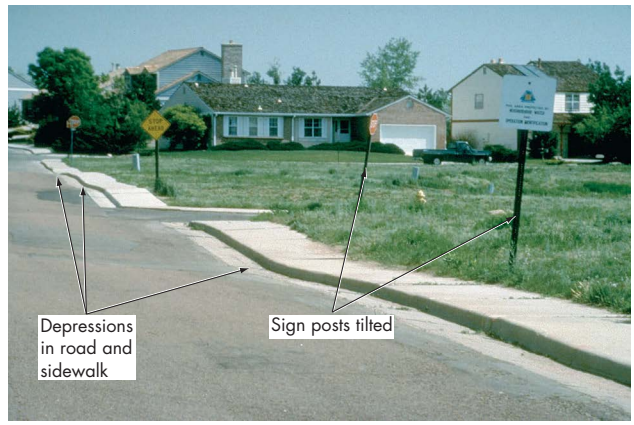
Expansive soils swell when they become wet and can produce an expansion pressure in excess of 500 kPa (~10,000 lb per ft.$^2$).[38] This intense pressure is strong enough to move the foundation and break open walls of multistory buildings, cause building support pilings to rise up out of the ground, and rupture major underground pipelines.




**< FIGURE 8.17 Expansive Soils**
(a) Smectite clay expands as water molecules are added onto and within the clay particles. (b) Effects of soil's shrinking and swelling at a home site. *(Based on Mathewson, C. C., and J. P. Castleberry, II,* Expansive Soils: Their Engineering Geology. *College Station, TX: Texas A&M University)*




(a)




(b)




(c)

**FIGURE 8.18 Damage from Expansive Soil**
(a) Drying of an expansive soil produces this popcorn-like surface and a network of polygonal desiccation cracks. Pen in lower left for scale. *(USGS)* (b) Uneven shrinking and swelling of expansive clays in layers of steeply dipping bedrock produced the rolling surface of this road and sidewalk in Colorado. *(David C. Noe/Colorado Geological Survey)* (c) Uneven shrinking and swelling of expansive soil cracked the concrete in this driveway. *(Edward A. Keller)*

## FROST-SUSCEPTIBLE SOILS

Freezing temperatures over a sufficient period of time can produce a great deal of expansion in silty soil. Silt is gritty sediment that is finer than sand but coarser than clay. Soils that have the potential to move and expand when they freeze are referred to as *frost-susceptible soils*. These soils expand because of the 9 percent volume increase that occurs when water changes to ice. This volume increase causes an upward movement of soil particles and the land surface in a process known as *frost heaving*. Upward movement is generally much greater than 9 percent because additional water is drawn to the zone of freezing, thereby increasing the amount of ice that is formed. The additional ice accumulates to form discrete pods or lenses of ice in the earth material (Figure 8.19).

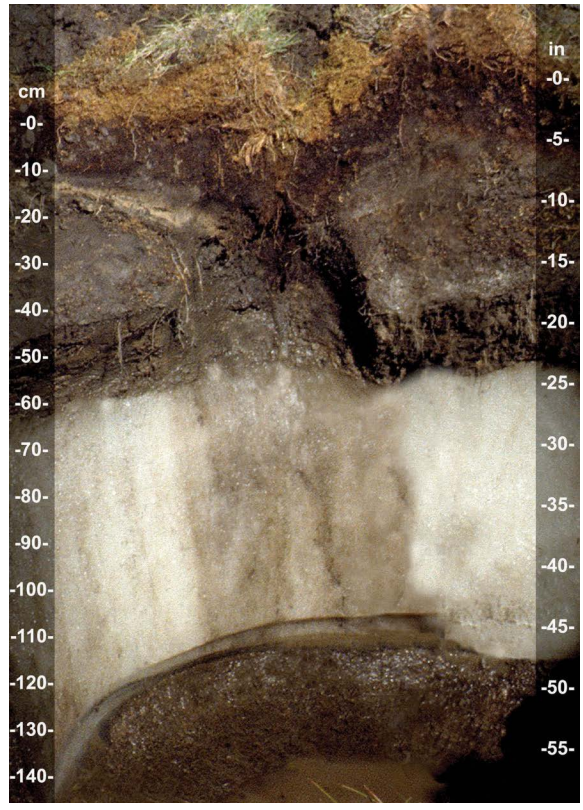



**FIGURE 8.19 Ice Formation in Soil Causes Frost Heaving**
In cold regions, pods or lenses of ice can form in the soil and cause the land surface to heave upward. This photo of Arctic tundra in northern Alaska shows ice lenses below mounds of heaved soil. *(John A. Kelley, USDA Natural Resources Conservation Service)*

Three conditions are necessary for frost heaving to occur in a soil: (1) Temperatures in the soil must remain below freezing long enough for ice to form, (2) water must be present to create a substantial amount of ice, and (3) there must be a significant proportion of silt-size particles to allow water to be drawn through and retained in the soil.

### 8.2 CHECK your understanding

1. Define subsidence.
2. How is karst topography formed? Give some examples of karst features.
3. Compare the different types of sinkholes.
4. How do limestone cave systems form?
5. Why is the Mississippi River Delta subsiding?
6. How are thermokarst, sediment and soil compaction, earthquakes, and drainage of magma linked to subsidence?
7. What is expansive soil?

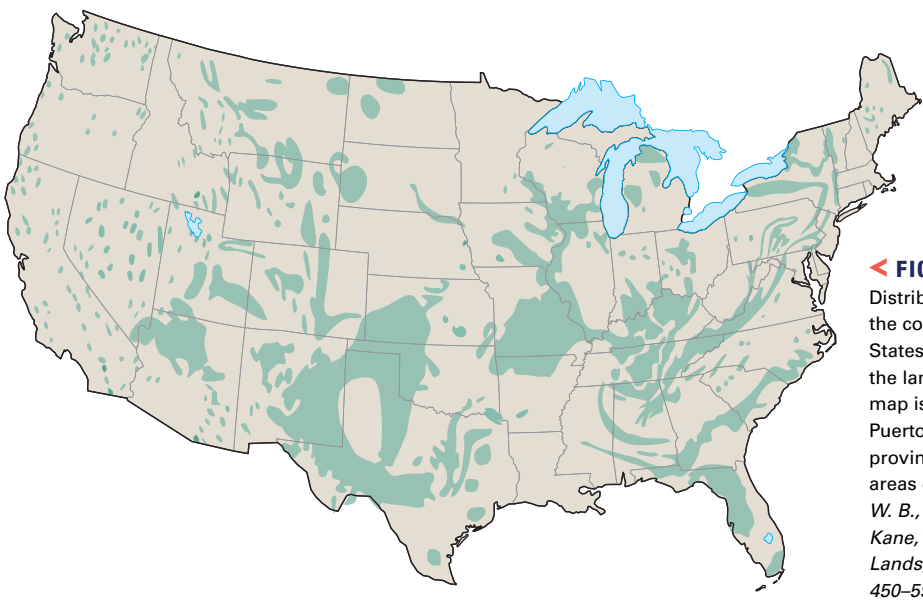
## 8.3 Geographic Regions at Risk for Subsidence and Soil Volume Change

Dissolution of soluble rocks, the presence of permafrost, and compaction of sediment and soil are the most common causes of subsidence. In particular, the dissolution of limestone produces karst topography, which is estimated to compose up to 10 percent of Earth's surface in all parts of the world. In the contiguous United States, approximately 25 percent of the land surface is underlain by limestone or evaporites that have some degree of karst development (Figure 8.20). Major belts of karst topography include (1) a region extending through Tennessee, Virginia, Maryland, and Pennsylvania; (2) south-central Indiana and west-central Kentucky; (3) the Salem-Springfield plateaus of Missouri and northernmost Arkansas; (4) the Edwards Plateau of central Texas; (5) most of central Florida; and (6) Puerto Rico. Subsidence and other karst-related phenomena are a major problem in these areas. The most extensive development of karst in evaporite rocks in the United States is in the Permian basin of eastern New Mexico and western Texas.[39]

Permafrost covers more than 20 percent of the world's land surface.[22] Most of Alaska and more than half of Canada and Russia are underlain by permafrost. Hazard maps show that many towns and smaller settlements are threatened by thawing permafrost, including Barrow, Alaska; Inuvik, Northwest Territories, Canada; and Yakutsk, Norilsk, and Vorkuta in Russia.[22]

Subsidence caused by the compaction of sediment is most pronounced in areas where the sediment was rapidly deposited or where it contains abundant organic matter. These areas include many of the world's marine deltas, such as those of the Mississippi River, the Sacramento–San Joaquin Rivers in California, and the Nile River in Egypt.

Organic-rich soils susceptible to subsidence are common in cold-region wetlands of New England, New



**< FIGURE 8.20 Karst Map**
Distribution of karst topography in the contiguous states of the United States. Approximately 40 percent of the land in the eastern half of this map is karst topography. Alaska, Puerto Rico, Hawaii, and Canadian provinces and territories also have areas of karst. *(Based on White, W. B., Culver, D. C., Herman, J. S., Kane, T. C., and Mylroie, J. E., "Karst Lands,"* American Scientist *83: 450–59, 1995)*

York State, the Upper Midwest, Washington State, Alaska, and parts of Canada, where these wetlands are variously called "bogs," "fens," "moors," and "muskeg." Coastal wetlands underlain by peat or muck deposits are also susceptible to subsidence in the Florida Everglades, the Sacramento–San Joaquin Delta of California, and coastal Louisiana and North Carolina.

In North America, expansive soils are a problem primarily in the western United States and Canada. Soils with the highest swelling potential are found in the blackland prairies from Texas to Alabama and in parts of the High Plains from eastern Colorado north to Saskatchewan and Alberta, Canada, although swelling clays are found in soils in all 50 U.S. states as well as Puerto Rico, the Virgin Islands, and in most Canadian provinces and territories.[40]

Frost heaving occurs in regions underlain by permafrost, as well as in colder parts of the United States and Canada that do not have permanently frozen ground. Frost-susceptible soils occur throughout Canada, Alaska, the northern contiguous United States, and at higher altitudes in the Appalachians, Rocky Mountains, Sierra Nevada, and Cascades.

Large-scale, seismic-related subsidence is a risk for areas of Alaska, Hawaii, and the Pacific Northwest in both Canada and the United States. Deflation of a magma chamber can cause subsidence in any volcanic area, and subsidence over lava tubes occurs in the Hawaiian Islands and in some lava flows of western North America.

### 8.3 CHECK your understanding

1. List some areas in the United States that are particularly vulnerable to subsidence, and explain why.

## 8.4 Effects of Subsidence and Soil Volume Change

Both karst formation and soil expansion and contraction cause significant economic damage each year. Karst regions are home to a host of problems such as sinkhole formation, groundwater pollution, and variable water supply. Heaving in expansive and frost-susceptible soils often damages highways, buildings, pipelines, and other structures. Additional damage from subsidence occurs in marine deltas, drained wetlands, areas of collapsible soils, and in many areas underlain by permafrost.

### SINKHOLE DAMAGE

Sinkholes have caused considerable damage to highways, homes, sewage facilities, and other structures. Both natural and artificial fluctuations in the water table are probably the trigger mechanism for the formation of collapse sinkholes. High groundwater table conditions enlarge caverns closer to the surface of Earth by dissolving the roof and side of the caves. As long as a cavern remains filled with water, the buoyancy of the water helps support the weight of the overlying earth material, but lowering of the groundwater table eliminates some of the buoyant support, and the cave roof may collapse. This situation was dramatically illustrated in Winter Park, Florida, on May 8, 1981, when a large collapse sinkhole began developing. The sinkhole grew rapidly and within 24 hours had swallowed a house, part of a community swimming pool, half of a four-lane street, parts of three businesses, and parking lots containing several Porsches and a pick-up camper (Figure 8.21).[41] Damage caused by this sinkhole exceeded $2 million.

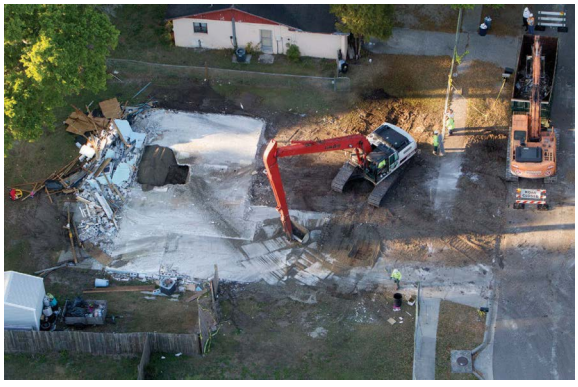
Sinkholes form nearly every year in central Florida when the groundwater level is lowest. Although exact positions cannot be predicted, more sinkholes form during droughts. The Winter Park sinkhole and several smaller sinkholes developed during the 1981 drought when groundwater levels were at a record low.

More recently, a sinkhole 6 m (~20 ft.) deep by 5 m (~16 ft.) wide quickly collapsed above a home in Seffner, Florida, in February 2013 (Figure 8.22). A 36-year-old man in his bedroom was swallowed as the room disappeared underground, and his body was never recovered. His brother heard him scream and jumped in the hole, but the sinkhole continued to collapse and the brother had to be rescued by emergency crews. The rest of the home had to be demolished and the hole filled with gravel. By the time the sinkhole was filled, it had grown to 20 m (~66 ft.) deep. Such deaths are rare but have occurred several times in the past. A spectacular sinkhole, about 15 m (~49 ft) in diameter, opened in August 12, 2013, near Walt Disney World (Orlando, Florida, area). A three-story building of condominiums partially collapsed into the developing sinkhole. Quick evacuation of tourists was successful, and there were no deaths.

In urban and some rural areas, the evidence of a subsidence hazard is sometimes masked by human activities. For example, a sinkhole in the Lehigh Valley in eastern Pennsylvania was first identified in the 1940s and was then completely filled with dead stumps, blocks of asphalt, and other trash and covered with a cornfield. Although no longer recognizable as a sinkhole, the filled depression collected urban runoff from nearby pavement and buildings. The runoff loosened




**< FIGURE 8.21 Sinkhole That Swallowed Part of a Town**
This sinkhole in Winter Park, Florida, grew rapidly for three days in 1981, swallowing part of a community swimming pool as well as several businesses, houses, and vehicles. The sides of the sinkhole have since been stabilized and landscaped, and it is now a park with a small lake. *(AP Images)*

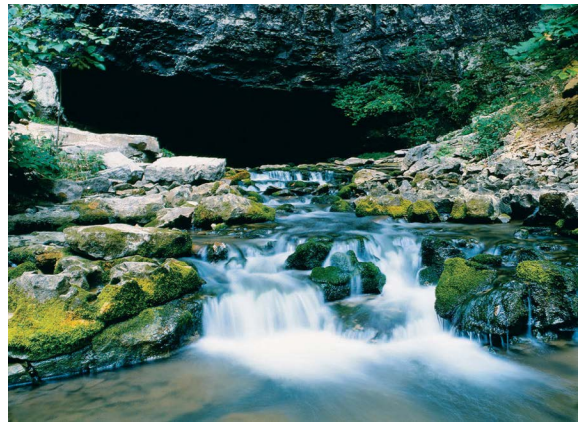


**^ FIGURE 8.22 Collapsing Sinkhole**
This small sinkhole collapsed under a home in Seffner, Florida, in February 2013. A man in his bedroom was swallowed and killed (his body was never recovered). The sinkhole collapsed several more times as emergency crews responded. Incidences of people killed by collapsing sinkholes, while rare, have occurred several other times. *(AP Photo/The Tampa Bay Times, Dirk Shadd)*

the plug of soil and trash and continued to dissolve the underlying limestone. An increased demand for groundwater in the area also contributed to lowering of the groundwater table. These factors combined to cause a catastrophic collapse of the land surface in 1986. Within only a few minutes, the collapse produced a pit that was at least 30 m (~100 ft.) in diameter and 14 m (~46 ft.) deep. Although the damage was confined to a street, parking lots, sidewalks, and utility lines, subsequent stabilization and repairs cost nearly $500,000.

## CHANGES IN GROUNDWATER CONDITIONS

Karst development creates a geologic environment in which groundwater is easily accessed and intensively used by humans and wildlife and is also easily polluted. Sinkholes, caves, and related karst features can form direct connections between surface water and groundwater (Figure 8.23). Such connections make the groundwater vulnerable to pollution and contribute to fluctuations in the groundwater table during droughts. These vulnerabilities are a major concern for both public and private sources of drinking water.



**^ FIGURE 8.23 Water from a Subterranean Stream**
In karst topography, groundwater and surface water may be directly connected. This waterfall develops from a subterranean groundwater flowing from a cave. *(Kenneth Murray/Science Source)*

One common source of pollution comes from sinkholes that have been used for waste disposal, especially where the bottom of the depression is near the groundwater table. Groundwater can also become contaminated where polluted water from surface streams flows into caves and fractures. This water can reach the groundwater table without the natural filtration provided by soil or sand.

Groundwater-table fluctuations in karst areas affect humans, plants, and wildlife. For example, groundwater from karst limestone is heavily used along the edge of the Edwards Plateau in central Texas. In this area, frequent drought and heavy groundwater use can rapidly lower the groundwater table and cause springs to reduce or stop their flow. Diminished groundwater flow impacts communities that rely on it as a source of water, such as the city of San Antonio, as well as threatens a number of unique plants and animals that are found only in the springs.

## DAMAGE CAUSED BY MELTING PERMAFROST

Early settlers in the Arctic built their homes directly on permafrost, only to find that heat radiated from the buildings thawed the soil. By the middle of the twentieth century, most Arctic structures were built on posts or pillars sunk into the permafrost. This technique elevates the floor of a building above the land surface and keeps its heat from melting the underlying soil. However, this use of pilings assumed that the permafrost would remain frozen. For the past several decades, that assumption has not always been the case.

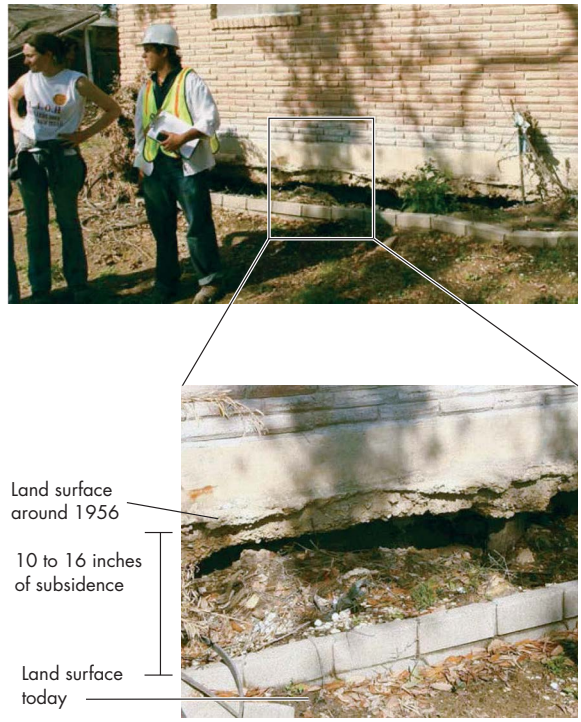
Thawing of permafrost has caused roads to cave in, airport runways to fracture, railroad tracks to buckle, and buildings to crack, tilt, or collapse (Figure 8.24).[22] In two Siberian cities alone, an estimated 300 apartment buildings have been damaged. The state of Alaska now spends around 4 percent of its annual budget repairing permafrost damage.[42]



**▲ FIGURE 8.24 Melting Permafrost Destroys Building**
The foundation of this apartment building in Cherskii in eastern Siberia was undercut by thawing permafrost. Structural damage from melting permafrost is becoming common in Russia, Alaska, and Canada. *(Professor V. E. Romanovsky/University of Alaska Fairbanks Press)*

## COASTAL FLOODING AND LOSS OF WETLANDS

Flooding of coastal areas and destruction of wetlands are two major effects of subsidence in marine deltas and bays. Subsidence of the Mississippi Delta during the past century has contributed to wetland loss and the sinking of New Orleans. The city of New Orleans and adjacent suburbs are subsiding relative to sea level at an average rate of 8 mm (~0.3 in.) per year (Figure 8.25). As a result, most of New Orleans is below sea level, and parts of east New Orleans have subsided to 3 to 5 m (~10 to 16 ft.) below sea level.[43] Rings of levees and flood walls surrounding New Orleans and many of its suburbs were established to keep urban areas from flooding by the Gulf of Mexico, Lake Pontchartrain, and the Mississippi River.




**▲ FIGURE 8.25 Subsidence in New Orleans**
Land surrounding many New Orleans buildings has subsided since they were built. The land surface around this house in the Lakeview area appears to have subsided 25 to 50 cm (~10 to 20 in.) since 1956. *(Professor David J. Rogers)*

Outside the levees and flood walls are wetlands that help protect the city and its suburbs from ocean waves and storm surges. Without intervention, this marsh and swampland will subside or erode by 2090, and New Orleans will be directly on the sea.[33]

## DAMAGE CAUSED BY SOIL VOLUME CHANGE

Expansive and frost-susceptible soils cause significant environmental problems. As one of our most costly natural hazards, soil volume change is responsible for many billions of dollars in damages annually to highways, buildings, and other structures. Annual costs from soil expansion and contraction exceed $15 billion in the United States and are substantial in Canada and Mexico as well.[44] Frost action on roads and streets in the United States alone costs several billion dollars each year for rebuilding thousands of miles of pavement.[45] In many years, damage caused by soil volume change exceeds the cost for all other natural hazards combined.

Every year, more than 250,000 new houses are constructed on expansive soils. Of these, about 60 percent will experience some minor damage, such as cracks in the foundation, walls, driveway, or walkway, and 10 percent will be seriously damaged, some beyond repair (see Figures 8.17, 8.18, and 8.26a).[46] Underground water lines in expansive soils may rupture when there is a significant change in soil moisture. This rupture can result in a loss of water pressure, which makes the line vulnerable to contamination and requires customers to boil their water before using it.

In frost-susceptible soils, frost heaving has some of the same effects as swelling in expansive soils (Figure 8.26b). Cracking occurs in foundations and asphalt and concrete pavement, and pipelines break. Frost heaving also moves larger particles in the soil upward at a faster rate than smaller particles. This upward movement, as much as 5 cm (~2 in.) per year, can simply be an annoyance, such as the continual appearance of large stones in a garden or farmer's field each spring, or it can be destructive, such as the lifting of fence posts and utility poles out of the ground. Even coffins have been known to rise to the surface by frost heaving![47]

### 8.4 CHECK your understanding

1. List the five main effects of subsidence and soil volume changes.
2. What are some of the damages resulting from soil volume changes?

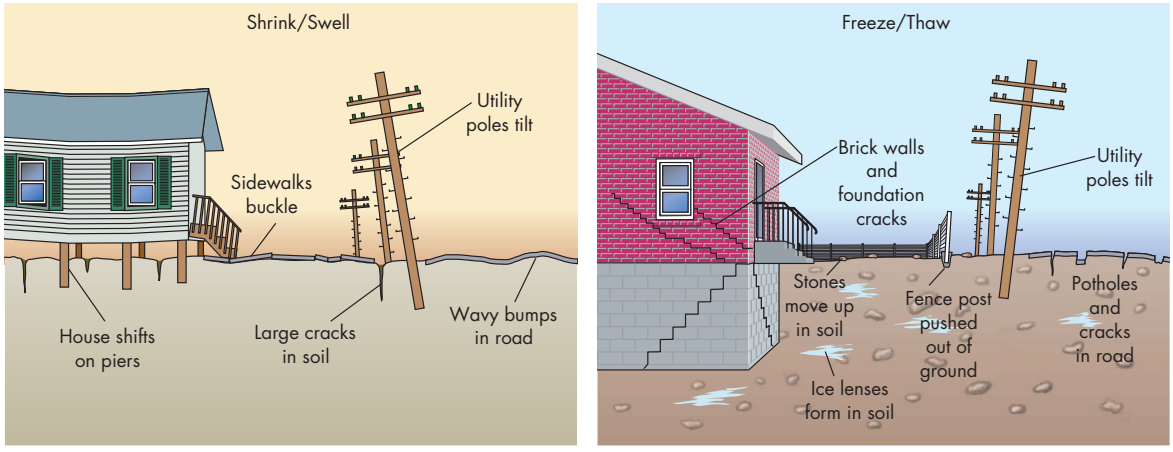



**FIGURE 8.26 Soil Movement Effects**

Shrinking and swelling of expansive soils (a) and freezing and thawing of frost-susceptible soils (b) have similar effects. Both types of soil movement crack and shift foundations and pavement and tilt utility poles, road signs, and fence posts. Shrinking of the soil can produce deep cracks in the ground, and swelling of the soil can create small mounds on the land surface. Freeze and thaw cycles move buried objects, such as stones, upward in the soil to the surface. These cycles also contribute to the formation of potholes in asphalt pavement.

## 8.5 Linkages between Subsidence, Soil Volume Change, and Other Natural Hazards

As mentioned previously, subsidence can be a side effect of earthquakes, volcanoes, severe weather, and climate change. However, subsidence may also cause other natural hazards to occur. As described earlier for the Mississippi Delta, the link between subsidence and flooding is a common one. Soil expansion and contraction are also linked to increased rates of mass wasting on slopes.

In areas undergoing rapid subsidence, especially those that are also subsiding because of the overpumping of groundwater, flooding can be a major problem. As the land is lowered relative to surrounding bodies of water, the incidence of flooding increases (see the chapter opener and Applying the Fundamental Concepts). In many growing cities, there is a high demand for clean drinking water. Unfortunately, this demand leads to the mining of groundwater, often depleting the resource faster than it can be replenished. Because of groundwater mining and the resulting subsidence, coastal and river floods have become more common and severe in low-lying coastal cities such as Bangkok, Thailand, which experienced disastrous floods in 2011, and urban flooding has become more common in Mexico City.[48]

On sloping land surfaces, frost heaving and the shrinking and swelling of clay interact with mass wasting (see Chapter 7). This interaction can increase the rate of gravity-driven creep and produce an uneven land surface.

Subsidence also has direct linkages to climate change. This linkage is apparent in hot deserts, cold Arctic regions, and coastal areas. In hot arid areas, drought conditions commonly lower the groundwater table. The withdrawal of groundwater can further compact and shrink unconsolidated earth materials. In the deserts of the southwestern United States, the drying of earth materials is contributing to regional subsidence and to the formation of large, polygonal *desiccation cracks* (Figure 8.27). These cracks are similar in shape to the cracks that you see in mud after it has dried out. Except for their polygonal form, the large desiccation cracks are the same size and depth as large linear cracks, called *earth fissures*, which are produced by the overpumping of groundwater.[49,50] In cold Arctic areas, global warming is the primary cause of the melting of permafrost. In turn, permafrost melting releases the greenhouse gases carbon dioxide and methane into the atmosphere, which could accelerate climate change (see Chapter 12). Global warming is also the primary cause for the increased rate of sea-level rise. In coastal communities, such as Venice, New Orleans, Galveston Bay near Houston, and the Nile Delta, subsidence increases the local rate of sea-level rise and the resulting loss of land.



**FIGURE 8.27 Large Desiccation Crack**
This crack in the road is part of a polygonal network of large desiccation (drying) cracks in Graham County, southeastern Arizona. Unlike similar earth fissures that result from overpumping of groundwater, these cracks appear to be the result of the natural lowering of the groundwater table in a drought. *(Arizona Geological Survey)*

### 8.5 CHECK your understanding

1. In what important ways do subsidence and soil volume changes link with other natural hazards?

## 8.6 Natural Service Functions of Subsidence and Soil Volume Change

Although subsidence and soil volume change cause many environmental and economic problems, there are also benefits from these processes. Expansion and

contraction of the soil form natural coherent blocks of soil material called peds that are similar to clods of soil produced by plowing or digging. The creation of peds contributes to soil productivity, especially in clay-rich soils, by facilitating root growth and soil drainage.

The same karst processes that cause subsidence also contribute water as well as aesthetic, scientific, and ecological resources. Karst terrains are some of the world's most productive sources of drinking water. Beautiful karst formations such as cavern systems and tower karst are important aesthetic and scientific resources (see Figures 8.12 and 8.13). Finally, the caves of karst areas are home to rare, specially adapted creatures, some of which are found nowhere else. For example, caverns and other karst features in the Edwards Limestone in Texas are home to more than 40 unique species, eight of which are legally designated as endangered.

### WATER SUPPLY

Karst regions contain the world's most abundant groundwater supply, thus providing a critical world resource. About 25 percent of the world's population either lives on or gets its drinking water from karst formations. In the United States, an estimated 40 percent of the groundwater used for drinking comes from karst terrains.[51] For example, the Edwards Formation, discussed previously, provides drinking water for more than 2 million people in Texas.

### AESTHETIC AND SCIENTIFIC RESOURCES

Rolling hills, extensive cave systems, and beautiful formations of tower karst are among the aesthetic resources found in karst areas. Unique landscapes, such as the tower karst regions of China, are areas of unparalleled beauty that offer stunning vistas. Caves, too, have proved to be a popular destination for both spelunkers and tourists. Mammoth Cave National Park, Kentucky, contains the world's longest cave system and attracts droves of visitors each year. Aesthetics aside, karst regions also provide scientists with a natural laboratory in which to study the record of climate change contained in cave formations. Caves also provide an ideal environment for preserving animal remains, making them important resources for paleontologists and archaeologists.

### UNIQUE ECOSYSTEMS

Caves are home to rare creatures specially adapted to live in the karst environment. Karst-dependent species known as *troglobites* have evolved to live in the total darkness of caves. Such species include eyeless fish, shrimp, salamanders, flatworms, and beetles. Other animals, such as bats, rely on caves to provide shelter. Karst areas generally support a diverse cross-section of species; preserving these areas and, hence, these organisms for the future should be a societal objective.

## 8.6 CHECK your understanding

1. Describe the main natural service functions of subsidence and soil volume change.

# 8.7 Human Interaction with Subsidence and Soil Volume Change

As discussed in the previous sections, subsidence can both cause problems and provide benefits. Commonly, when human beings live in areas underlain by karst formations, compacting sediment and soil, permafrost, and expansive or frost-susceptible soil, previously existing problems are exacerbated and new problems arise. Human beings contribute to problems associated with subsidence and soil volume change by withdrawing subsurface fluids, excavating underground mines, thawing frozen ground, restricting deltaic sedimentation, altering surface drainage, and using poor landscaping practices.

### FLUID WITHDRAWAL

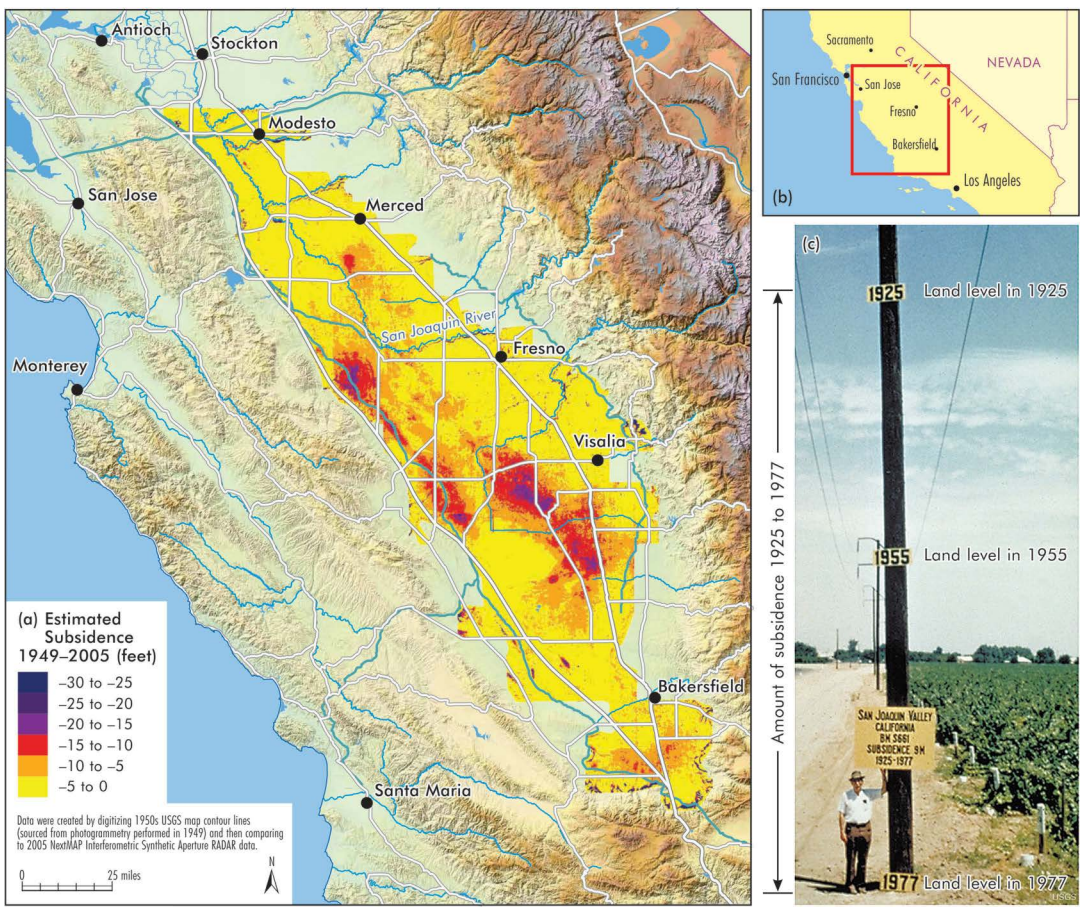
The withdrawal of subsurface fluids, such as oil with associated natural gas and water, groundwater, and mixtures of steam and water for geothermal power, have all caused subsidence.[52] In each case, the high fluid pressure within the sediment or rock helped support the earth material above. A large rock at the bottom of a swimming pool seems lighter for the same reason: Buoyancy produced by the liquid tends to lift the rock. Support or buoyancy by means of fluid pressure can be especially important in shallow or rapidly deposited earth material. In these instances, pumping out the fluid reduces support and causes surface subsidence.

**Groundwater mining**—extracting groundwater through wells and springs in volumes greater than that being replenished through the percolation of rain and surface water—is a leading cause of regional subsidence. A classic example can be found in the central

valley of California where thousands of square kilometers have subsided from overpumping groundwater for irrigation and other uses (Figure 8.28a). One of the areas of greatest subsidence has been across the valley from Fresno, where most of the land surface has subsided more than 0.3 m (~1 ft.) and locally up to 9 m (~30 ft.) (Figure 8.28). As the groundwater was mined, water pressure was reduced, sedimentary grains compacted, and the surface subsided (Figure 8.29).[53,54] Similar examples of subsidence caused by overpumping have been documented near Phoenix, Arizona; Las Vegas, Nevada; the Houston–Galveston area in Texas; San Jose, California; and Mexico City, Mexico. Such subsidence has reactivated geologic faults and formed extremely long earth fissures in unconsolidated sediment (Figure 8.30).[54]

## UNDERGROUND MINING

Serious subsidence events have been associated with the underground mining of coal and salt. Most subsidence in coal mining is caused by the failure of pillars of coal that have been left behind to support the mine roof. With time, these pillars weather, weaken, and collapse, causing the roof to cave in and the land surface above the mine to subside (see Case Study 8.4: Professional Profile). In the United States, more than 8000 km$^2$ (~3100 mi.$^2$) of land, an area twice the size of Rhode Island, has subsided because of underground coal mining. This subsidence continues today, long after mining has ended. In 1995, a coal mine that was last operated in the 1930s collapsed beneath a 600 m (~1970 ft.) length of I-70 in Ohio; repairs of the highway took three months.[55] Although coal mine




**▲ FIGURE 8.28 Land Subsidence from Groundwater Extraction**

(a) Principal areas of land subsidence in California resulting from groundwater withdrawal. *(Adapted from California Department of Water Resources)* (b) Location map showing the approximate location shown in (a). (c) Photograph illustrating the amount of subsidence in the San Joaquin Valley, California. The marks on the telephone pole are the positions of the ground surface in recent decades. The photo shows nearly 8 m (~26 ft.) of subsidence. *(Richard Ireland/USGS)*

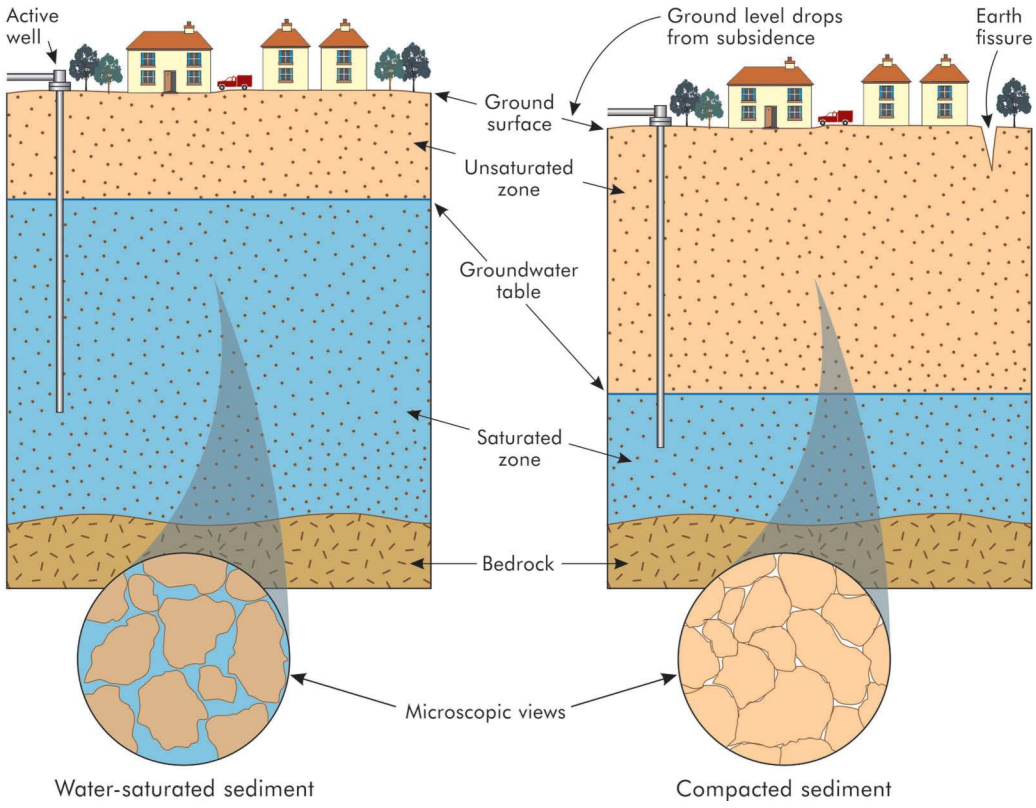



**FIGURE 8.29 Subsidence from Pumping of Fluids**

Idealized diagram showing how surface subsidence results from pumping groundwater. The unsaturated zone is the area above the groundwater table where the holes (pores) between grains contain both air and water. In the saturated zone beneath the groundwater table, the pores are completely filled with water. When groundwater is pumped out, the pores collapse and the surrounding earth material compacts. This compaction can cause the land surface to subside.




**FIGURE 8.30 Earth Fissures Damage Road**

A caution sign was erected after an earth fissure damaged this road in rural Pima County, Arizona, in 1981. Earth fissures have developed in the desert of the southwestern United States where overpumping has lowered the groundwater table. *(USGS)*

subsidence most often affects farmland and rangeland, it has also damaged buildings and other structures in urban areas such as Scranton, Wilkes-Barre, and Pittsburgh, Pennsylvania; Youngstown, Ohio; and Farmington, West Virginia.[55,56]

In the case of salt, subsidence has taken place over both solution and open-shaft mines. Solution mines, the source for most of our table salt, use wells to inject freshwater into salt deposits. The dissolved salt is then pumped out of the well, leaving a cavity behind. Collapse of this cavity and subsequent surface subsidence have taken place in solution mines in Kansas, Michigan, New York, and Texas.[39]

Open-shaft mining is used to extract rock salt from Earth and is taking place underground below Detroit, Michigan, and Cleveland, Ohio. In the past three decades, the catastrophic flooding of two underground salt mines has caused surface damage and subsidence. One, the Retsof Mine near Geneseo, New York, was the largest salt mine in the world. Collapse of its roof in

1994 allowed groundwater to flood the mine. Flooding produced two large sinkholes and subsidence damage to roads, utilities, and buildings.[57]

The second flooding event occurred on the Jefferson Island salt dome in southern Louisiana. In 1980, an oil rig drilling for natural gas accidentally penetrated an underground salt mine (Figure 8.31). The rig was mounted on a floating barge in a small lake above the salt dome. After drilling into the mine shaft, the 45 m tall (150 ft.) rig disappeared into the 3 m (10 ft.) deep lake, followed by eight large barges that were on the water that day. Fortunately, 50 miners and seven people on the drilling rig escaped injury. The mine was a total loss, and buildings and gardens were damaged. Within three hours the entire lake had drained, and a 90 m (~300 ft.) deep, 0.8 km (~0.5 mi.) wide subsidence crater formed above the flooded mine. The structural integrity of underground salt mines is of particular concern because the U.S. Strategic Petroleum Reserve is stored in four Gulf Coast salt mines. A fifth storage site below Weeks Island, Louisiana, was emptied of oil in 1999 because of groundwater seepage through a sinkhole.

## MELTING PERMAFROST

Humans have contributed to the thawing of permafrost, with resulting changes in soil volume, through global warming and poor building practices. Shoddy construction practices, inadequate removal of heat from beneath buildings, and burial of warm utility lines have locally melted permafrost, broken pipelines, and damaged buildings.[22,58]

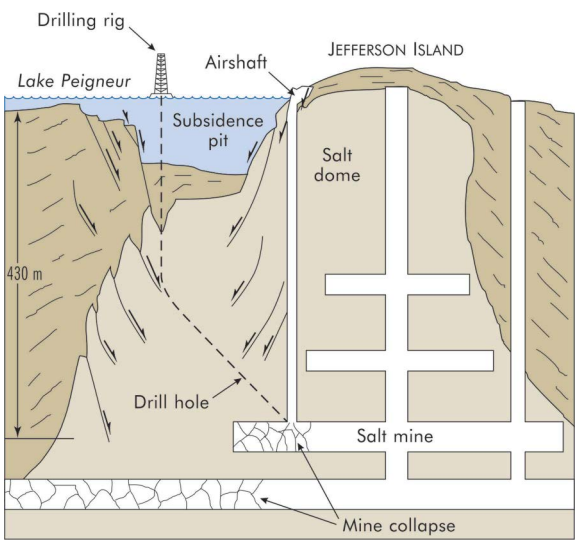



**FIGURE 8.31 Subsidence from Salt Dissolution**
Idealized diagram showing the Jefferson Island salt dome collapse that caused a large subsidence pit to form in the bottom of the lake. An estimated 15 million $m^3$ (~530 million $ft.^3$) of water flooded the salt mine after a natural gas well penetrated the mine shaft.

## RESTRICTING DELTAIC SEDIMENTATION

Marine deltas require the continual addition of sediment to their surfaces to remain at or above sea level. This sediment comes from the distributary channels that carry river water, sand, and mud to an ocean. In many deltas, humans have stopped or reduced this sedimentation by constructing dams upstream, building levees on both sides of distributary channels, and diverting sediment-laden river water into canals. All these practices may contribute to subsidence of the delta plain.

## ALTERING SURFACE DRAINAGE

People have altered surface drainage for agriculture and settlement for centuries. These alterations are designed to remove or add water to the soil. In organic soils, draining water causes or increases soil compaction and subsidence. In the United States, draining organic soils has caused or increased subsidence in the Mississippi Delta, the Florida Everglades, and the Sacramento–San Joaquin River Delta. Subsidence in the Sacramento–San Joaquin River Delta threatens the integrity of levees that protect cropland from flooding and keep saltwater from intruding into California's massive water supply system.[59] Adding water to the soil, such as through irrigation, can cause land subsidence on collapsible soils and, as described next, increase the swelling of expansive soils.

## POOR LANDSCAPING PRACTICES

The shrinking and swelling of expansive soils are often amplified by poor landscaping practices. Planting trees and large shrubs close to foundations may cause damage from soil shrinkage during dry periods as plant roots pull moisture from the soil.[37] At the other extreme, planting a garden or grass that needs frequent watering close to foundations can cause damage from soil swelling. Rather than keeping the soil at a constant moisture level, irrigation systems commonly leave excess water in the soil. Excess water is considered the most significant cause of damage from swelling soil.[26]

CASE study

# 8.4 Professional Profile

# Helen Delano, Environmental Geologist

For those looking to build a house in Pennsylvania, any number of natural hazards need to be considered. "We have something for everyone," says Helen Delano, from the Pennsylvania Bureau of Topographic and Geologic Survey. "As a geologist working for the state of Pennsylvania, one of my tasks is looking at where hazards may occur" (Figure 8.4.A).

Some of those dangers include deadly gases, such as methane and radon, which can migrate up from buried organic or radioactive material, respectively, but one of the more common problems is the potential for sinkholes and subsidence, particularly given the many abandoned coal mines in the area. According to Delano, the southwestern region of the state has been mined for coal since the mid-1700s, and the shallower mines are only 15 to 30 m (~50 to 100 ft.) below the surface. Although the technology does exist to empirically test an area, Delano said a lot of information can be gained simply by consulting coal mining maps.

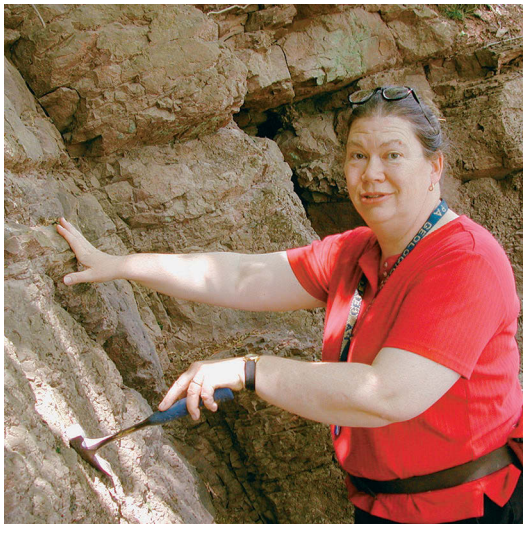
But when the maps do not provide a complete picture, relatively simple and inexpensive technology can help geologists determine whether there are any major cavities in the ground. Delano said geologists sometimes use what's called a "television borehole camera," literally drilling a hole and lowering a small camera into the ground to examine the underground contents. This technology, however, is available for only relatively shallow depths. Delano said geophysical methods for deeper depths are far more expensive.

In addition to old coal mines, shallow caves, which have the potential to form sinkholes, can be detected with ground-penetrating radar—useful information for anyone considering a construction project in several parts of the state. "In eastern Pennsylvania, we get sinkholes from limestone subsidence," says Delano.

Delano began her career examining problems from natural hazards in the Pittsburgh area. "When I first started working, I would go out and look at people's backyard problems and help them understand what was going on and collect data for our use, trying to keep track of the scope of the problems for the state," she recalls.

Now she also deals with municipalities, advising them when natural hazards, including subsidence, pose problems for building projects. "I have a folder on my desk right now for a rural community that has a proposal for a housing project over eighteenth- and nineteenth-century iron mines," Delano said.

When a major construction project is slated to be built over a region where subsidence is a risk, there are several options, according to Delano. "Usually, the cheapest thing to do is build your house somewhere else," she said. But when the location is just too good to pass up, there are engineering



**< FIGURE 8.4.A Fieldwork Required for Natural Hazard Assessments**
Environmental geologist Helen Delano is the Pennsylvania Geological Survey contact for local governments in southeastern Pennsylvania. Here she examines an exposure of the Gettysburg Formation in her area of responsibility. *(James Shaulis/Pennsylvania Geological Survey)*

solutions, such as digging a deep foundation in firm bedrock.

The key, says Delano, is in knowing the risks ahead of time: "It's much, much cheaper to factor in those costs at the beginning." But for the most part, a close study of geological hazards, such as subsidence, is not yet routine in Pennsylvania when it comes to small construction projects. "Most residential construction doesn't take into account geological hazards," Delano said, adding that, as more and more valuable land is occupied, it will become increasingly necessary to consider such dangers.

— CHRIS WILSON

## 8.7 CHECK your understanding

1. Explain how land subsides from extracting fluids such as oil and groundwater.
2. Why can underground mining of coal and salt cause subsidence?
3. How may melting permafrost affect soils?
4. How can altering surface drainage cause subsidence?
5. What is the role of vegetation in causing shrinking or swelling of soil?

# 8.8 Minimizing Subsidence and Soil Volume Change

Minimizing the hazards related to subsidence and the expansion and contraction of soil requires an understanding of the landscape from a geologic perspective. Even with this understanding, it is difficult to prevent natural subsidence and changes in soil volume. However, there are steps that can be taken to minimize the damage associated with this hazard.[17]

**Reducing Fluid Withdrawal** We will always be plagued with subsidence problems in areas where bedrock is aggressively being dissolved or where groundwater levels are continuing to fall because of drought. Natural sinkholes will continue to open up. We can, however, prevent some human-caused subsidence associated with the mining of groundwater or pumping of oil and gas. Where groundwater, oil, or gas removal is causing the land surface to subside, it is possible to prevent or minimize further subsidence.

For example, from the early 1900s to the mid-1970s, groundwater mining in the Houston–Galveston area of Texas was the primary cause for up to 3 m (~10 ft.) of subsidence over an 8200 $km^2$ (~3200 $mi.^2$) area.[60] This prompted the 1975 Texas legislature to create a regulatory district to issue well permits. Since creation of this district, subsidence has essentially stopped in areas where groundwater pumping has decreased. This has not been the case in parts of Florida, Arizona, and Nevada, where increasing use of groundwater continues to cause sinkholes or earth fissures.

Installation of *injection wells* is often suggested as a way to minimize or stop subsidence from fluid withdrawal. This technique was used with some success in the 1950s when water was injected at the same time that oil was being pumped from the Long Beach, California, oil field. However, this method does not work for most groundwater mining because irreplaceable water has been extracted from layers of fine earth material. Once fine earth material has been compacted, it is not possible to push the particles back apart.[38]

**Regulating Mining** The best way to prevent damage from subsidence caused by mining activities is to prevent mining in urban areas. Although such laws are currently in place in many countries, the threat from older mines still exists.

**Preventing Damage from Thawing Permafrost** Most existing engineering practices for building on permafrost have assumed that the permafrost will remain frozen if heat from a building or pipeline does not radiate into the ground. With the recent widespread thawing of permafrost, new and more costly practices are being developed, such as putting buildings on adjustable screw jacks or latticelike foundations to allow for the freezing and thawing of permafrost.[22]

**Reducing Damage from Deltaic Subsidence** Completely stopping further subsidence of human settlements on delta plains and restoring the deltas to natural conditions is unrealistic. Levees must continue to be elevated to protect urbanized areas, and adequate pumping systems must be maintained to remove excess surface water from the levee-protected enclosures. However, in undeveloped areas, levees could be breached to restore the sediment and freshwater supply necessary to rebuild marshes (see Case Study 8.3: Subsidence of the Mississippi Delta). The restored

marshes would again help protect subsided urban areas from storms and rising sea levels.

**Managing Drainage of Organic and Collapsible Soils** As with most groundwater-induced subsidence, restoration of drained organic soils or collapsed soils is not possible. Only proper water management of existing drainage to marshes and swamps will minimize future subsidence from organic soils. For collapsible soils, it is especially important to limit irrigation and modify the land surface so that water does not pond near buildings.

**Preventing Damage from Expansive Soils** Proper design of subsurface drains, rain gutters, and reinforced foundations can minimize the damage from expansive soil. These techniques improve drainage and allow the foundation to accommodate some shrinking and swelling of the soil.[37] Another preventive method is to construct buildings on a layer of compacted fill that acts as a barrier between the structure above and the expansive soil below. This method helps control the moisture level in the soil and provides a stable base upon which to build. For larger buildings, roads, and airports, it may be cost-effective to excavate and redeposit the upper part of an expansive soil or to mix in calcium-based stabilizers, such as quicklime, to bind soil particles together.

### 8.8 CHECK your understanding

1. How might subsidence due to groundwater extraction be minimized?
2. Discuss ways to minimize subsidence from mining.
3. How can subsidence from thawing permafrost be prevented?
4. How might we minimize subsidence on deltas and collapsible soil?
5. List ways to minimize damage from expansive soil.

## 8.9 Perception of and Adjustment to Subsidence and Soil Volume Change

### PERCEPTION OF SUBSIDENCE AND SOIL VOLUME CHANGE

Subsidence and expansion and contraction of the soil are natural hazards that get little media coverage. Few people living in the United States are concerned about subsidence or soil volume change hazards. However, people living in areas directly affected, such as those in areas of expansive soils, permafrost, or rapid groundwater withdrawal, are more likely to understand the hazard. Furthermore, people living in regions where sinkholes commonly develop are generally familiar with the hazard and perceive it to pose a real risk to property.

### ADJUSTMENT TO SUBSIDENCE AND SOIL VOLUME CHANGE

The most appropriate adjustment to subsidence and soil volume change is to avoid building in areas prone to these hazards. Clearly, this is not always possible because a significant portion of the eastern United States is underlain by karst, large areas of the western United States are underlain by swelling soil, and areas of the northern United States and Canada have frost-susceptible or organic soils or permafrost. The best we can do is to identify high-risk areas in which construction should be prohibited or limited. Unfortunately, in areas of natural subsidence such as karst regions, subsidence may be difficult or impossible to predict. The groundwater system is constantly altering the subsurface rock, and sinkholes are common. There are, however, some methods that can help identify areas of potential subsidence and soil volume change.

**Geologic and Soil Mapping** Detailed geologic and soil maps can be made to identify the hazards present as accurately as possible. An understanding of the geology and soil, coupled with the surface and groundwater systems in an area, will greatly aid in the prediction and avoidance of subsidence and soil expansion and contraction.

**Observing Surface Features** In areas underlain by limestone, surface features such as cracking of the land surface should be noted. The appearance of cracks in the ground may indicate that sinkhole collapse is imminent, and appropriate steps should be taken to avoid damage and injury.

In the western United States, cracks in the ground may indicate expansive soils or, in some desert areas, a falling groundwater table due to over-pumping and aquifer compaction. To minimize subsidence and preserve precious aquifer pore space, rapid and detailed observations of ground surface elevation changes are needed in order to know where pumping should be limited and/or where ground water injection is necessary. Fortunately, new satellite-based radar technology are now capable of measuring millimeter-scale (0.4 in.) vertical movements over large areas of the Earth's surface over spans of days to years (Figure 8.32). It is clear

that over the next few decades, such radar techniques and other technological advances in space-based Earth observing will provide a greater understanding of the causes and rates of subsidence around the world.

**Subsurface Surveys** When planners must make decisions about where to build structures in karst regions, knowledge of the subsurface environment is critical. Subsurface exploration with *ground penetrating radar* (GPR) and drilling boreholes to examine the subsurface geology are often desirable before construction begins. These techniques may help prevent structures from being built above shallow caves. Additional geologic surveys may be needed to evaluate high-risk areas encountered during construction. In areas of expansive and frost-susceptible soils or areas underlain by permafrost, geotechnical borings and soil testing may be needed to properly design foundations.

Some states, such as Colorado, require disclosure of the presence of expansive soils when houses are sold. Disclosure requirements apply to new-home builders, homeowners, and real-estate brokers.[61] A recent lawsuit for construction defects on expansive soils, brought by owners of a 246-unit condominium complex in suburban Denver, Colorado, resulted in a settlement of more than $39 million. Homeowners who live in areas where subsidence hazards are present should check the hazard coverage in their insurance policies. For example, in many areas, neither sinkholes nor mine subsidence is covered in standard homeowners' policies, and they require additional coverage.

## 8.9 CHECK your understanding

1. What is the most appropriate adjustment to subsidence and soil volume change?
2. What three main methods can help identify areas where soils prone to subsidence exist?

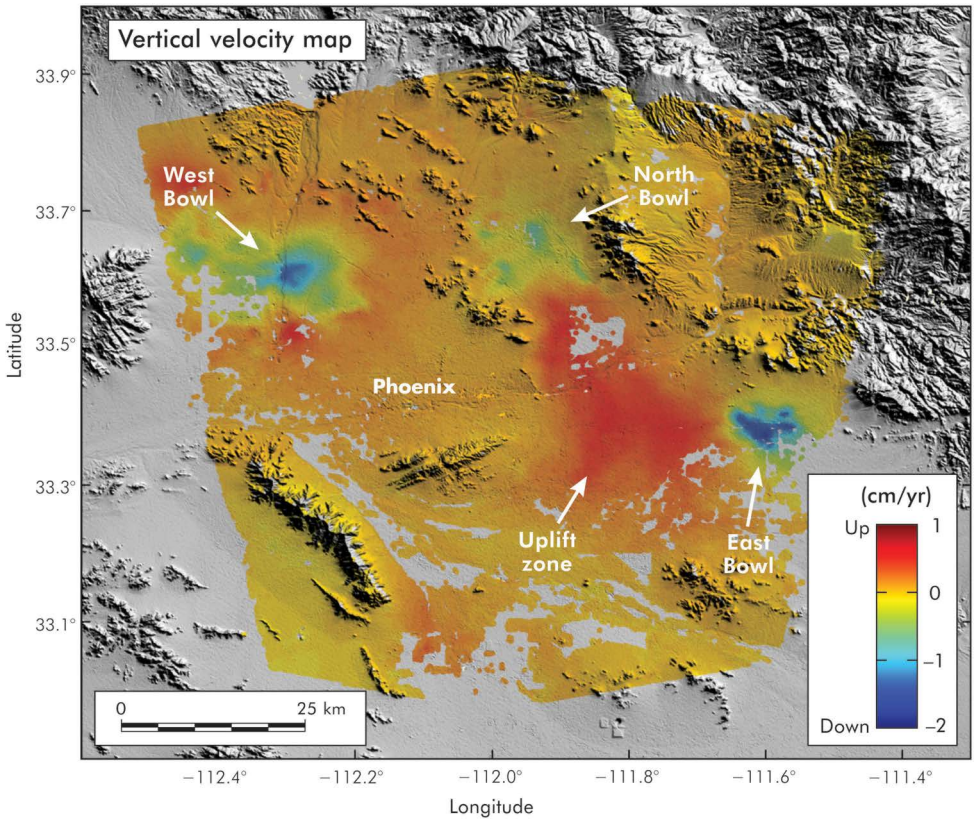



**FIGURE 8.32 Subsidence From Space**
InSAR (Interferometric synthetic-aperature RADAR) data of the greater Phoenix metropolitan area showing local annual rates of surface subsidence (blue) and uplift (red) across the region due to groundwater withdrawal between 2003 and 2010. *(Courtesey Megan Miller and Manoochehr Shirzael; adapted from J. Geophys. Res. Solid Earth, 120, 5822–5842)*

## APPLYING the 5 Fundamental Concepts

# Venice Is Sinking

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

The Italian people have studied the subsidence of Venice for decades and have kept records of flooding and subsidence for hundreds of years. The famed city, once a flourishing trading center and now an important tourist destination in Italy, is located on 118 small islands near the center of the 500 km$^2$ (~190 mi.$^2$) Venetian Lagoon on the Adriatic Sea (Figure 8.33).[62] The city's structures are built on thousands of closely spaced wooden pilings driven through the marshy wetlands to rest on a dense clay layer on the lagoon floor and waterways between islands take the place of streets.

Flooding is an age-old problem in Venice. Rivers flowing into the lagoon were diverted to reduce the input of sediment that would decrease the space available for water flow. People were so concerned with flooding in the thirteenth century that the Venetian empire considered moving its city inland to Constantinople. Changes in water levels were recorded as early as the mid-1860s.

Tidal-induced seasonal flooding, along with storms from the ocean and inland, rising sea level due to global warming, and natural geologic subsidence and tilting, along with human-caused subsidence is increasing the incidents of flooding in Venice. Although only about one half that of the United States, the annual population growth rate of Italy during the early part of the twentieth century was more than 10 percent, doubling the country's population by 1960, many of whom settled near the coast. This growth lead to an increase in the demand for fresh water, so in the 1930s pumping of groundwater on the Italian mainland surrounding the Venetian Lagoon (Figure 8.33) commenced. For the next 30 years excess groundwater pumping caused compaction of the aquifer and regional subsidence. Of the 25 cm (~10 in.) of Venetian subsidence in historic times, it is estimated that about 15 cm (~6 in.) was caused by pumping. It wasn't until the great flood of 1966, which caused significant loss of life and property when lagoon water level rose more than 2 m (~7 ft.) that the Italian government was prompted to ban groundwater pumping to prevent further subsidence.[62]

Contrary to the belief a decade or so ago that subsidence had stabilized, the city has continued

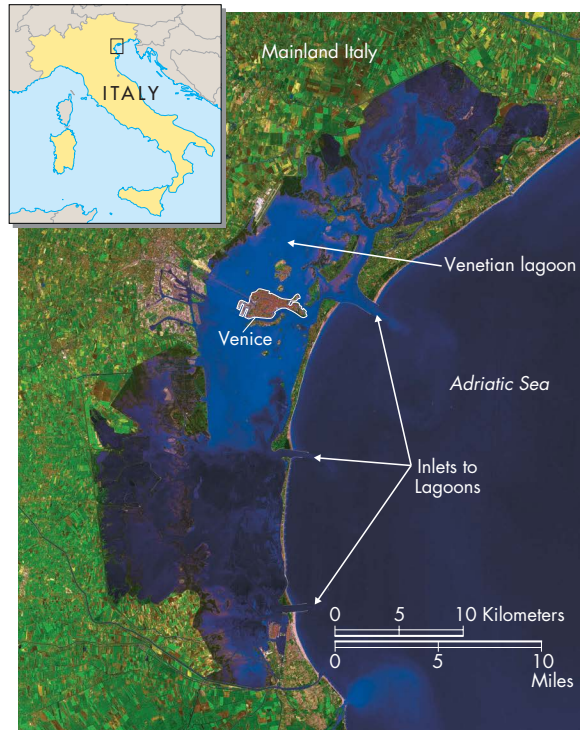



**FIGURE 8.33 The Venetian Coast**
Satellite image showing the location of Venice and important geographic features of this part of Italy. *(NASA)*



**FIGURE 8.34 Gondola Pushes Away from Flooded Walkway in 2008**
Built on a lagoon, Venice is known for its gondolas and water buses but accelerating subsidence is causing regular flooding of walkways and its famed architectural treasures. About 40 percent of the buildings in Venice were affected by the 2008 floods. *(Luigi Costantini/AP Images)*

to subside at a rate of about 1 to 2 mm (~0.04 to 0.08 in.) year over the past decade. The Venetian Lagoon is subsiding even faster, at about 2–4 mm (~0.08 to 0.16 in.) per year with an eastward tilt.

The most serious flooding in over 20 years occurred in 2008 (Figure 8.34), when days of heavy rain resulted in more than 95 percent of the historic city center being under water. Significant flooding also occurred in 2010 and 2012. Thus, plans to control the flooding must consider ongoing subsidence, as well as the effects of sea-level.[63]

To combat the flooding, the Italian government has started a $7 billion project that it calls the Moses Project (Moses, according to legend, parted the Red Sea). The public works project, which started in 2004 and may be finished as early as 2014, is the largest in the history of Italy.

The Moses Project will place 78 hinged, steel flood gates across the three tidal inlets to the Venetian Lagoon (Figure 8.33).[64] The floodgates are designed to swing upward using compressed air when a storm warning is received in order to prevent the wind-driven surge of seawater from the Adriatic Sea from entering the lagoon (Figure 8.35). The gates are

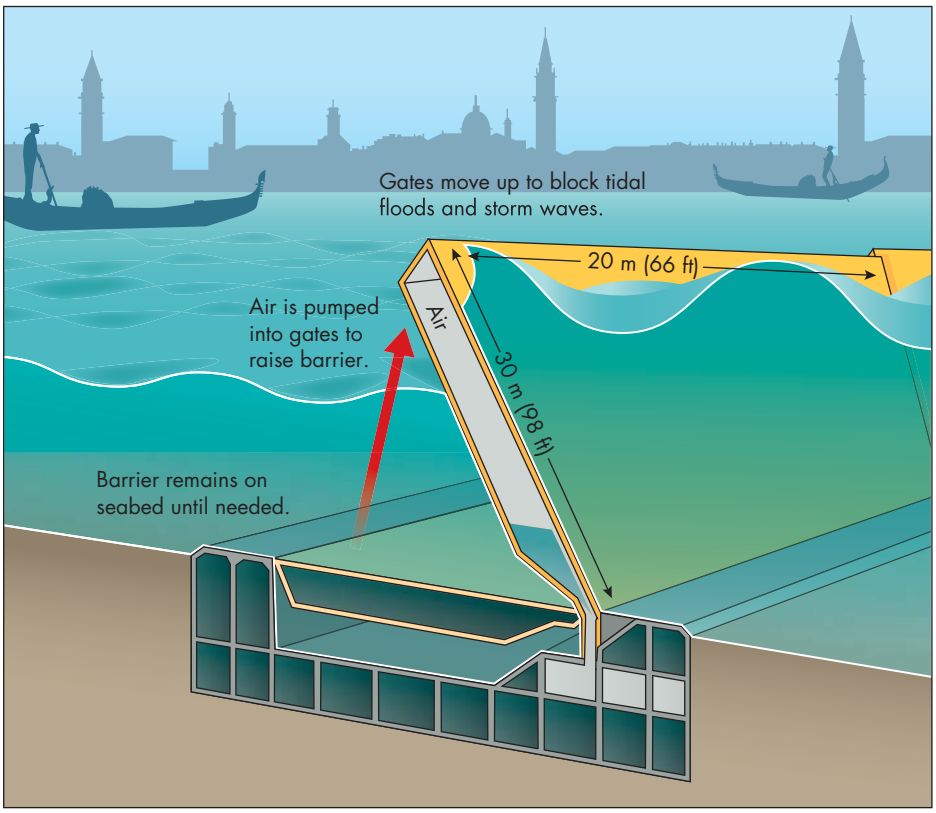



**FIGURE 8.35 Barriers to Protect the City of Venice**
Idealized diagram shows how barriers in the seabed may be raised to block tidal floods and storm surges from flooding Venice.

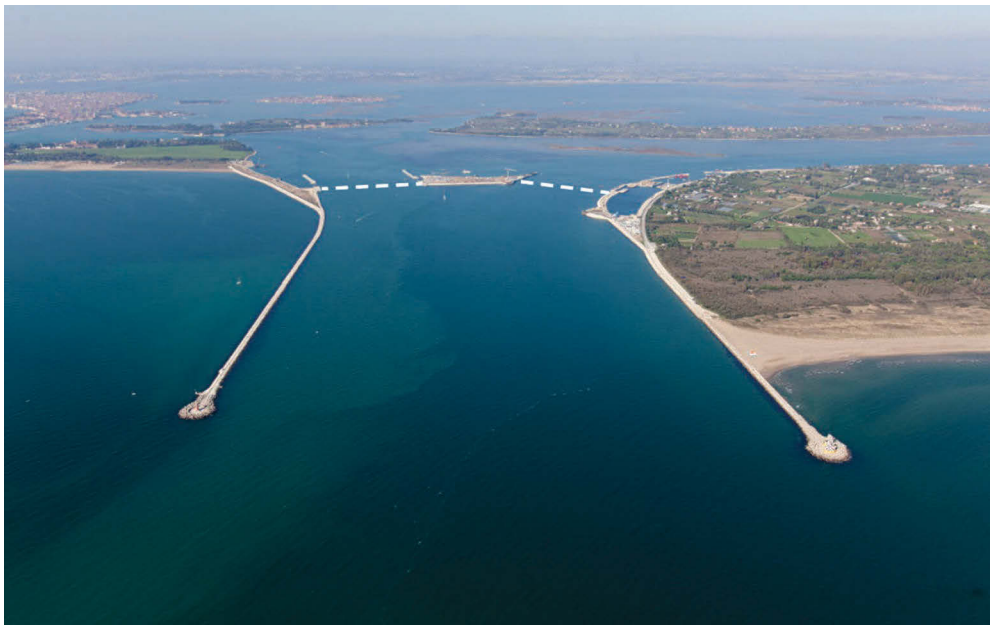


**FIGURE 8.36 Flood Control Structures during Construction**
Photograph of the Venetian lagoon beyond the construction site where retractable flood control structures are being built. Dashed white lines show the locations where the flood control structures will rise from the channel to restrict flow of sea water into the lagoon. *(Magistrato alle Acque di Venezia – Consorzio Venezia Nuova/Wikimedia)*

supported by steel and concrete structures 38 m (~125 ft.) long driven into the bed of the lagoon (Figure 8.36).

In addition to being expensive, the project has caused controversy. The lagoon, as is the case with many large wetlands, is a fragile environment. The waters of the lagoon are home to large numbers of migrating water birds. Any program to control flooding must also protect the greater lagoon environment. Moreover, these gates will neither slow the subsidence of the city nor completely stop flooding, and their long-term utility has been questioned.[65] As worldwide sea levels continue to rise, the future of Venice is uncertain.

The story of the subsidence of Venice involves linkages among soil, rock, compaction of sediment, tectonics, hydrology, and human use of the land. Although methods exist to minimize the subsidence hazard, application of these methods may address some but not all aspects of the problem when a complex set of factors is at work, as is the case in this historic city.

## APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. Describe how scientific investigations have contributed to understanding the processes involved in causing subsidence of Venice?
2. Risk is defined as the probability of an event occurring times the consequences. How can we evaluate the risk to Venice from flooding to help make decisions on future actions?
3. What other hazards are linked to the sinking of Venice? Will the effect of these hazards increase or decrease in the future? What do you need to know to make such a determination?
4. Name two or three human-induced factors that are linked to the flooding of Venice.
5. Human processes, such as including preparedness plans for an event, is part of the equation of determining the consequences of future flooding in Venice. Discuss the actions taken by the population and the Italian government to minimize the effects of subsidence? What else could be done to minimize the effects of future flooding events?

# CONCEPTS in review

## 8.1 Soil and Hazards

**LO:1** Describe what a soil is and the processes that form and maintain soils.

**LO:2** Explain why soil erosion might threaten our society.



**KEY WORDS**

**soil** (p. 300), **soil erosion** (p. 307), **soil horizons** (p. 300), **weathering** (p. 300)

- Engineers define soil as earth material that may be removed without blasting; soil scientists define soil as solid earth material that can support rooted plant life. A basic understanding of soils and their properties is crucial to land-use planning, waste disposal, and evaluation of natural hazards such as flooding, landslides, and earthquakes.
- Soils result from interactions of the rock and hydrologic cycles and are affected by variables such as climate, topography, parent material, time, and organic activity. Soils tend to have distinctive layers, or horizons, defined by the processes that formed them and the type of materials present. Of particular importance are the processes of leaching, oxidation, and accumulation of materials in various soil horizons. Development of the argillic B horizon, for example, depends on the translocation of clay minerals from upper to lower horizons. Three important properties of soils are color, texture (particle size), and structure (aggregation of particles).
- An important concept in studying soils is relative profile development. Young soils are weakly developed. Soils older than 10,000 years tend to show moderate development, with more pronounced soil structure, redder soil color, and more translocated clay in the B horizon. Strongly developed soils are similar to those of moderate development but with better-developed B horizons. Such soils can range in age from several tens of thousands of years to several hundred thousand years or older. A soil chronosequence is a series of soils arranged from youngest to oldest in terms of relative soil profile development. A soil chronosequence in a region is useful in evaluating rates of processes and recurrence of hazardous events such as earthquakes and landslides.
- A soil may be considered as a complex ecosystem in which many types of living things convert soil nutrients into forms that plants can use. *Soil fertility* refers to the capacity of the soil to supply nutrients needed for plant growth.
- Water may flow vertically or laterally through the pores (spaces between grains) of a soil. The flow is either saturated (all pore space filled with water) or, more commonly, unsaturated (pore space partially filled with water). The study of soil moisture and how water moves through soils is an important topic in environmental geology.
- Soil erosion refers to the erosion process of grain by grain removal of soil or removal of soil at an unacceptable rate or where the removal rate exceeds that of soil formation. The natural rate of soil erosion is about 1.0 ton per hectare per year. Poor soil conservation in agricultural practices may increase the rate by 10 to 30 times.

## 8.2 Introduction to Subsidence and Soil Volume Change

**LO:3** Summarize the causes and effects of subsidence and volume changes in the soil.

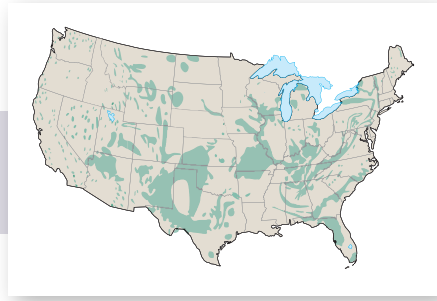


**KEY WORDS**

**cave systems** (p. 310), **collapsible soil** (p. 317), **expansive soil** (p. 318), **karst topography** (p. 309), **permafrost** (p. 313), **sinkhole** (p. 309), **subsidence** (p. 309)

- Subsidence is a type of ground failure characterized by nearly vertical deformation, or the downward sinking, of earth materials. This failure may be caused by natural processes, human activities, or a combination of the two. Most subsidence is caused by the underground dissolution of soluble rocks. Other causes include lowering groundwater levels and fluid pressures in sediment, thawing permafrost, reduced sedimentation on delta plains, flooding of collapsible soils, and draining organic soils. Earthquakes, the deflation of magma chambers, and the drainage of lava tubes also may cause some subsidence.
- Underground dissolution of limestone by acidic groundwater creates a landscape of caves and sinkholes known as karst topography. Other karst features include disappearing streams, springs, and tower karst. Most sinkholes form by the slow dissolution of limestone. Other sinkholes form from the collapse of cave roofs. This collapse is often caused by a falling groundwater table during a drought or by an increase in groundwater pumping. Karst topography also develops where layers of highly soluble rock salt or rock gypsum are near the surface.
- During the past several decades, permafrost thawing has become a major hazard in Arctic and near-Arctic regions. Most of this melting is a direct result of climatic warming. Thawing permafrost causes subsidence and structural damage, as well as the formation of thermokarst, a terrain consisting of uneven ground with sinkholes, mounds, ponds, and caves.
- Loosely compacted fine sediment subsides where the groundwater table has fallen or fluid pressure has been reduced. Groundwater changes may be natural or result from human activities. This subsidence is often irreversible because of the drying of underground layers of very fine sediment. Surface features associated with this compaction include large earth fissures or desiccation cracks.
- Marine deltas are areas of natural compaction and subsidence. The continual deposition of sediment on the delta plain generally keeps up with the compaction of sediment underground. Reducing or stopping sedimentation on the delta plain by the construction of dams, levees, and canals causes the delta surface to subside below the sea. This subsidence destroys wetlands and can produce flooding in urban areas such as New Orleans.
- Soil expansion and contraction can cause the land surface to either heave upward or sink downward. Both heaving and sinking occur in expansive and frost-susceptible soils, and sinking takes place in collapsible soils.
- Expansive soils are those that swell when wet and shrink when dry, commonly a result of changes in the amount of water clinging onto the surface of fine smectite clay. These volume changes can cause extensive structural damage. Factors that affect the moisture content of an expansive soil include climate, vegetation, topography, and drainage.
- Frost-susceptible soils are those that are likely to accumulate ice in pockets or lenses between silty earth material. Growth of these ice accumulations displaces the surrounding soil and produces frost heaving. The upward heaving and later thawing of the soil cause structural and pavement damage in areas underlain by permafrost and in soils that are only intermittently frozen.
- Collapsible soils are normally dry, with particles loosely packed or weakly cemented together. These soils are susceptible to subsidence when water ponds on the surface.

## 8.3 Geographic Regions at Risk for Subsidence and Soil Volume Change

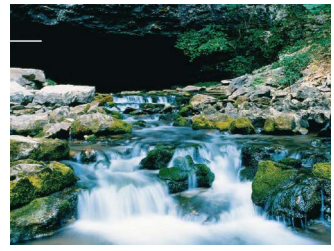


**LO:4** Locate on a map the geographic regions at risk for subsidence and volume changes in the soil.

**LO:5** Discuss the hazards associated with karst regions.

- Subsidence is a hazard in more than 45 U.S. states and most Canadian provinces. Karst hazards include sinkhole collapse, groundwater pollution, and unreliable water supplies. Large areas of karst topography are found in a region extending through Tennessee, Virginia, Maryland, and Pennsylvania; parts of Indiana and Kentucky; the Salem-Springfield plateaus of Missouri and Arkansas; central Texas; central Florida; and Puerto Rico.
- Soil volume change is also a common hazard in many areas. Permafrost and frost-susceptible and organic soils are common in Alaska, Canada, and Russia. Organic soils are also abundant in the Upper Midwest, the Pacific Northwest, and the Gulf and Atlantic Coasts in the United States. Frost-susceptible soils are found in the northern contiguous United States and at high altitudes in mountainous areas. Collapsible soils occur in arid and semiarid regions, such as the southwestern United States. Expansive soils are a problem primarily in the western United States and Canada.

## 8.4 Effects of Subsidence and Soil Volume Change



**LO:6** Summarize the effects of subsidence and soil volume changes.

- Sinkholes may cause damage to highways, homes, and other structures and affect water quality if they are used as disposal sites.
- Melting permafrost causes soil volume changes and soil instability that can damage structures such as roads and buildings.
- Subsidence on deltas causes flooding and loss of wetlands.
- Soil volume changes, especially from expansive soils, cause billions of dollars in damages to structures, mostly to highways, buildings, and pipelines.

## 8.5 and 8.6 Linkages between Subsidence, Soil Volume Change, and Other Natural Hazards
## Natural Service Functions of Subsidence and Soil Volume Change



**LO:7** Identify linkages between subsidence, soil expansion and contraction, and other hazards, as well as natural service functions of karst.

- Subsidence may be linked to volcanic, earthquake, flood, and landslide hazards.
- About 25 percent of the world's population gets its drinking water from karst formations.
- Karst regions offer important aesthetic and scientific resources. They are home to rare creatures that are specially adapted to living underground.

## 8.7, 8.8, and 8.9 Human Interaction with Subsidence and Soil Volume Change
## Minimizing Subsidence and Soil Volume Change
## Perception of and Adjustment to Subsidence and Soil Volume Change




**KEY WORD**
**groundwater mining** (p. 326)

**LO:8** Explain how humans interact with subsidence and soil hazards.

**LO:9** Evaluate what can be done to minimize the hazard from subsidence and volume changes in the soil.

- Human beings exacerbate subsidence by removing subsurface fluids, underground mining, melting permafrost, reducing sediment accumulation on deltas, and draining organic soils.
- Effects of soil volume change can be intensified by poor landscaping and drainage practices on expansive and collapsible soils.
- Natural subsidence and changes in the volume of the soil are difficult to prevent, but human-induced subsidence may be avoided or minimized. Methods for limiting human-induced subsidence include injecting water during crude oil production and regulating groundwater pumping and underground mining. Problems with soil volume change may be minimized with sound construction and landscaping techniques.
- An understanding of the local geologic and hydrologic systems can help prevent water pollution in karst areas.
- Adjustments to the subsidence and soil volume change hazard include identifying problem areas through geologic, soil, and subsurface mapping. Homeowners can protect themselves with insurance that covers the subsidence and soil volume change hazards in their area.

# CRITICAL thinking questions

1. You are considering building a home in rural Kentucky. You know the area is underlain by limestone, and you are concerned about possible karst hazards. What are some of your concerns? What might you do to determine where to build your home?
2. You work in the planning department in one of the parishes (counties) close to New Orleans. What would you advocate in the long term and in the short term to protect your community from subsidence and flooding? Consider both regional and local solutions to the problem.
3. You have inherited a ranch house built on a concrete slab on clay soil in a suburb east of Denver, Colorado. How would you determine if the house is built on expansive soil? If you found that the soil was expansive, how would you minimize damage from the shrinking and swelling of the soil?
4. You would like to build a home in a desert community in Arizona or New Mexico. What would you look for to determine if subsidence or soil volume change is a potential problem? What could you do to protect your investment?
5. As a town council representative in a small village in New England or Ontario, Canada, you have been asked to approve a building permit on property that is partly underlain by silty glacial deposits and partly by a marsh. What questions should you ask the permit applicant regarding planned construction on the silty

soil and the applicant's proposal to drain and build on the wetland?

6. Defend or criticize the contention that soil erosion is threatening our civilization, as it has done to previous societies that have disappeared or literally eroded away.
7. What might be the reactive policies following sudden formation of a large collapse sinkhole measuring 200 m (~650 ft.) in diameter and 30 m (~100 ft.) deep in a housing area? How might these policies compare to proactive steps that could be taken before the event? Which plan of action is better? Why?

# References


1. **Bock, Y., Wdowinski, S., Ferretti, A., Novali, F.,** and **Fumagalli, A.** 2012. *Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperature radar.* Geochemistry, Geophysics, Geosystems, an American Geophysical Union publication.
2. **Waltham, T.** 2002. Sinking cities. *Geology Today* 18(3): 95–100.
3. **Birkland, P. W.** 1984. *Soils and geomorphology.* New York: Oxford University Press.
4. **Brady, N. C.,** and **Weil, R. R.** 1996. *The nature and properties of soils*, 11th ed. Upper Saddle River, NJ: Prentice Hall.
5. **Keller, E. A., Bonkowski, M. S., Korsch, R. J.,** and **Shlemon, R. J.** 1982. Tectonic geomorphology of the San Andreas fault zone in the southern Indio hills, Coachella Valley, California. *Geological Society of America Bulletin* 93: 46–56.
6. **Van der Woerd, J., Klinger, Y., Sieh, K., Tapponnier, P., Ryerson, F. J.,** and **Meriaux, A. S.** 2006. Long-term slip rate of the southern San Andreas fault from 10Be-26Al surface exposure dating of an offset alluvial fan. *J. Geophys. Res.*, 11 B04407: 10.1029/2004 JB00359.
7. **Krynine, D. P.,** and **Judd, W. R.** 1957. *Principles of engineering geology and geotechnics.* New York: McGraw-Hill.
8. **Singer, M. J.,** and **Munns, D. N.** 1996. *Soils*, 3rd ed. Upper Saddle River, NJ: Prentice Hall.
9. **Montgomery, D.** 2007. Is agriculture eroding civilization's foundation? *GSA Today* 17(10): 4–10.
10. **Montgomery. D. R.** 2007. *Dirt: The erosion of civilizations*. Berkeley, CA: University of California Press.
11. **Diamond, J.** 2010. Intra-island and inter island comparisons. In *Natural experiments of history*, ed. J. Diamond, and J. A. Robinson, pp. 120–4. Cambridge, MA: Belknap Press of Harvard University Press.
12. **Mongabay.** 2010. Deforestation figures for selected countries. http://rainforest.mongabay.com/deforestation. Accessed 5/17/10.
13. **Author unknown.** Erosion: Erosion from inappropriate agricultural practices on crop lands. http://people.oregonstate. edu/~muirp/erosion.htm. Accessed 6/25/13
14. **Pimentel, D.** and **10 others.** 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* 267(5021): 1117–23.
15. **Wischmeier, W. H.,** and **Meyer, L. D.** 1973. Soil erodibility on construction areas. In *Soil erosion: Causes, mechanisms, prevention and control*, pp. 20–29. Highway Research Board Special Report 135. Washington, DC: Highway Research Board.
16. **Dunne, T.,** and **Leopold, L. B.** 1978. *Water in environmental planning.* San Francisco: W. H. Freeman.
17. **Veni, G., DuChene, H., Crawford, N. C., Groves, C. G., Huppert, G. N., Kastning, E. H., Olson, R., and Wheeler, B. J.** 2001. *Living with karst: A fragile foundation.* Alexandria, VA: American Geological Institute.
18. **Galloway, D., Jones, D. R.,** and **Ingebritsen, S. E.** 1999. Introduction. In *Land subsidence in the United States*, ed. D. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 1–6. U.S. Geological Survey Circular 1182.
19. **Waltham, T., Bell, F.,** and **Culshaw, M.** 2005. Sinkholes and subsidence: Karst and cavernous rocks in engineering and construction. New York: Springer-Verlag.
20. **Bloom, A. L.** 1991. *Geomorphology: A systematic analysis of late Cenozoic landforms*, 3rd ed. Upper Saddle River, NJ: Prentice Hall.
21. **Nelson, F. E., Anisimov, O. A.,** and **Shiklomanov, N. I.** 2001. Subsidence risk from thawing permafrost. *Nature* 410: 889–90.
22. **Goldman, E.** 2002. Even in the high Arctic nothing is permanent. *Science* 297: 1493–94.
23. **Stanley, J.-D., Goddio, F., Jorstad, T. F.,** and **Schnepp, G.** 2004. Submergence of ancient Greek cities off Egypt's Nile Delta—a cautionary tale. *GSA Today* 14(1): 4–10.
24. **Penvenne, L. J.** 1996. The disappearing delta. *Earth* 5(4): 16–17.
25. **Roberts, H. H.** 1997. Dynamic changes of the Holocene Mississippi River delta plain: The delta cycle. *Journal of Coastal Research* 13(3): 605–27.
26. **Morton, R. A., Bernier, J. C.,** and **Barras, J. A.** 2006. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. *Environmental Geology* 50: 261–74.
27. **Dokka, R. K.** 2006. Modern-day tectonic subsidence in coastal Louisiana. *Geology* 34: 281–84.
28. **Torbjörn, T. E., Bick, S. J., van de Borg, K.,** and **De Jong, A. F. M.** 2006. How stable is the Mississippi Delta? *Geology* 34: 697–700.

29. **Louisiana Coastal Wetlands Conservation and Restoration Task Force.** 1998. *Coast 2050: Toward a sustainable coastal Louisiana.* Baton Rouge, LA: Louisiana Department of Natural Resources.
30. **Penland, S., Wayne, L. D., Britsch, L. D., Williams, S. J., Beall, A. D.,** and **Butterworth, V. C.** 2000. *Process classification of coastal land loss between 1932 and 1990 in the Mississippi River delta plain, southeastern Louisiana.* U.S. Geological Survey Open-File Report 00–0418.
31. **Scheffe, K. F.** 2005. Collapsible soils in the Rio Grande Valley of central New Mexico. *Geological Society of America Abstracts with Programs* 37(7): 327.
32. **Scheffe, K. F.,** and **Lacy, S. L.** 2004. Hydrocompactible soils. In *Understanding soil risks and hazards: Using soil survey to identify areas with risks and hazards to human life and property*, ed. G. B. Muckel, pp. 60–64. Lincoln, NE: U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center.
33. **Fischetti, M.** 2001. Drowning New Orleans. *Scientific American* 285(10): 76–85.
34. **Ingebritsen, S. E., McVoy, C., Glaz, B.,** and **Park, W.** 1999. Florida Everglades: Subsidence threatens agriculture and complicates ecosystem restoration. In *Land subsidence in the United States*, ed. D. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 95–106. U.S. Geological Survey Circular 1182.
35. **Grunwald, M.** 2006. The swamp: The Everglades, Florida, and the politics of paradise. New York: Simon & Schuster.
36. **Wilding, L. P.,** and **Tessier, D.** 1988. Genesis of vertisols: Shrink-swell phenomena. In *Vertisols: Their distribution, properties, classification and management*, ed. L. P. Wilding and R. Puentes, pp. 55–81. College Station, TX: Texas A&M University Soil Management Support Services Technical Monograph No. 18.
37. **Noe, D. C., Jochim, C. L.,** and **Rogers, W. P.** 1999. *A guide to swelling soils for Colorado homebuyers and homeowners.* Colorado Geological Survey Special Publication 43.
38. **McCarthy, D. F.** 2002. *Essentials of soil mechanics and foundations: Basic geotechnics*, 6th ed. Upper Saddle River, NJ: Prentice Hall.
39. **Johnson, K. S.** 2005. Subsidence hazards due to evaporite dissolution in the United States. *Environmental Geology* 48: 395–409.
40. **Olive, W. W., Chleborad, A. F., Frahme, C. W., Schlocker, J., Schneider, R. R.,** and **Schuster, R. L.** 1989. *Swelling clays map of the conterminous United States.* U.S. Geological Survey Miscellaneous Investigations Series Map I-1940.
41. **Schmidt, W.** 2001. Sinkholes in Florida. *Geotimes* 46(5): 18.
42. **Comiso, J. C.,** and **Parkinson, C. L.** 2004. Satellite-observed changes in the Arctic. *Physics Today* 57(8): 38–44.
43. **Dixon, T. H., Amelung, F., Ferretti, A., Novali, F., Rocca, F., Dokka, R., Sella, G., Kim, S.-W., Wdowinski, S.,** and **Whitman, D.** 2006. Subsidence and flooding in New Orleans: A subsidence map of the city offers insight into the failure of the levees during Hurricane Katrina. *Nature* 441: 587–88.
44. **Wray, W. K.,** and **Meyer, K. T.** 2004. Expansive clay soil … a widespread and costly geohazard. *Geo-Strata* 5(4): 24–25, 27–28.
45. **DiMillo, A.** 2005. *A quarter-century of geotechnical research.* U.S. Department of Transportation Federal Highway Administration. www.fhwa.dot.gov/engineering/geotech/pubs/century/. Accessed 6/25/06.
46. **Jones, D. E.,** and **Holtz, W. C.** 1973. Expansive soils—the hidden disaster. *Civil Engineering—ASCE* 43(6): 49–51.
47. **Ritter, D. F., Kochel, R. C.,** and **Miller, J. R.** 2002. *Process geomorphology.* New York: McGraw-Hill.
48. **National Research Council (U.S.) Joint Academies Committee on the Mexico City Water Supply.** 1995. *Mexico City's water supply: Improving the outlook for sustainability.* Washington, DC: National Academies Press.
49. **Harris, R. C.** 2004. Giant desiccation cracks in Arizona. *Arizona Geology* 34(2): 1–4.
50. **Slaff, S.** 1993. *Land subsidence and earth fissures in Arizona.* Arizona Geological Survey Down-to-Earth Series 3.
51. **Karst Waters Institute.** 2002. *What is karst (and why is it important)?* www.karstwaters.org/kwitour/whatiskarst.html/. Accessed 7/23/06.
52. **Holzer, T. L.,** and **Galloway, D. L.** 2005. Impacts of land subsidence caused by withdrawal of underground fluids in the United States. In *Humans as geologic agents*, ed. J. Ehlen, W. C. Haneberg, and R. A. Larson, pp. 87–99. Geological Society of America, Reviews in Engineering Geology XVI.
53. **Bull, W. B.** 1973. Geologic factors affecting compaction of deposits in a land subsidence area. *Geological Society of America Bulletin* 84: 3783–802.
54. **Kenny, R.** 1992. Fissures: Legacy of a drought. *Earth* 1(3): 34–41.
55. **Craig, J. R., Vaughan, D. J.,** and **Skinner, B. J.** 1996. *Resources of the Earth: Origin, use, and environmental impact*, 2nd ed. Upper Saddle River, NJ: Prentice Hall.
56. **Rahn, P. H.** 1996. *Engineering geology: An environmental approach*, 2nd ed. Upper Saddle River, NJ: Prentice Hall.
57. **Kappel, W. M., Yager, R. M.,** and **Miller, T. S.** 1999. The Retsof Salt Mine collapse. In *Land subsidence in the United States*, ed. D. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 111–20. U.S. Geological Survey Circular 1182.
58. **Péwé, T. L.** 1982. *Geologic hazards of the Fairbanks area, Alaska.* Alaska Division of Geological & Geophysical Surveys Special Report 15.

**59. Ingebritsen, S. E., Ikehara, M. E., Galloway, D. L.,** and **Jones, D. R.** 2000. *Delta subsidence in California: The sinking heart of the state.* U.S. Geological Survey Fact Sheet FS-005–00.

**60. Coplin, L. S.,** and **Galloway, D.** 1999. Houston-Galveston, Texas: Managing coastal subsidence. In *Land subsidence in the United States*, ed. D. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 35–48. U.S. Geological Survey Circular 1182.

**61. Galloway, D., Jones, D. R.,** and **Ingebritsen, S. E.** 1999. Mining ground water—Introduction. In *Land subsidence in the United States*, ed. D. Galloway, D. R. Jones, and S. E. Ingebritsen, pp. 7–13. U.S. Geological Survey Circular 1182.

**62. Merali, Z.** 2002. Saving Venice. *Scientific American*, August 19. www.scientificamerican.com/article.cfm?id=saving-venice

**63. Bock, Y., Wdowinski, S., Ferretti, A., Novali, F.,** and **Fumagalli, A.** 2012. Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar. *Geochemistry Geophysics Geosystems* 13:Q03023: AGU 10.1029/2011gc003976

**64. Fletcher, C.,** and **Da Mosto, J.** 2004. *The science of saving Venice.* New York: Umberto Allemandi & Co.

**65. Nosengo, N.** 2003. Save our city! *Nature* 424: 608–09.