# 11 Slope Systems

Most of Earth's surface is not perfectly horizontal; sloping surfaces are everywhere. On Earth, most slopes are formed by stream erosion and are related to the walls of stream valleys. Some, however, are the result of tectonic activity such as faulting; others result from wave erosion, extrusion of lava, glaciation, and even impact of meteorites. Regardless of a slope's origin, gravity has a universal tendency to pull materials on it to a lower gravitational potential. Consequently, the downslope transfer of material through the direct action of gravity—mass movement—is extremely common.

Slope failures can be rapid and devastating, as in great landslides on steep cliffs, or they can be imperceptibly slow, as in the creep of soil down the gentle slope of a grass-covered field. Slope failures occur on all planetary surfaces—modifying impact crater rims on the Moon and on Mercury, enlarging the huge canyons on Mars, in addition to shaping stream valleys, sea cliffs, and mountain fronts on Earth. In all cases, the net effect of mass movement is the transportation of loose rock material from hillsides onto low-lying areas.

Mass movement is also common on steep slopes on the ocean floor. The largest landslides known on Earth occur on the flanks of volcanic seamounts and on steep continental

slopes and are spaced thousands of years apart. The smallest ones occur on hill slopes like those shown above everyday. This glaciated landscape is part of Banff National Park in Alberta, Canada. Coarse angular rock fragments accumulated to make large talus cones that coalesced into a nearly continuous apron on the mountain front. As on all slopes, the inexorable, continuous force of gravity works in concert with weathering to slowly create a new landscape from these steep cliffs.

As geologic hazards, slope failures and related subsidence features pose a constant threat to people in many regions of the world. The 1997–1998 El Niño rains caused millions of dollars of damage in California alone as steep oceanfront properties slumped into the Pacific Ocean. In Central America, hillsides, drenched by torrential rains from Hurricane Mitch, gave way and destroyed whole villages. Many lives were lost in the region as a result of these debris flows and other kinds of slope failures. Consequently, assessment of slope stability is an important job for many geologists.

In this chapter, we will consider the various types of mass movement, some rapid and others extremely slow. We will also consider the fundamental factors that determine if a slope is stable or unstable and susceptible to failure. The great overriding theme in this chapter is that all slopes are mobile and constantly changing under the continuous pull of gravity.

## MAJOR CONCEPTS

1. Mass movement is the downslope transfer of material through the direct action of gravity. It is a major geologic process operating on all slopes.
2. The most important factors influencing slope failures are saturation of slope material with water, earthquakes, oversteepening of slopes, freezing and thawing, and the strength of the materials in the slope.
3. The major types of mass movement are creep, debris flows,, landslides, and subsidence.
4. Creep is the very slow downslope movement of soil and rock, produced primarily by the expansion and contraction of the surface materials.
5. Debris flows are mixtures of rock fragments and water that flow rapidly downslope as a viscous fluid. A lahar is a special type of debris flow composed of volcanic materials.
6. Landslides are a type of mass movement in which the material moves as a unit or block along definite slippage planes.
7. Subsidence is essentially vertical motion caused by collapse into voids or as a result of compaction of loose materials.
8. Slopes are open dynamic systems in which regolith and near-surface bedrock move downslope toward the main stream, where they are removed through the drainage system.

## FACTORS INFLUENCING MASS MOVEMENT

Gravity is the driving force for the downslope movement of material, but several factors are important in causing movement to occur. The most important are (1) saturation of material with water, (2) vibrations from earthquakes, (3) oversteepening of slopes by undercutting, (4) alternating freezing and thawing, and (5) strength of the slope materials.

Gravity pulls continuously downward on all materials everywhere on Earth's surface. Bedrock is usually so strong that it remains fixed in place, but if a slope becomes too steep or if fractures form, masses of bedrock may break free and move downslope. Soil and regolith, in contrast, are held together poorly and are much more susceptible to downslope movements. There is abundant evidence that, on most slopes, at least a small amount of downhill movement is occurring all of the time.

**What factors influence mass movement?**

Gravity is the driving force behind all slope processes. Mass movement is not limited to stream valleys but occurs on all slopes, including sea cliffs and fault-block mountain fronts, on the ocean floor, and even on the slopes of craters on other planets. The force of gravity is continuous, of course, but it can move material only when it exceeds the **cohesive strength** of the surface material. As the products of weathering accumulate on a hill slope, the dry, loose rock fragments will tend to accumulate at a nearly uniform slope angle inclined at what geologists call the **angle of repose.** This angle is the steepest slope at which loose material, such as talus, will remain at rest without rolling farther downslope. This is the inclination of a slope at equilibrium. The angle of repose is commonly about 30° for dry sand, but it varies depending on the size, shape, and sorting of the fragments and the amount of moisture between the grains. Rock slopes also have a profile of equilibrium. Some rocks, such as sandstone, form steep cliffs, whereas soft shale form gentle slopes. That is why in many areas, alternating layers of sandstone and shale develop a profile of alternating cliffs and slopes. The profile of equilibrium on any rock surface is the preferred profile, and any time it is modified (naturally or by humans), it will readjust to the original profile.

Some factors that influence mass movement can be understood by considering the forces acting on a rock fragment that rests on a slope (Figure 11.1). The weight of the object (the force caused by gravity) is directed vertically downward, here 1 kg. The force directed down this hill slope is only 0.5 kg (1 kg ∞ sine 30°). On a stable slope, the frictional cohesion of the object to the slope is greater than this downhill force, and the rock fragment remains stationary. Any factor that either weakens the cohesion of the object with the surface or increases the downslope force may initiate downslope movement. Such factors include (1) saturation of the material with water, (2) vibrations from earthquakes, (3) alternating expansion and contraction of the regolith, (4) the undercutting of slopes by streams or waves, and (5) modification of slopes by humans, including the removal of vegetation.

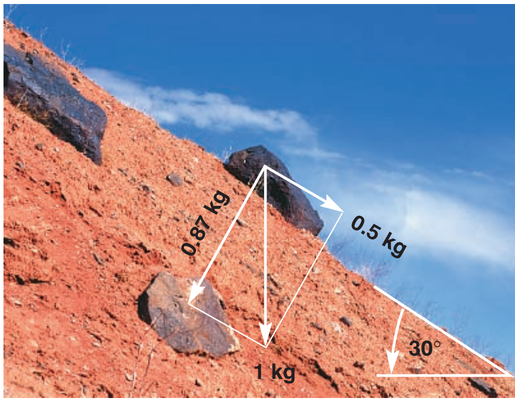



**FIGURE 11.1 Forces acting on a rock on a hill slope** determine if it will move downslope. The force of gravity is vertical, but it can be separated into one component that is parallel to the surface and another that is perpendicular to the slope. Consequently, the force directed downslope depends on the weight of the object and the angle of the slope. If the downhill force exceeds the forces of friction that resist movement, the rock will start to move.

Water is an important factor in mass movement because it lubricates the unconsolidated material on slopes (reduces cohesion) and adds weight to the mass (increases downhill force), thereby promoting mobility and downslope movement. Heavy rainfalls, whether prolonged over many days or in a single storm, are particularly effective in triggering mass movement.

Earthquakes, with their initial shock and aftershocks, can loosen fragments of rocks on steep slopes, overcoming the cohesion of the slope, and set the regolith in motion. In many areas, more damage is caused by mass movement than by the earthquake itself. For example, an earthquake in Guatemala in 1976 set off more than 10,000 mass movements. Most occurred on steep slopes, but some were on gentle slopes where water-saturated regolith was mobilized and turned into debris flows.

Undercutting of slopes is a fundamental cause of slope failures in that it creates steep gravitationally unstable surfaces. Natural undercutting is caused by streams eroding their banks, or by waves cutting cliffs on a shoreline. Home and road construction commonly undercut natural slopes that were at the angle of repose. The new steeper slope is unstable and susceptible to failure. Almost everyone has seen the evidence of slope failure on a steep road cut.

A significant factor in mass movement has been the modification of natural slopes to suit humans. Since prehistoric times, farming and deforestation have brought changes in vegetation cover, soil, and drainage. In more recent times, large scale engineering works have modified coastlines, river systems, and landforms on an even larger scale. All of these changes by humans result in new and artificial surfaces imposed on existing geologic systems that had attained some degree of equilibrium. They commonly provoke unforeseen reactions that cause widespread damage. A dramatic example is the deforestation of large areas in Madagascar that resulted in tens of thousands of major slope failures and accelerated erosion (Figure 11.2).

The strength of the materials in the slope is obviously important. We have alluded to this already in the discussion about frictional cohesion of a rock to the hillside. But the rocks and regolith that make up the slope will also control its failure. Consider the strength of a well-cemented sandstone compared to a shale. Shale are weak and fail easily. Fractures and bedding planes also impart weakness to a bock body.

Another example of slope failure related to human activities is the landslide that occurred at Vaiont Dam in northern Italy. This, the worst dam disaster in history, resulted from a huge landslide into the Vaiont Reservoir on October 9, 1963 (Figure 11.3). The landslide moved slowly downhill over a 3-year period. The rate of creep had been as much as 7 cm per week, until a month before the catastrophe; then, it increased to 25 cm per day. On October 1, animals grazing on the slopes sensed the danger and moved away. Finally, on the day before the slide, the rate of creep was about 40 cm per day. Engineers expected a small landslide and did not realize, until the day before the disaster, that a large area of the mountain slope was moving en masse at a uniform rate. When the slide broke loose, more than 240 million cubic meters of rock rushed down the hill

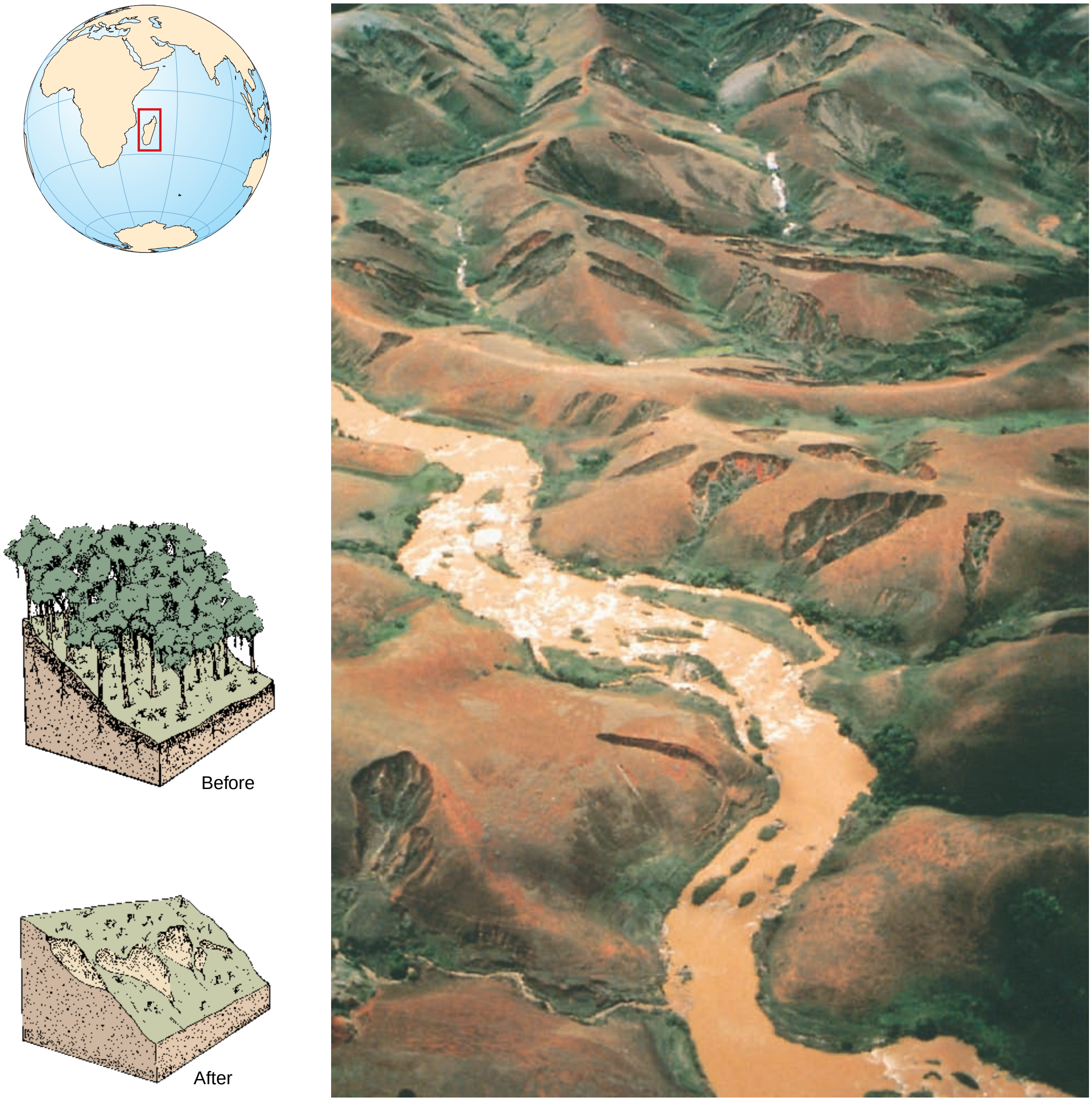
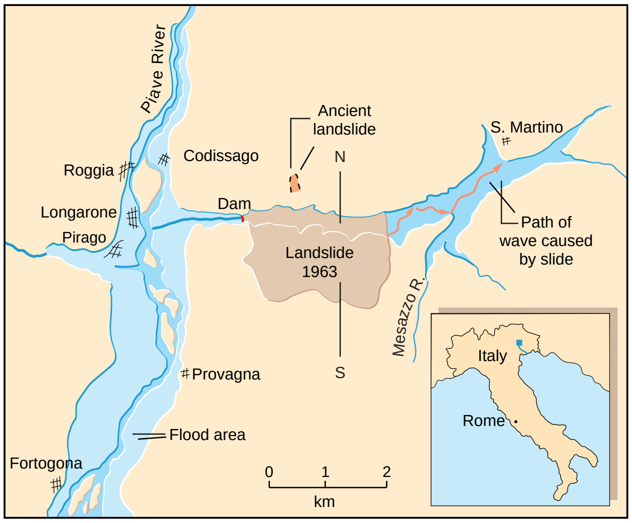



**FIGURE 11.2** **Accelerated mass movement resulting from deforestation** in Madagascar is vividly shown in these diagrams and photograph. As a consequence of removing the forests, numerous landslides formed and deep gullies eroded into the hillsides and fed sediment into adjacent streams. The ocean around Madagascar is colored red by the silt eroded from the recently deforested areas. *(Photograph by National Geographic Society)*

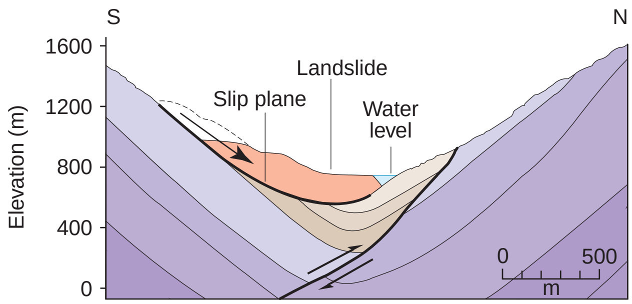
slope and splashed into the reservoir. It produced a wave of water more than 100 m high that swept over the dam and rushed down the valley, destroying everything in its path for many kilometers downstream. The entire catastrophic event, including the slide and flood, lasted only 7 minutes, but it took approximately 2600 lives and caused untold property damage. Several adverse geologic conditions contributed to the slide. Compare these conditions with the list of important factors just discussed. The rocks in the mountainside were weak limestone interbedded with thin layers of clay. The beds were inclined steeply toward the reservoir, creating inherent planes of weakness in the bedrock beneath the slope. Finally, it was the rising water level in the reservoir, saturating the adjacent soil and rock along the banks, that reduced the slope's cohesiveness and caused the slide.

(A) Longarone before the flood.




**(B)** Longarone is downstream from a a dam with a larger reservoir. In 1963, a large landslide into the reservoir created a huge wave that swept away part of the town.

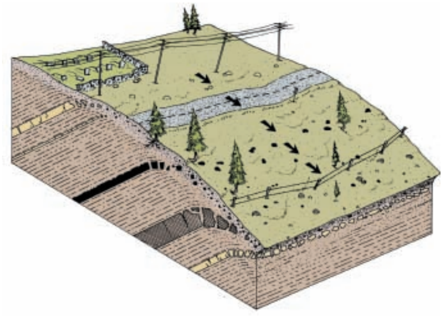
**(C)** Longarone after the landslide drove flood waters into the town.



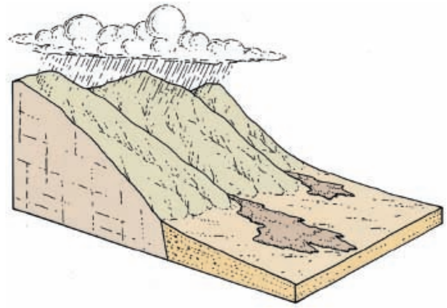

**(D)** Cross section through the Vaiont landslide shows the role played by a tilted succession of weak sedimentary rocks.

**FIGURE 11.3** **The Vaiont Dam disaster** is illustrated in this map, cross section, and photographs. The map shows the location of the landslide and the area covered by the resulting flood. The photographs show part of the town of Longarone, Italy, before and after the flood.

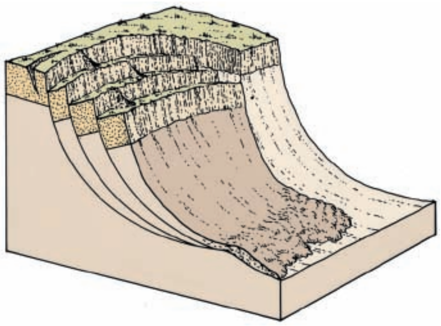
Landslides are natural processes and constantly occur, but as slopes are artificially modified for building sites and roads, the magnitude and frequency of mass movement increases greatly. As a result, millions of dollars in property are lost each year. Careful geologic investigations and proper land-use planning could greatly reduce these losses. However, it also takes stringent laws that are enforced to make a real difference. Landowners often object to regulations that limit their ability to sell their property. This right has to be balanced with the need to protect the buyers and to protect the government (and its tax-paying citizens) from the need to pay for the eventual damages. As a result of our inability to predict all landslides, millions of dollars in property are lost each year. Careful geologic investigations and proper land-use planning could greatly reduce these losses.



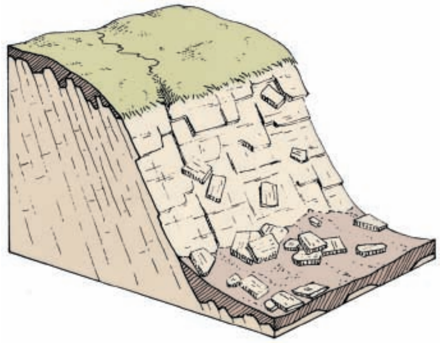
**(A)** Creep is the slow downslope migration of soil and loose rock fragments resulting from a variety of processes, including frost heaving.



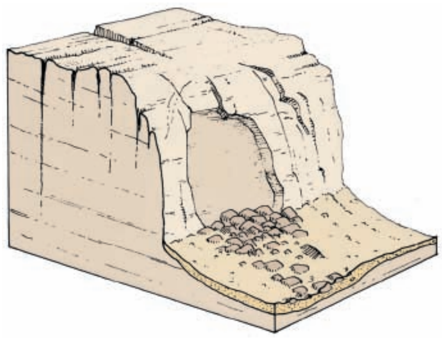
**(B)** A debris flow is the rapid flow of a mixture of rock fragments, soil, mud, and water. The mixture generally contains a large proportion of mud and water.



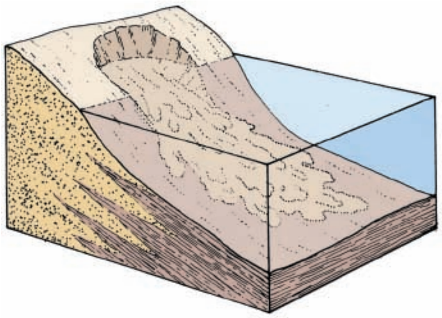
**(C)** Slump is the slow or moderately rapid movement of a coherent body of rock along a curved rupture surface. Debris flows commonly occur at the end of a slump block.



**(D)** A rockslide is the rapid downslope movement of rock material along a bedding plane, joint, or other plane of structural weakness.



**(E)** A rockfall is the free-fall of rock from steep cliffs.



**(F)** Subaqueous slope failures form on steep submarine slopes involving clasts of all sizes.

**FIGURE 11.4** **Mass movement** takes various forms, all of which produce slope retreat and enlarge valleys. Examples of various types of mass movement are illustrated in the diagrams.

## TYPES OF MASS MOVEMENT

Many types of mass movement can be recognized on the basis of the behavior of the material and the mechanics of movement. The most important are (1) creep, (2) debris flows, and (3) landslides.

**Mass movements** include all types of slope failure. Because of their potential for destruction, such movements have been studied extensively by engineers and geologists. As a result, they have been classified in various ways, depend-

**FIGURE 11.5** **Creep,** the slow downslope movement of soil and rocky debris, is a common phenomenon on slopes. This photo shows how creep downhill bent the upper edges of these stratified rocks to the right.

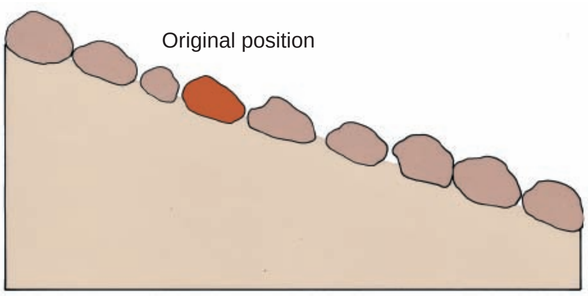
ing on the type of motion, type of material involved, and rate of movement (Figure 11.4).

## Creep

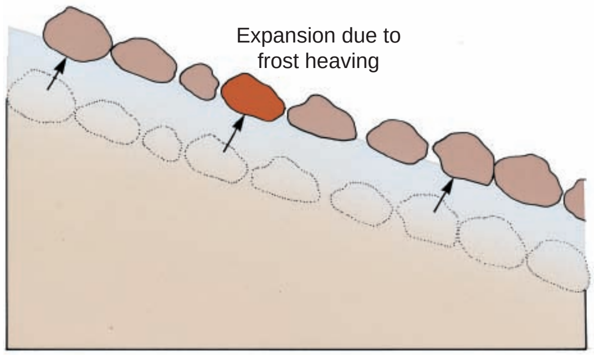
**Creep** is an extremely slow, almost imperceptible downslope movement of soil and rock debris that results from the constant minor rearrangement of the constituent particles (Figure 11.4A). The motion is so slow that observing it directly generally is difficult, but it is expressed in a variety of ways. On weakly consolidated, grass-covered slopes, evidence of creep can be seen as bulges or low, wavelike swells in the soil. In road cuts and stream banks, creep can be expressed by the bending of steeply dipping strata in a downslope direction or by the movement of blocks of a distinctive rock type downslope from their outcrop (Figure 11.5). Additional signs of creep include curved tree trunks and tilted posts, deformed roads and fence lines, and damage to retaining walls. The slow movement of large blocks of bedrock (block slides) can be considered a type of creep.

**How is creep expressed on a hillside?**

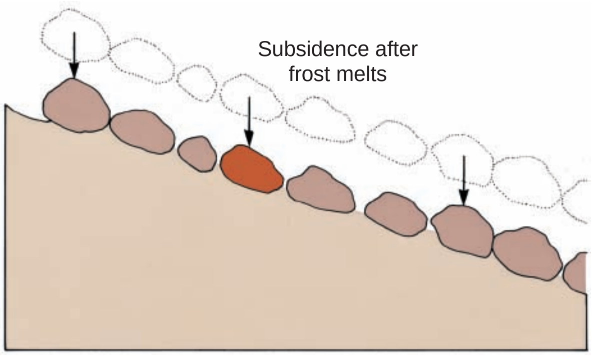
Many factors combine to cause creep, but the heaving process that results from the alternating expansion and contraction of the loose rock fragments in the regolith is probably the most important. The heaving process is accomplished in two principal ways: (1) by wetting and drying and (2) by freezing and thawing. In both instances, the regolith expands and shifts upward perpendicular to the hill slope. When it contracts, it settles back vertically under the force of gravity. With each cycle of expansion and contraction, each particle of rock comes to rest slightly downslope from its original position (Figure 11.6). Repeated expansion and contraction cause the particles to move downslope in a zigzag path. Freeze-thaw cycles are most numerous in regions where the temperature regularly crosses the freezing point. Therefore, creep is facilitated by cold climates. Cycles of wetting



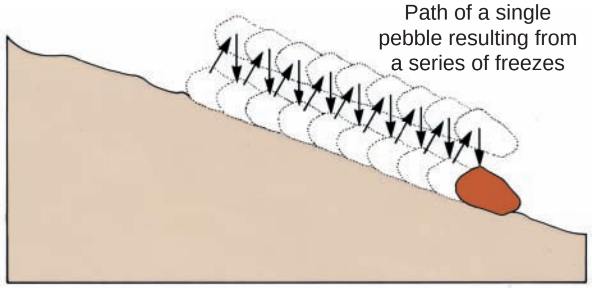

**(A)** Water seeps into the pore spaces between fragments of loose rock debris.




**(B)** As the water freezes and expands, the soil and rock fragments are lifted perpendicular to the ground surface.




**(C)** As the ice melts, gravity pulls the particles down vertically, displacing them slightly downhill.




**(D)** Repeated freezing and thawing cause a significant net displacement downslope.

**FIGURE 11.6 Creep can result from repeated expansion and contraction of the regolith.** With each cycle, there is a net downslope displacement of all loose material.

**In what parts of the world would you most likely find solifluction?**

and drying will occur in greatest number where heavy precipitation alternates with periods of desiccation.

Many other factors also contribute to creep. Growing plants exert a wedgelike pressure between rock particles in the soil and thus cause them to be displaced downslope. Burrowing organisms also displace particles, and with each movement, however slight, the force of gravity pulls the particles downslope. In addition, creep can be facilitated by undercutting from rain runoff and streams, increased loads of rainwater and snow, and disturbance of slope surfaces by earthquakes and construction by humans.

Studies in various parts of the world show that the rate of creep is highly variable, but some general patterns have been discovered. On moderately steep slopes (10° to 15°), a rate of 1 to 2 mm/yr is common in humid temperate regions. In semiarid regions with cold winters, creep reaches an average of 5 to 10 mm/yr.

**Solifluction** (soil flowage) is a special type of creep. It is common in polar regions, where groundwater in the pore spaces of soil and rock is permanently frozen (Figure 11.7). The layer of permanently frozen ground is called the **permafrost** layer. It ranges from less than a meter to several hundred meters thick and occupies some 20% of the world's land. The presence of permafrost presents some special conditions for the downslope movement of regolith. During the spring and early summer, the ground begins to thaw from the surface downward. Because the meltwater cannot percolate downward into the impermeable permafrost layer, the upper zone of soil becomes completely saturated, and large areas of the regolith will flow slowly down even the gentlest slopes. These hillsides are covered by lobes of moving debris and look like melted wax on a candle. Solifluction can also occur

**FIGURE 11.7** **Solifluction** is a major type of mass movement in cold polar regions and in some high mountains. On this hill in Alaska, the water-saturated regolith moves slowly downslope like a viscous fluid to form a series of lobate terraces. *(Courtesy of Emily Binnian, USGS/EROS Data Center)*

**(A)** Debris flows in Coast Ranges of California have stripped away vegetation and exposed the light-colored sedimentary rocks.

**(B)** Debris flow from the Lemhi Range, Idaho, for a broad lobe at the mouth of a narrow canyon. *(Courtesy of U.S. Department of Agriculture)*

**FIGURE 11.8** **Debris flows** are rapidly moving slurries of rock fragments, mud, and water.

in temperate regions in nonfrozen soil if a sufficient amount of water accumulates in the upper soil. Once liquefied the soil can start moving downslope.

## Debris Flows

**Debris Flows**

**Debris flows** consist of mixtures of rock fragments, mud, and water that flow downslope as viscous fluids (Figure 11.8). They are commonly mislabelled mudslides. Movement can range from a flow that is similar to the flow of freshly mixed concrete to one that is similar to the flow of a stream of mud, in which rates of mudflow are nearly equal to those of running water. Debris flows are a common type of mass movement that generally occur during intense rainfall. They commonly begin on steep hill slopes as soil slumps that soon liquefy and flow at speeds as great as 50 km/hr. They are capable of transporting huge boulders, cars, and buildings. The consequences of a debris flow can be catastrophic if human habitation lies in its path. The reason for the high velocity of flow is the presence of large amounts of water that penetrate and soak into the regolith. Water acts as a lubricant by decreasing the friction between grains, and it adds weight to the mass because it replaces the air in the open spaces between the fragments. Therefore, the more water present, the greater the speed of the flow.

**Why do debris flows move so quickly and so far from their sources?**

A new type of debris flow is created on mine dumps where unstable slopes of mine waste accumulate at the angle of repose for dry rock fragments. Perhaps the best known, and certainly one of the most tragic, was the disastrous flow of 1966 that destroyed the village school at Aberfan, South Wales, with the loss of 140 lives. The debris flow had its origin in a large mine dump 40 m high. During a period of heavy rain, the debris became saturated with water and flowed down into the valley, covering a school and adjacent buildings.

A volcanic debris flow is called by its Indonesian name **lahar** (Figure 11.9). Many occur because the abundant loose pyroclastic material that accumulates on the flanks of a steep-sided volcano is inherently unstable. During explosive eruptions, the material commonly becomes saturated by rain or by melting snow warmed by volcanic heat or from water expelled from a crater lake. Lahars are especially dangerous because they travel at high velocities and can flow for great distances. The explosive eruption of Mount St. Helens, for example, triggered several large mudflows that flowed many kilometers down the Toutle River (Chapter 21). Other lahars from prehistoric eruptions of Mount Rainier in Washington traveled more than 80 km. More recently, on November 13, 1985, a lahar raced down the slopes of the ice-capped Andean volcano called Nevado del Ruiz at speeds of more than 150 km/hr. The lahar roared down the Lagunillas River valley, completely destroying the city of Armero, Colombia, 50 km away. It buried more than 25,000 people—90% of the city. This lahar was a watery mass of mud 40 m deep traveling 40 km/hr through town. Nothing could escape it; humans and livestock were engulfed and swept away by the slurry of mud. Because it took more than an hour for the flow to reach Armero, a single telephone call from an observer nearer the mountain could have averted the human tragedy.

**How are lahars different from other kinds of debris flows?**

**Mudflows** are a variety of debris flows that consist mostly of small silt and clay-sized particles. Mudflows almost invariably result from an unusually heavy rain or a sudden thaw. Their water content can be as much as 30%. As a result of the predominance of fine-grained particles and the high water content, mudflows typically follow stream valleys. They are common in arid and semiarid regions and typically originate in steep-sided gullies where there is abundant loose, weathered debris (Figure 11.8). If they reach a mountain front, they spread out in the shape of a large lobe, or fan. Because of their density, mudflows can transport large boulders by "floating" them over slopes as gentle as 5°, and they have been known to move houses and barns from their foundations. Many disastrous "landslides" in southern California are really mudflows that move rapidly down a valley for considerable distances. Mudflows vary in size and rate of flow, depending on water content, slope angle, and available debris. Many are more than 80 km long.

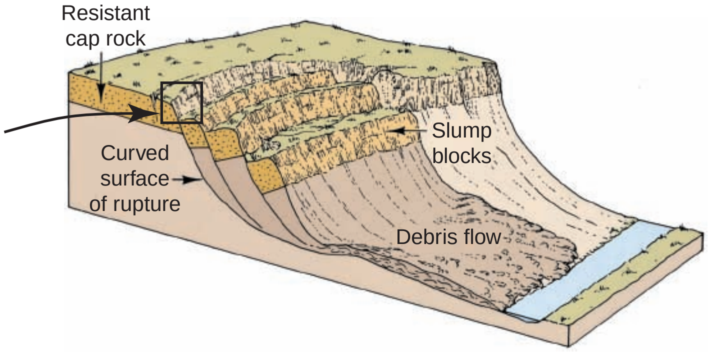
**FIGURE 11.9** **These light-colored lahars** from the Mt. Pinatubo volcano in the Philippines filled river valleys with flowing volcanic debris moving at speeds of over 30 km/hr. Most of the Pinatubo lahars were triggered by torrential rains from typhoons that mobilized loose volcanic ash on the flanks of the volcano. Fifty thousand homes were destroyed, but only a few hundred deaths were reported because of the advance warning provided by volcanologists. Lahars are still being spawned on the volcano, twelve years after the eruption. *(Yann Arthus-Bertrand/CORBIS)*

Illustrations of a special type of mudflow are found in the St. Lawrence valley in eastern Canada and in various parts of Scandinavia. In both regions, marine mud deposited near the margins of receding glaciers has a remarkable property known as "sensitive clay" or "quick clay." The sediment particles are loosely packed and consequently have a high water content. With only a slight disturbance, the material can become liquefied, or "quick" (transformed from a weak solid to a viscous fluid). The material can flow rapidly, even on very gentle slopes, once this change takes place. Disastrous flows of quick clay have affected several settlements along the valley of the St. Lawrence. Large masses of clay may become liquefied completely and flow as fast as a river.

## Landslides

Although the vague term **landslide** has been applied to almost any kind of slope failure, true landslides involve movement along a well-defined slippage plane. Landslides, therefore, differ from creep and debris flows in their mechanics of movement. A landslide block moves as a unit (or series of units) along a definite fracture (or system of fractures), with much of the material moving as a

**(A)** This photograph shows the upper part of a landslide in California, where homes were displaced along the curved rupture surface of the slump block. *(Courtesy of Geophoto)*




**(B)** Landslides occur along rather well-defined slippage surfaces. Large blocks slump and rotate downslope, and many grade into debris flows at their lower margins.

**(C)** This landslide along a hillside in Hong Kong destroyed four major roads and many buildings. As development continues, so will devastation from landslides. *(Courtesy of C. Fletcher)*

**(D)** A landslide into a harbor in Hong Kong. Note the trucks and cars in the upper part of the slide. *(Courtesy of C. Fletcher)*

**FIGURE 11.10** **Landslides** are a significant kind of mass movement that have discrete planes or rupture surfaces along which rocks slip or slide downhill. They are often extremely destructive where human development encroaches on hill slopes as seen in these three examples.

large **slump block** (Figure 11.10). The detached block leaves behind a distinct curved incision, or scar. The slippage plane is typically spoon-shaped. As the block moves downward and outward, it commonly rotates so that bedding or other identifiable surfaces are tilted backward toward the source (Figure 11.10). In the lower part of the slump block, part of the displaced material may move as a debris flow. Several slippage planes commonly develop in the same slide, so the top of the slump block is broken into a series of steps, or small terraces. The characteristic scar, tilting of bedding or other surfaces, and jumbled, poorly drained small hills formed by previous slides serve to identify terrains that are prone to landslides.

Landslides are common phenomena and occur on a small scale nearly everywhere. Large slides are less numerous, but they commonly develop on steep slopes of weak shale. They can move in a matter of seconds or slip gradually over a period of weeks and months.

**Landslides**

Many landslides come to rest on a valley floor and often dam the stream flowing through the valley, forming a lake behind them. Such lakes are temporary because the impounded water soon overflows the barrier and rapidly erodes through the unconsolidated rock debris. This sequence may result in catastrophic flooding downstream as the lake is almost instantly drained. Many other landslides are started by earthquakes.

The term **rockslide** is used to denote the rapid movement of a large block of rock along a bedding plane, joint, or other plane of structural weakness (Figure 11.4D). A large block may move en masse for a short distance, but generally there is some disintegration as the body moves downslope and breaks into smaller blocks of rubble. A rockslide may grade into a rockfall or into a landslide, with the entire mass moving as a coherent unit. Joint systems are critical in the development of rockslides because they are continuous fractures through massive rock that ultimately weaken the structure and lead to failure. Once the stress exceeds the cohesive strength along any plane in a rock, mass movement will be initiated. The

**FIGURE 11.11 The Frank rockfall,** Alberta, Canada, involved a huge mass of rock that broke away from the mountain face, completely burying the mining town of Frank, Alberta. Among the factors that contributed to this slope failure were the steepness of the mountain front, the dip of the bedding planes parallel to the mountain face, and underlying weak shale and coal beds. Mining activity may have triggered the movement. *(Courtesy of P. Nixon)*

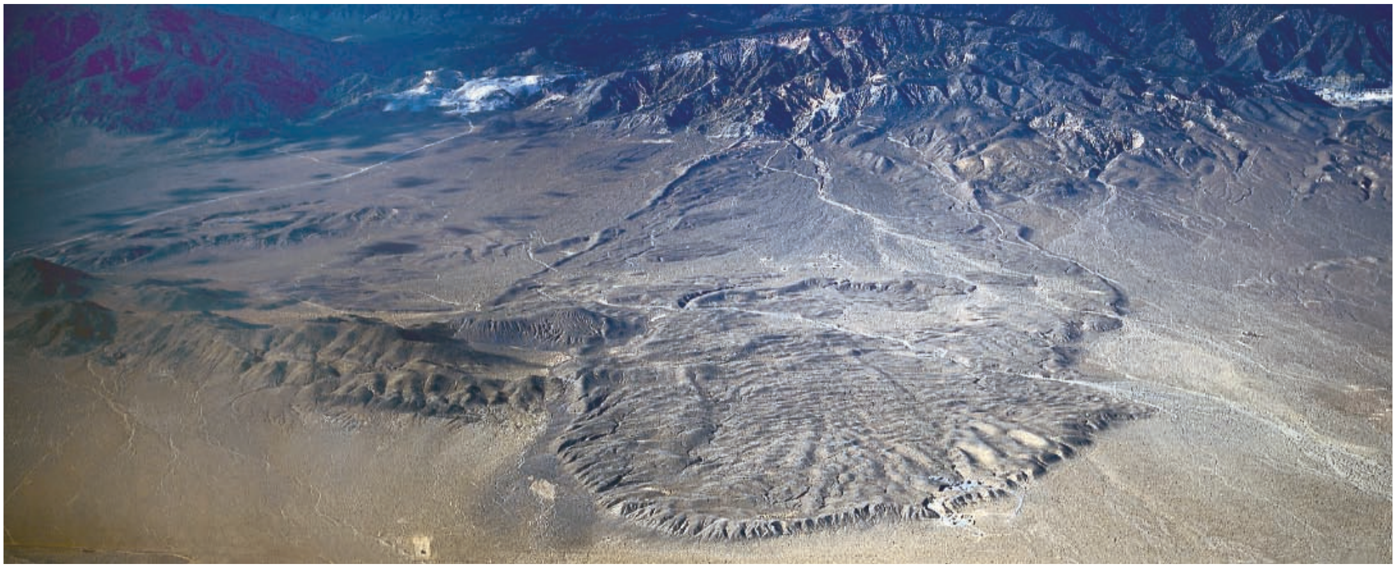


**FIGURE 11.12** **The Blackhawk slide** in southern California is a good example of a long rock avalanche. The vertical fall was only 1.5 km, but the flow spread out 9 km beyond the mountain front.

failure tends to be progressive because weakening along one joint will direct additional stress onto others.

Rockslides usually occur on steep mountain fronts, but they can develop on slopes with gradients as low as 15°. They are among the most catastrophic of all forms of mass movement. Sometimes millions of metric tons of rock plunge down the side of a mountain in a few seconds.

## Rock Flows and Avalanches

**Rockfalls** include the free-fall of a single fragment ranging from a small grain upward to huge blocks (Figure 11.4E). Over time, great quantities of small to moderate-sized fragments (a few centimeters to a few meters long) shower down from the face of a cliff and accumulate at the base as talus. Ice wedging is a major process in dislodging the fragments.

**Are all rapidly moving slope failures saturated with water like debris flows?**

Some rockfalls are much larger; a whole hillside may break off from the face of a mountain and evolve into a flowing mass of particles called a **rock avalanche** (Figure 11.11). Even though it flows like a fluid, a rock avalanche is dry. The huge rock avalanche that buried the town of Frank, Alberta, Canada, in 1903 was among the largest of such mass movements in the world. A gigantic wedge of limestone 400 m high, 1200 m wide, and 160 m thick crashed down from Turtle Mountain at 4:10 A.M. on April 29 and destroyed much of the town. Seven million tons of rock fell off the mountain face and swept over the valley floor, burying many homes, mines, railways, and 3200 acres of farmland to a depth of 30 m. The fall occurred in 100 seconds, dammed the Crowsnest River, and created a small lake at the base of Turtle Mountain.

A fascinating aspect of some large rock avalanches is their capacity to move rapidly and spread out over vast distances, seemingly violating the laws governing friction. Most dry rockfalls move horizontally less than twice the distance they fall, but some show remarkable mobility, traveling roughly 10 to 100 times as far as they fall. One of the more spectacular examples is the Blackhawk "slide" in the Mojave Desert about 135 km east of Los Angeles (Figure 11.12). This rock avalanche occurred about 17,000 years ago when a large part of Blackhawk Mountain collapsed and a mass of rock debris fell about 1.5 km down the mountainside and spread out 9 km beyond the mountain front. The great avalanche came to rest as a huge lobe on the almost flat surface of the valley floor. The velocity of movement is estimated to have been 120 km/hr.

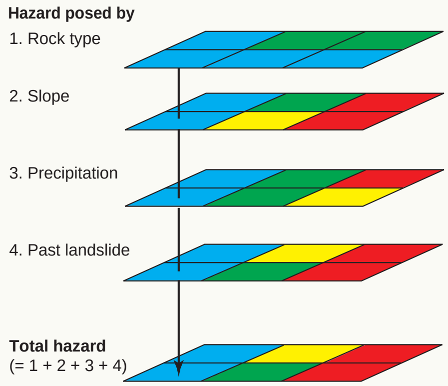
# State of the Art — Landslide Hazard Maps and GIS

Landslides and other types of slope failures are some of the most damaging of all geologic hazards, even though they are not as dramatic as earthquakes or volcanic eruptions. Each year more than two billion dollars of damage results from landslides in the United States alone. As a consequence, some governments have devoted significant efforts to understanding slope failures and to preventing some of the damage. Only a few things can be done to stop natural landslides, but much can be done to prevent people from living and developing properties where landslides are a threat.

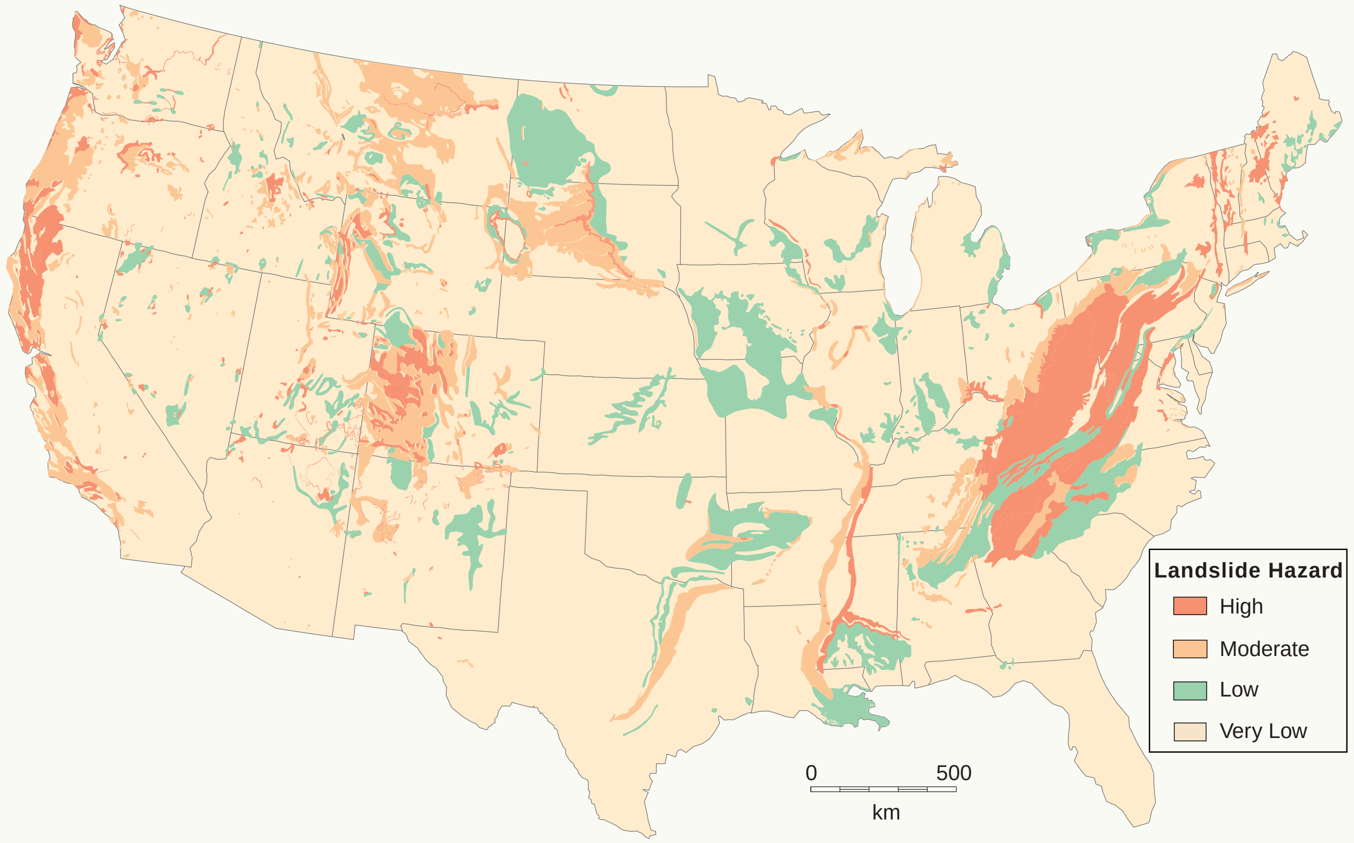
One tool used in this effort is the development of landslide hazard maps. Such maps show the relative risk of a landslide. Modern hazard maps are constructed using *Geographic Information Systems (GIS)*. Geographic Information Systems use "layers" of computerized maps. Each spot on a map layer represents a specific property, for example, rainfall, elevation, angle of slope, or any other parameter that can be measured (or calculated) in an area.

What types of information would be useful in predicting where landslides might occur in the future? By reviewing the information in this chapter, you should be able to come up with a list of important factors. Four very important factors are slope, precipitation, past occurrence of landslides, and rock type.

Elevation above sea level is not important, but the slope of a hillside is very important. The steeper the slope, the greater the chance for landslides. The slope can be calculated from a topographic map and is recorded on a grid for each spot in the map area. Precipitation is also important. Water adds to the weight of the material in a slope, reduces its cohesiveness and lubricates flowing materials. Precipitation is measured at many meteorological stations and estimated between the stations so that it can also be represented as a grid of values on a map.




A hazard value is assigned to each spot on the map for each of these separate factors. Then they are, in effect, added together to make a composite map of the overall landslide hazard, like the one shown here. Locate your area and compare the relative hazard with your understanding of local topography and precipitation.




*(Courtesy of U.S. Geological Survey and Jonathan Godt)*

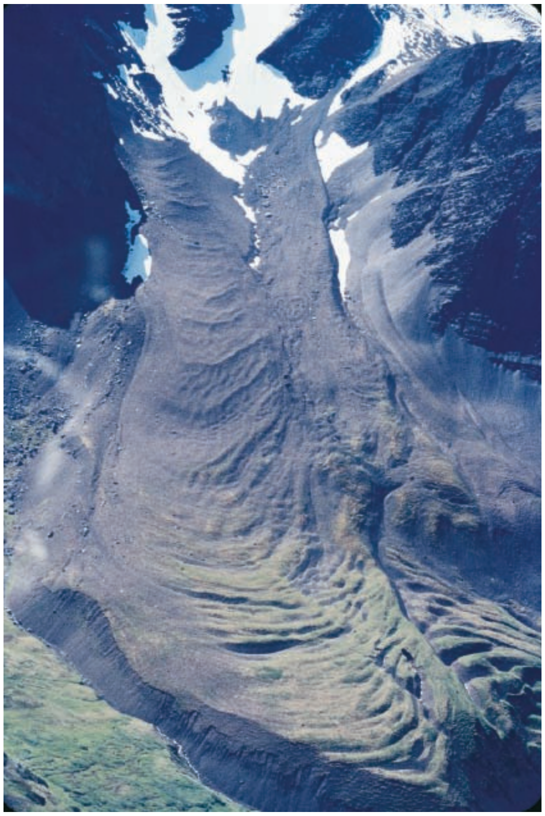


**FIGURE 11.13** **A rock glacier** in the Canadian Rockies, British Columbia, illustrates many features of this type of mass movement. Note the long tongues of moving rock debris and the wrinkled surface resulting from this flow of rock fragments and ice. *(Courtesy of Lehi Hintze)*

Several theories have been proposed to explain how a dry mass of rock debris can flow like a fluid. Some consider that the debris moves over a cushion of compressed air beneath it. Others think that the vibration of the fragments lowers the friction between them and allows them to move more freely. This acoustic fluidization permits the mass of debris to flow like a liquid. Laboratory experiments show that vibrating sand has mechanical properties quite different from ordinary sand and can be "fluidized" by the vibrations.

## Other Types of Slope Failures

**Rock glaciers** are long, tonguelike masses of angular rock debris that resemble glaciers in general outline and form. The surface of a rock glacier is typically furrowed by a series of parallel flow ridges similar to those in an advancing lava flow (Figure 11.13). Evidence of movement includes concentric ridges within the body, the rock glacier's lobate form, and its steep front. Measurements show that rock glaciers move as a body downslope at rates ranging from 5 cm a day to 1 m a year. Rock glaciers commonly occur at the heads of glaciated valleys and are fed by a continuous supply of rock fragments produced by ice wedging on the cirque wall. Excavations into rock glaciers reveal ice in the pore spaces between the rock fragments. Presumably, the ice is responsible for much of the flow movement. With a continuous supply of rock fragments from above, the constantly increasing weight causes the ice in the pore spaces to flow. Favorable conditions for the development of rock glaciers thus include steep cliffs and a cold climate. The steep cliffs supply coarse rock debris with large spaces between fragments in which ice can form; the cold climate keeps the ice frozen. Some rock glaciers may be debris-covered, formerly active glaciers.

**Subaqueous mass movements** affect large areas of the seafloor and are probably as common as those that occur on land (Figure 11.4F). They are especially active near deltas and convergent continental margins, where sediment accumulates rapidly and slopes are steep. Weak, water-saturated sediment may slide or flow downhill if a slope becomes unstable. Landslides with slump blocks are common along the continental slope (Figure 11.14). Sand flows and turbidity currents commonly move farther downslope and out across the abyssal plain, where they can damage submarine cables and other installations and are potential dangers to offshore oil fields. Submarine mass movements are often triggered by earthquakes or large storms, but the giant Storegga slide off the coast of Norway may have been set off by the break down of an icy cement called methane hydrate.

**Storegga Landslide**

Other spectacular submarine landslides have scarred the flanks of volcanic islands and seamounts, such as Hawaii (Figure 11.15). Recent detailed mapping of the ocean floor around the Hawaiian island chain shows that 17 giant submarine landslides have occurred off the Hawaiian Islands and 40 more surround the submerged volcanoes that extend from Kauai to Midway. These are among the largest landslides on our planet. One occurred when the northern part of the island of Oahu collapsed, sending debris 235 km out across the deep ocean floor. The horizontal extent of this landslide was more than 30 times the height of its fall. Huge blocks of debris, one the size of Manhattan Island, were swept across the ocean floor. Such an event must have created a tremendous tsunami, much larger than any created by an earthquake (see Chapter 15). The tsunamis created by giant submarine landslides in Hawaii swept debris onto slopes 300 m above sea level! Fragments of coral reefs are embedded in the mountainside of an adjacent island 365 m above sea level. Elsewhere, large scour marks and rip-up channels are found on other islands, indicating wave erosion far beyond anything witnessed in historic times.

**Where are subaqueous landslides most likely to occur?**

The process of giant submarine landslides and their associated tsunamis has been going on for many millions of years as volcanic islands grow from the seafloor and then collapse, with huge sections of the islands peeling off every 100,000 to 200,000 years. A long fault marked by a prominent escarpment has formed as a 300-km segment of the island of Hawaii slowly moves seaward. The block is moving at

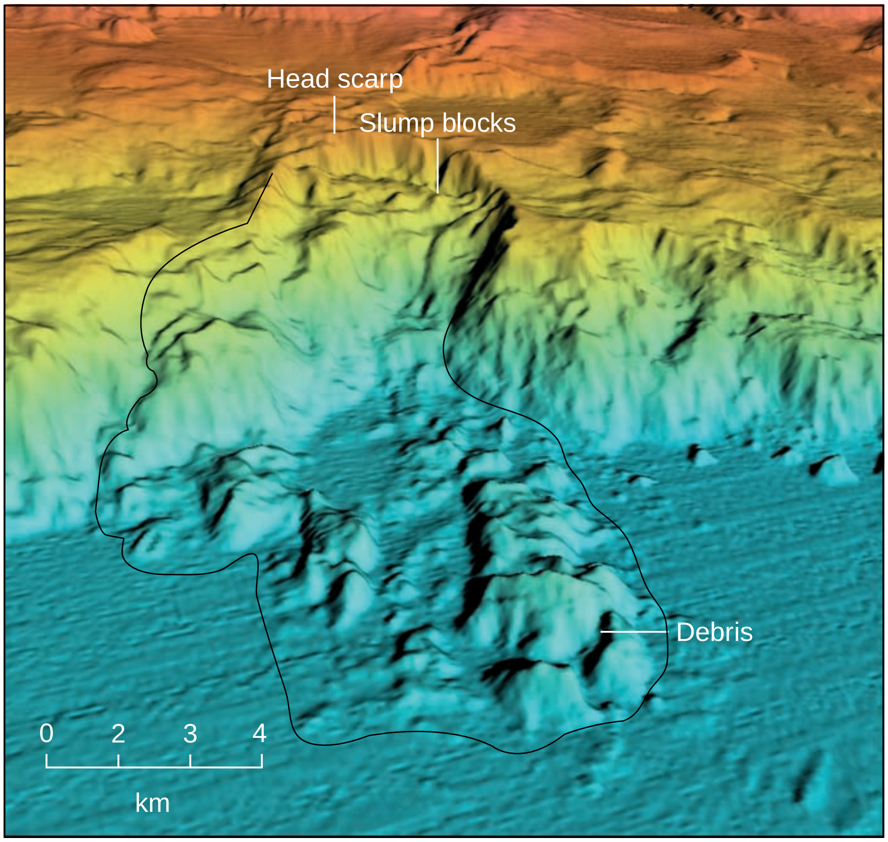



**FIGURE 11.14** **A subaqueous landslide** of the coast of central Oregon formed when tectonic activity made the slope too steep, as seen in this shaded relief map. A trail of debris extends downslope from the arcuate head of the landslide. The crescent-shaped head of the slope failure is 6 km across. Some of the blocks are hundreds of meters high and kilometers across. The collapse may have been triggered by an earthquake on the underlying subduction zone. *(Courtesy of W. Haxby and L. Pratson)*

a rate of more than 10 cm/yr (Figure 11.15). The giant landslides around Hawaii are almost certainly driven by the active magmatic systems inside the volcanoes (Figure 22.14). A magma chamber inflates when new magma enters from the mantle, and extrusion follows. Every day, lava flows dump millions of tons of new rock along the edge of the island. Eventually the stress and weight of the new land will trigger another great landslide and a catastrophic tsunami. Geologists agree that if the south side of the island breaks free suddenly, the results will be one of the worst disasters in recorded history, far beyond anything ever witnessed by humankind. The force of this catastrophic landslide crashing into the ocean could trigger a tsunami that could travel across the ocean at the speed of a jet plane inundating the coasts of the Pacific Rim. The south flank of the island of Hawaii is unstable. It is going to slide into the sea, and there is nothing we can do to stop it.

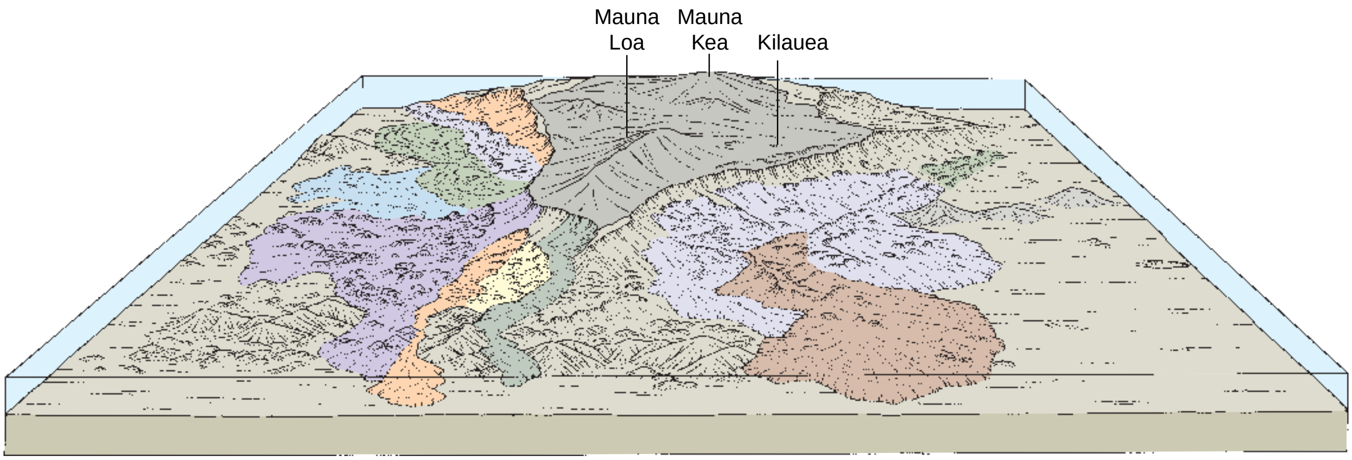



**FIGURE 11.15** **Vast subaqueous slumps** and flows flank the island of Hawaii and others in the seamount chain. Each major lobe is outlined. The names of the major shield volcanoes are also given.

**FIGURE 11.16** **Subsidence** is a major type of mass movement that affects roads and buildings, causing millions of dollars of damage each year. Repeated swelling and contraction of clays have caused this road in Colorado to buckle into waves like a roller coaster. *(Courtesy of D. C. Noe, Colorado Geologic Survey)*

## Land Subsidence

**Subsidence** is the downward movement of earth material lying at or near the surface. It differs from other types of mass movement in that movement is essentially vertical; there is little or no horizontal component. The primary force producing subsidence, of course, is gravity, but before gravity can act, other processes must operate to create space into which the earth can sink. The formation of caves by dissolution of rock by groundwater is a major cause of subsidence and is discussed in Chapter 13. The natural burning of combustible materials, such as peat and coal, in the subsurface also removes support for overlying rock, as does the melting of isolated blocks of glacial ice covered with glacial sediment. When swampy areas, such as Florida's Everglades, are drained, bacteria can oxidize the organic materials to make water and carbon dioxide gas. The loss of carbon in the soil can cause subsidence of several centimeters per year. Lava tubes are also areas of potential subsidence.

Examples of subsidence that result from human activity are varied and numerous. Where subsurface mining has removed large quantities of rock, subsidence into the abandoned workings may be so widespread that entire towns are abandoned. Subsidence may also follow the removal of fluids such as water, oil, or gas from the subsurface. A notable example is the subsidence of buildings in Mexico City because of the excessive pumping of groundwater from aquifers below them (see Figure 13.29). Subsidence like this also occurred in arid southern Arizona. Since 1900, a tremendous amount of groundwater was pumped from wells to provide for the rapidly expanding metropolitan areas and for agriculture. In some areas 500 times the amount of water that naturally replenished the groundwater system was withdrawn and water levels in some wells dropped by 150 m . Fissures ruptured the surface when the water was removed and the loose sediment compacted unevenly. The fissures typically form in linear swarms, with individual fissures as much as 1 m wide. A total area of more than 7500 $km^2$ was affected. Since 1985, the problem has lessened because water has been imported to the arid valleys of southern Arizona through a system of canals. This imported water reduced the demand for groundwater and has also been used to artificially recharge the groundwater system. In Long Beach, California, pumping from the Wilmington oil field caused the surface to subside 10 m in 30 years. Pipelines, bridges, roads, and harbor facilities had to be modified to counter the effect of subsidence. The injection of water into the petroleum reservoir rock has now reduced subsidence in the area by raising the fluid pressure in the subsurface rock.

Perhaps the most devastating type of subsidence results from the expansion and contraction of clay-rich soils. The process may at first seem harmless enough, but the damage is very expensive. When dry, expansive soils are hard and strong,

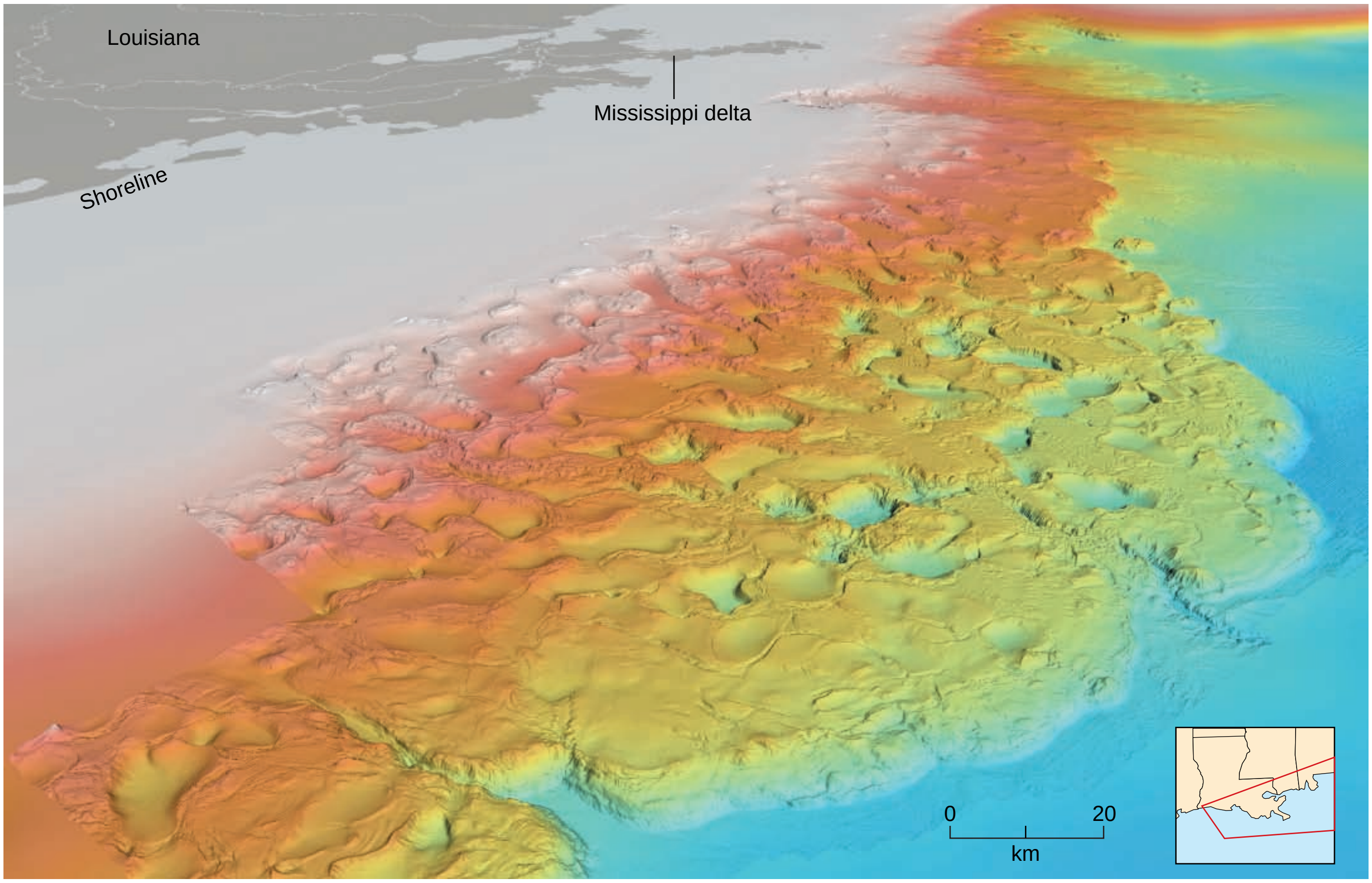


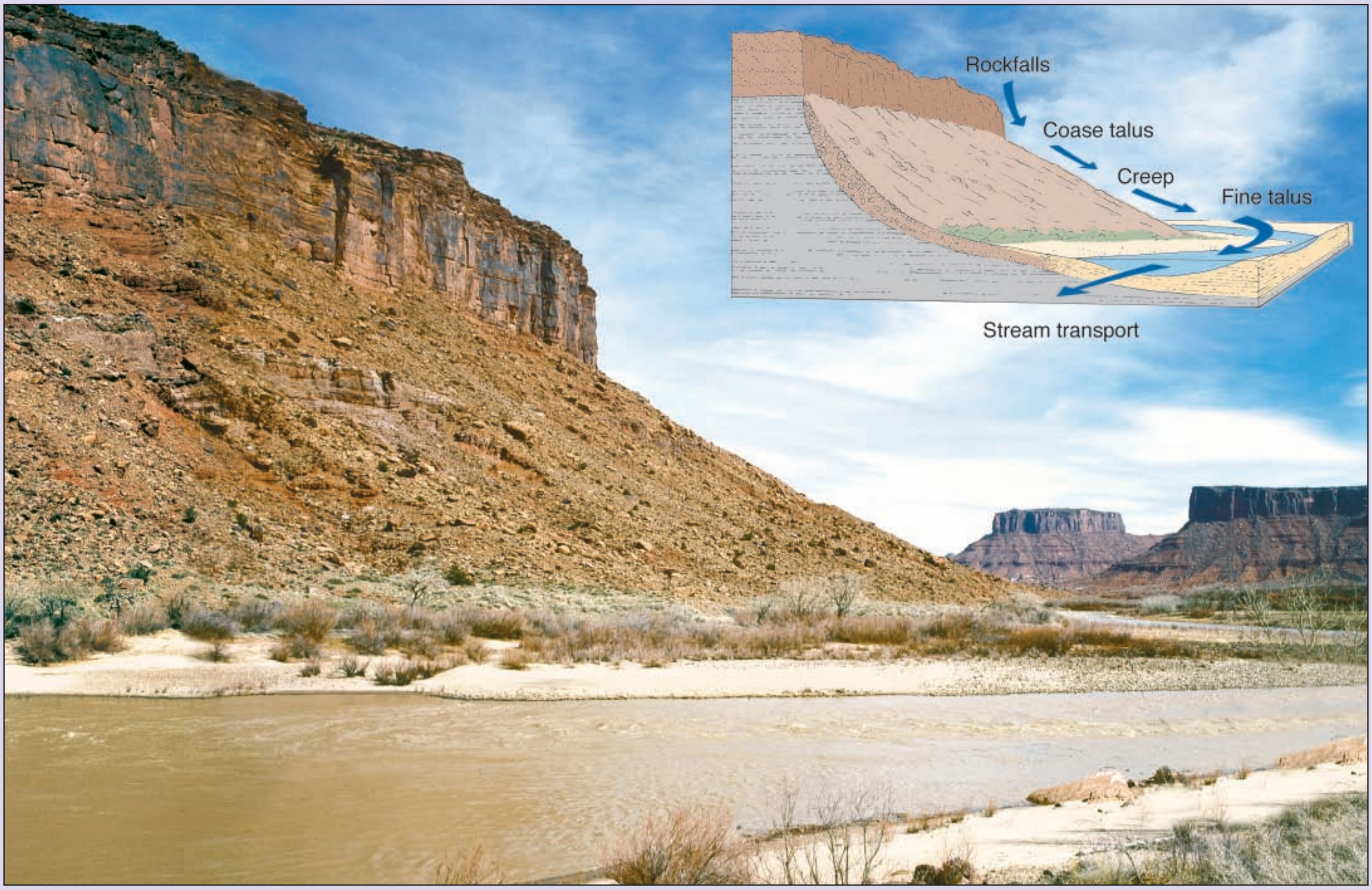

**FIGURE 11.17** **Subaqueous subsidence** occurred in thick deposits of sediment and salt near the delta of the Mississippi River. This pockmarked, Moonlike seascape was created by the shifting flow of the salt. The movement of salt created the high scarp on the right side of the map. Elsewhere, salt diapirs mushroomed into domes that eventually collapsed to make the bowl-shaped depressions as the salt flowed away. *(Courtesy of W. Haxby and L. Pratson)*

they are almost like rock, but when water is added, they expand and soften. Some clay-rich soil will expand more than 15 times its dry volume. Expansion of one and a half times the dry volume is common. When fully saturated with water, these soils lose much of their strength and become soft and slippery, much like lubricating grease. Upon drying, they shrink, causing the structures built upon them to collapse or buckle (Figure 11.16).

The shrinking and swelling of soils inflict enormous loss—of homes, commercial buildings, roads, and pipelines. The average annual loss in the United States is more than $2.3 billion—more than twice the loss from floods, hurricanes, tornadoes, and earthquakes combined. The damage from expansive soils is not sensational and draws little attention because it happens to individuals one by one throughout the country.

Less damaging to human constructions, but nonetheless spectacular, are the subsidence features formed on the ocean floor as a result of the flow of salt interlayed with marine sediments (Figure 11.17). Subsidence bowls several kilometers across dot the seafloor west of the Mississippi delta. They developed while salt diapirs welled upward (see Figure 7.18). The horizontal and vertical displacement of the salt caused adjacent areas to collapse.

# GeoLogic Slope Systems




If you carefully study this photograph and the accompanying sketch, you will soon see what geologists see as they look at a hillside. What makes the difference in slope angle? Why are the rocks in the cliff so jointed, whereas those below are not? What processes shaped the form of the cliff and slope? Abundant angular boulders litter the slope. Where did they come from? Do you see any systematic changes in particle size away from the cliff? Why is there a network of small gullies even in this arid region? Finally, does the stream at the foot of the hill play a role in the evolution of the slope?

## Observations

1. The cliff is receding by rockfalls.
2. Talus produced by frost action and rockfalls accumulates at the base of the cliff.
3. Larger blocks of rock occur on the higher slopes below the cliff.
4. Small rocks are found progressively downslope.
5. Near the river the slope is covered by mostly fine-grained material (sand) and a few very small blocks.
6. Sediments carried by the river are mostly sand-size particles (note sand bars) and mud (note muddy water).

## Interpretations

The basic elements of a **slope system** are shown in the diagram. Rockfalls from the cliff are produced by weathering and frost action along points in the sandstone formation. Coarse boulders accumulate at the base of the cliff. They are then transformed into smaller and smaller particles by mechanical and chemical weathering and move downslope by creep and other types of mass movement. Some debris may be collected by minor tributaries on the slope and move into the main stream by running water. The remainder of the fine-grained debris continues to move downslope by gravity (mostly by creep). It eventually enters the main stream and is carried away as sand, salt, and mud.

A slope is perhaps best thought of as an open and very dynamic system where gravity is the major source of energy. The system has inputs of rock material produced by physical and chemical weathering, and an output of fine rock fragments into a stream as shown above. Mass movement, together with weathering, and erosion of small gullies transport regolith and loose rock material downslope to a stream.

## KEY TERMS

angle of repose (p. 276)
cohesive strength (p. 276)
creep (p. 281)
debris flow (p. 284)
lahar (p. 284)
landslide (p. 285)
mass movement (p. 280)
mudflow (p. 284)
permafrost (p. 282)
rock avalanche (p. 288)
rockfall (p. 288)
rock glacier (p. 290)
rockslide (p. 287)
slope system (p. 294)
slump block (p. 287)
solifluction (p. 282)
subaqueous mass movement (p. 290)
subsidence (p. 292)

## REVIEW QUESTIONS

1. List the factors that affect mass movement on a slope.
2. How would you decide if a building lot was safe with regard to slope failure?
3. Calculate the downhill force on a boulder weighing 2.5 kg that rests on a slope inclined at 27°.
4. Why does deforestation cause unstable slopes and accelerate mass movement?
5. Describe four types of rapid mass movement.
6. List the types of mass movement that are dominantly slow.
7. List five ways in which creep is expressed on a hill slope.
8. What factors promote debris flows?
9. Speculate about the variety of ways that a lahar might be generated.
10. What causes creep?
11. What is solifluction? In what climates is it common?
12. How does subsidence differ from other kinds of mass movement?
13. What kinds of slope failures occur below sea level? What causes them?
14. Explain why slopes are considered open systems.

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## MULTIMEDIA TOOLS

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

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

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

- Animations of landslides and debris flows
- Slide shows with examples of mass movement
- A direct link to the Companion Website