CHAPTER

13 Unsafe Ground: Landslides and Other Mass Movements

Workers search for victims of a 2010 landslide in Taiwan, after debris from a rain-soaked hillslope buried a highway.

Chapter Objectives

By the end of this chapter, you should know . . .

- the characteristics and consequences of different types of mass movements (landslides).
- factors that determine whether a slope is stable or unstable.
- events that can trigger a mass-movement event.
- how landslide hazards can be identified, evaluated, and in some cases prevented.

13.1 Introduction

It was Sunday, May 31, 1970, a market day, and thousands of people had crammed into the Andean town of Yungay, Peru, to shop. Suddenly they felt the jolt of an earthquake, strong enough to topple some masonry houses. But worse was yet to come. This earthquake also broke an 800-m-wide ice slab off the end of a glacier at the top of Nevado Huascarán, a nearby 6.6-km-high mountain peak. As it tumbled down over 3.7 km, the ice disintegrated into a chaotic avalanche of chunks traveling at speeds of over 300 km per hour. Near the base of the mountain, most of the avalanche channeled into a valley and thickened into a churning cloud as high as a ten-story building, ripping up rocks and soil along the way. Frictional heating transformed the ice into water, which mixed with rock and dust to produce 50 million cubic meters of a muddy slurry viscous enough to carry boulders larger than houses. This mass, sometimes floating on a compressed air cushion that allowed it to pass without disturbing the grass below, traveled over 14.5 km in less than four minutes.

At the mouth of the valley, most of the debris overran the village of Ranrahirca before coming to rest and creating a dam that blocked the Santa River. But some shot up the sides of the valley and became airborne for several seconds, flying over the ridge bordering Yungay. As the town's inhabitants and visitors stumbled out of earthquake-damaged buildings, they heard a deafening roar and looked up to see a wall of debris burst above the nearby ridge. The debris engulfed the town and buried it. Only the top of the church and a few palm trees remained visible to show where Yungay once lay (Fig. 13.1a, b). Today, the site is a grassy meadow with a hummocky (irregular and lumpy) surface, spotted with crosses left by relatives mourning the 18,000 people entombed by the debris.

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People often assume that the ground beneath them is *terra firma*, a solid foundation on which they can build their lives. But the catastrophe at Yungay says otherwise. Much of the Earth's surface is unstable and capable of moving downslope, due to the pull of gravity, in seconds to weeks. Geologists refer to the downslope transport of rock, regolith (soil, sediment, and debris), snow, and ice as **mass movement**, or mass wasting. Like earthquakes, volcanic eruptions, storms, and floods, mass movements are a type of **natural hazard**, meaning a natural feature of the environment that can cause damage to living organisms and to buildings. Unfortunately, mass movement becomes more of a threat every year, because as the world's population grows, cities expand into areas of unsafe ground. Mass movement also plays a critical role in the rock cycle, as the first step in the transportation of sediment, and in the evolution of landscapes, as the most rapid means of modifying the shapes of slopes.

In this chapter, we look at the types, causes, and consequences of mass movement (both on land and under the sea), and the precautions society can take to protect people and property from its dangers. You might want to consider this information when selecting a site for your home or when voting on land-use propositions for your community.

13.2 Types of Mass Movement

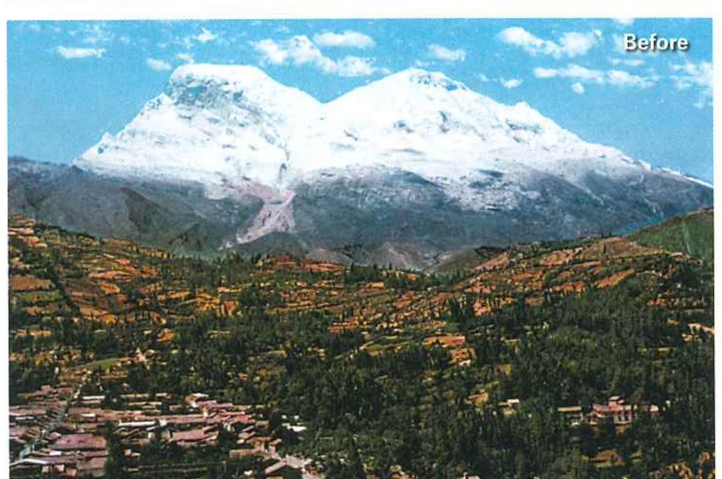
Most people refer to any mass movement of rock and/or regolith down a slope as a *landslide*. Geologists and engineers, however, find it useful to distinguish among different kinds of landslides based on four features: (1) the type of material involved (rock or regolith); (2) the velocity of movement (slow, intermediate, or fast); (3) the character of the moving mass (coherent, chaotic, or slurry); and (4) the environment in which the movement takes place (subaerial or submarine). Below, we examine mass movements that occur on land roughly in order from slow to very fast (**See for Yourself M**).

Creep and Solifluction

Creep (also known as soil creep) refers to the slow, gradual downslope movement of regolith on a slope. Creep happens when regolith alternately expands and contracts in response to freezing and thawing, wetting and drying, or warming and cooling. To see how the process of creep works, let's focus on the consequences of seasonal freezing and thawing. In the winter, when water freezes, the regolith expands, and particles move outward, perpendicular to the slope. During the spring thaw, water becomes liquid again, and gravity makes the particles sink vertically and thus migrate downslope slightly (**Fig. 13.2a, b**). You can't see creep by staring at a hillslope because it occurs too slowly, but over a period of years, creep causes trees, fences, gravestones, walls, and foundations built on a hillside to tilt downslope. Notably, trees that continue to grow after they have been tilted display a pronounced curvature at their base (**Fig. 13.2c**).

In Arctic or high-elevation regions, regolith freezes solid to great depth during the winter. In the brief summer thaw, only the uppermost 1 to 3 m of the ground thaws. Since meltwater cannot sink into the permanently frozen ground, or permafrost, the melted layer becomes soggy and weak and flows slowly downslope in overlapping sheets. Geologists refer to this kind of creep as **solifluction** (**Fig. 13.2d**).

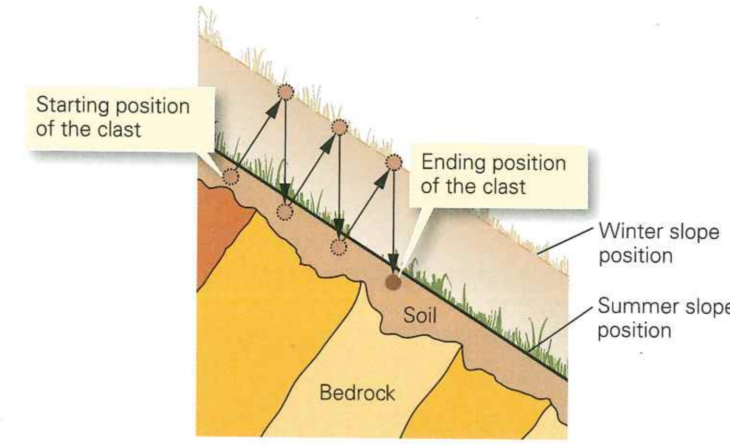
FIGURE 13.1 The May 1970 Yungay landslide disaster in Peru.



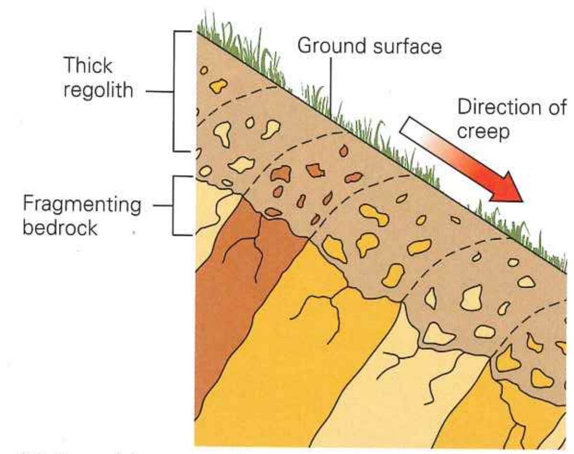
(a) Before the landslide, the town of Yungay perched on a hill near the ice-covered mountain Nevado Huascarán.

(b) The landslide completely buried the town beneath debris. A landslide scar is visible on the mountain in the distance.

FIGURE 13.2 The process and consequences of slow mass movements (creep and solifluction).

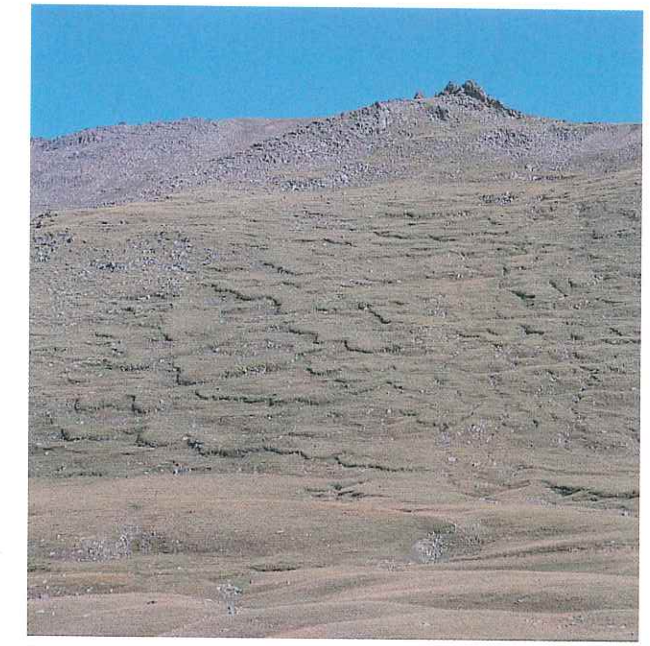


(a) Creep due to freezing and thawing: The clast rises perpendicular to the ground during freezing, and sinks vertically during thawing. After 3 years, it migrates to the position shown.



(b) As rock layers weather and break up, the resulting debris creeps downslope.

(c) Soil creep causes walls to bend and crack, building foundations to sink, trees to bend, and power poles and gravestones to tilt.



(d) Solifluction on a hillslope in the tundra.

Slumping

During the summer of 2011 after weeks of drenching rains, a 1.5-km-wide portion of a slope began to move down and out into the floor of Keene Valley, New York. The mass moved at only centimeters to tens of centimeters per day, but even at this slow rate, the accumulated displacement destroyed several expensive homes. The boundary between the moving mass and the unmoving land upslope evolved into a 5-m-high escarpment.

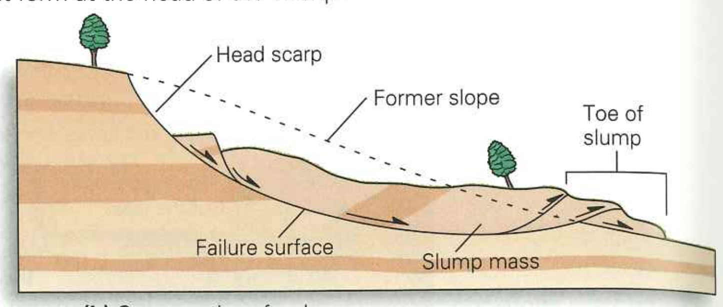
Geologists refer to such relatively slow-moving mass-movement events, during which moving rock and/or regolith does not disintegrate but rather stays somewhat coherent, as a **slump**, and they refer to the moving mass itself as a slump block (**Fig. 13.3a–d**). A slump block slides on a **failure surface**. Some failure surfaces are planar, but commonly they curve and resemble a spoon lying concave side up. The exposed upslope edge of a failure surface forms a **head scarp**, a new cliff face. Geologists refer to the downslope end of a slump block as the block's "toe." On a hillslope, the toe can move up and over the pre-existing land surface to form a curving ridge, but along sea coasts or river banks, the toe ends up in the water, where it eventually washes away. In some cases, the upslope and downslope ends of a slump block break into a series of discrete slices, each separated from its neighbor by a small sliding surface (**Fig. 13.3e**). Slumps come in all sizes, from only a few meters across to tens of kilometers across. They move at speeds from millimeters per day to tens of meters per minute.

Mudflows, Debris Flows, and Lahars

Rio de Janeiro, Brazil, originally occupied only the flatlands bordering beautiful crescent beaches that had formed

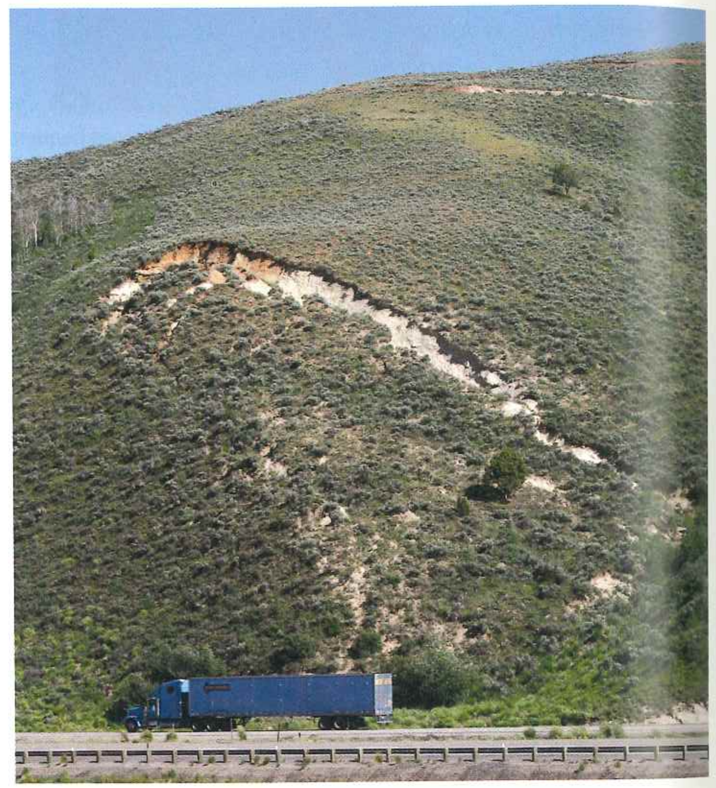
FIGURE 13.3 The process of slumping on a hillslope. Note the scarps that form at the head of the slump.

(a) A head scarp on the hillslope.

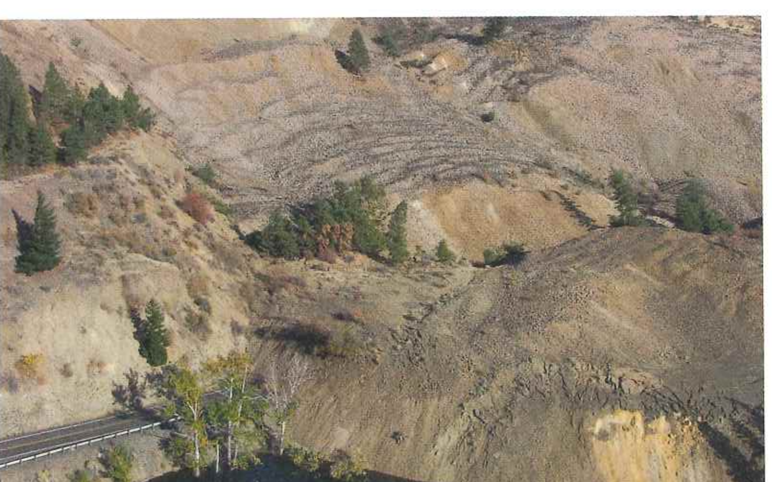


(b) Cross section of a slump.

(c) Slumping dumped sediment into this river in Costa Rica.



(d) A slump beginning to form along a highway in Utah.



(e) A 1-km-wide slump buried a highway and blocked a river in the Cascade Mountains of Washington in 2009.

between steep hills along the shore. But in recent decades, the population has grown so much that, in many places, densely populated communities of makeshift shacks cover the steep slopes. These communities, which have inadequate storm drains, were built on the thick regolith that resulted from long-term weathering of bedrock in Brazil's tropical climate. In 2011, particularly heavy rains saturated the regolith north of Rio, which turned into a viscous slurry of mud, resembling wet concrete, that flowed downslope. Whole communities disappeared overnight, replaced by a hummocky muddle of mud and debris. And at the base of the cliffs, the flowing mud knocked over and buried buildings of all sizes. Similar mass movements ripped away forests in nearby hills (**Fig. 13.4a**). Geologists refer to a moving slurry of mud as a **mudflow** or mudslide, and a slurry consisting of a mixture of mud and larger, pebble- to boulder-sized fragments as a **debris flow** or debris slide (**Fig. 13.4b**).

The speed at which mud or debris moves depends on the slope angle and on the water content. Flows move faster if they contain more water and are less viscous, and if they move on steeper slopes. On a gentle slope, drier mudflows move like molasses; but on a steep slope, low-viscosity, very wet mud may move at over 100 km per hour. Because mudflows and debris flows have greater viscosity than clear water, they can carry large rock chunks as well as houses and cars. They typically follow channels downslope and at the base of the slope they spread out into a broad lobe (**Box 13.1**).

FIGURE 13.4 Examples of mudflows and lahars.

(a) Mudslides of 2011 stripped away forests on hillslopes in Brazil.

(b) A recent debris flow in Utah. Note the chaotic mixture of rock chunks and mud.

(c) The aftermath of a lahar that flowed down the side of Mt. St. Helens following an eruption in 1982.

Particularly devastating mudflows spill down the river valleys bordering volcanoes. These mudflows, known as **lahars**, consist of a mixture of volcanic ash and water from the snow and ice that melts in a volcano's heat or from heavy rains (**Fig. 13.4c**; see Chapter 5). One of the most destructive lahars occurred on November 13, 1985, in the Andes Mountains in Colombia. That night, a major eruption melted a volcano's thick snowcap, creating hot water that mixed with ash. A scalding lahar rushed down river valleys and swept over the nearby town of Armero while most inhabitants were asleep. Of the 25,000 residents, 20,000 perished.

Rockslides and Debris Slides

In the early 1960s, engineers built a huge new dam across a river on the northern side of Monte Toc, in the Italian Alps, to create a reservoir for generating electricity. This dam, the Vaiont Dam, was an engineering marvel, a concrete wall rising 260 m (as high as an 85-story skyscraper) above the valley floor (**Fig. 13.5a**). Unfortunately, the dam's builders did not recognize the hazard posed by nearby Monte Toc. The side of Monte Toc facing the reservoir was underlain with limestone beds interlayered with weak shale beds. These beds dipped parallel to the surface of the mountain and curved under the reservoir (**Fig. 13.5b**). As the reservoir filled, the flank of the mountain cracked, shook, and rumbled. Local residents began to call Monte Toc *la montagna che cammina* (the mountain that walks).

After several days of rain, Monte Toc began to rumble so much that on October 9, 1963, engineers lowered the water level in the reservoir. They thought the wet ground might slump a little into the reservoir, with minor consequences, so no one ordered the evacuation of the town of Longarone, a few kilometers down the valley. Unfortunately, the engineers underestimated the problem. At 10:30 that evening, a huge chunk of Monte Toc—600 million tons of rock—detached from the mountain and slid downslope into the reservoir. Some debris rocketed up the opposite wall of the valley to a height of 260 m above the original reservoir level. The displaced water of the reservoir spilled over the top of the dam and rushed down into the valley below. When the flood had passed, nothing of Longarone and its 1,500 inhabitants remained. Though the dam itself still stands, it holds back only debris and has never provided any electricity.

Geologists refer to such a sudden movement of rock and debris down a nonvertical slope as a **rockslide** if the mass consists only of rock or as a **debris slide** if it consists mostly of regolith. Once a slide has taken place, it leaves a scar on the slope and forms a debris pile at the base of the slope. Slides happen when bedrock and/or regolith detaches from a slope, slips rapidly downhill on a failure surface, and breaks

BOX 13.1 CONSIDER THIS . . .

What Goes Up Must Come Down

Along the coast of California, waves slowly erode the land and produce low, flat areas called wave-cut benches (see Chapter 15). While this happens, tectonic motions slowly raise the land surface. When uplifted, these benches form small plateaus, or terraces. One such terrace lies at an elevation of 180 m above sea level, about 500 m east of the present-day beach at La Conchita; the west face of this terrace is a cliff-like bluff (**Fig. Bx13.1a**). Repeated slip along the San Andreas plate boundary has broken up the bedrock of the area, and fragments have weathered substantially, so the substrate of the terrace and bluff consists of weak clay and debris.

Relatively little vegetation covers the bluff or the terrace above. Rain that falls on the face of the bluff drains away quickly via a network of small, temporary streams. But the water falling on the terrace infiltrates into the ground, sinks down, and saturates clay and debris meters below the surface of the bluff, turning into very weak mud. When this happens, the weight of surface material causes the bluff to give way, and a mass of mud and debris flows downslope at rates of up to 10 m per second.

If the region of La Conchita were uninhabited, such mass wasting would just be part of the natural process of landscape evolution—gravity brings down land that had been raised by tectonic activity. But when downslope movements take place in La Conchita, it makes headlines, because on the modern wave-cut bench between the shore and the base of the bluff, developers built a community housing 350 people. In 1995, a mud and debris flow overwhelmed 9 houses at the base of the bluff. An even more devastating flow happened in 2005, burying 13 houses, damaging 23, and killing 10 people (**Fig. Bx13.1b, c**). These events have sent a clear message about the importance of reading the landscape before planning construction.

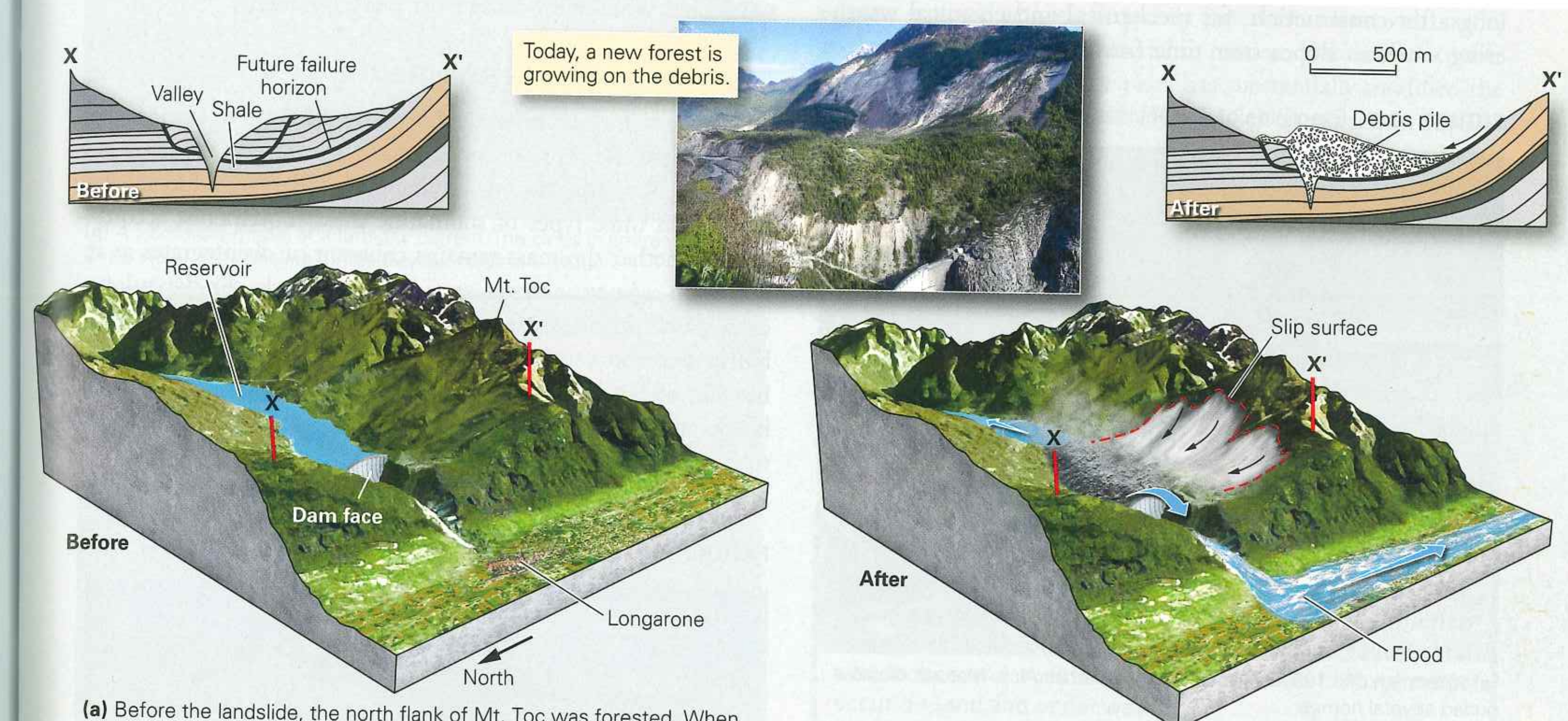
FIGURE Bx13.1 The 2005 La Conchita mudslide along the coast of California.

(a) A housing development was built in a narrow strip between the beach and steep cliffs.

(b) During heavy rains, the slope gave way and heavy mud flowed down, burying houses and taking several lives.

(c) Rescuers at the toe of the mudslide.

FIGURE 13.5 The Vaiont Dam disaster—a catastrophic landslide that displaced the water in a reservoir with rock debris.



(a) Before the landslide, the north flank of Mt. Toc was forested. When the reservoir filled, the slope became unstable. A shale bed a few hundred meters below the ground surface became a failure surface.

(b) 33 million cubic meters of debris slid and displaced water in the reservoir. The water surged over the dam and swept away a village in the valley below.

up into a chaotic jumble. Slides may move at speeds of up to 300 km per hour; they are particularly fast when a cushion of air gets trapped beneath, so there is virtually no friction between the slide and its substrate, and the mass moves like a hovercraft. Rockslides and debris slides sometimes have enough momentum to climb the opposite side of the valley into which they fell. Slides, like slumps, come at a variety of scales.

Avalanches

In the winter of 1999, an unusual weather system passed over the Austrian Alps. First it snowed. Then the temperature warmed and the snow began to melt. But then the weather turned cold again, and the melted snow froze into a hard, icy crust. This cold snap ushered in a blizzard that blanketed the ice crust with tens of centimeters (1–2 ft) of new snow. With the frozen snow layer underneath acting as a failure surface, 200,000 tons of new snow began to slide down the mountain. As it accelerated, the mass transformed into a **snow avalanche**, a chaotic jumble of snow surging downslope. At the bottom of the slope, the avalanche overran a ski resort, crushing and carrying away buildings, cars, and trees, and killing over 30 people. It took searchers and their specially trained dogs many days to find buried survivors and victims under the 5- to 20-m-thick pile of snow that the avalanche deposited (**Fig. 13.6a**).

What triggers snow avalanches? Some happen when a cornice, a large drift of snow that builds up on the lee side of a windy mountain summit, suddenly gives way and falls onto slopes below, where it knocks free additional snow. Others happen when a broad slab of snow on a moderate slope detaches from its substrate along an icy failure surface. *Wet* avalanches move as a slurry of solid and liquid water, whereas *dry* avalanches tumble as a cloud of powder (**Fig. 13.6b**).

Rockfalls and Debris Falls

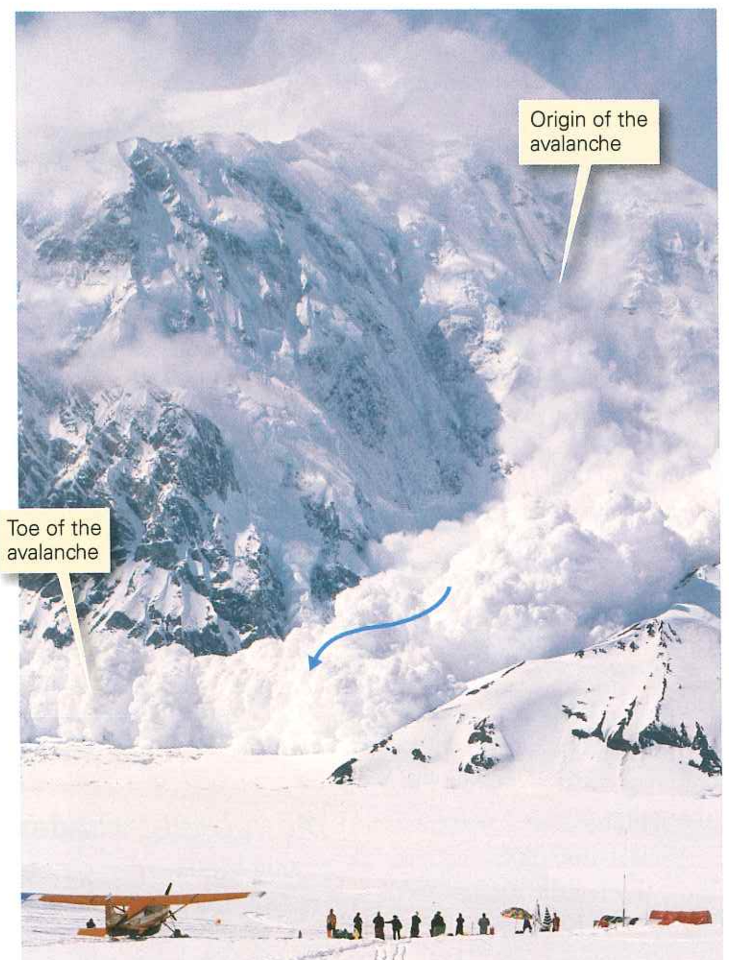
Rockfalls and **debris falls**, as their names suggest, occur when a mass free-falls from a cliff (**Fig. 13.7a, b**). Commonly, rockfalls happen when a body of rock separates from a cliff face along a joint. Friction and collision with other rocks may bring some blocks to a halt before they reach the bottom of the slope; these blocks pile up to form a **talus**, a sloping apron of rocks along the base of the cliff. Debris that has fallen a long way can reach speeds of 300 km per hour and may have so much momentum that it keeps moving as an avalanche-like cloud of fragments mixed with air when it reaches the base of a cliff. Large, fast rockfalls push the air in front of them, creating a short blast of hurricane-like wind. For example, the wind in front of a 1996 rockfall in Yosemite National Park flattened over 2,000 trees.

Did you ever wonder . . . why highway engineers erect "falling rock" signs?

Small rockfalls happen fairly frequently along steep highway roadcuts, leading to the posting of "falling-rock zone" signs. Such rockfalls commonly take place soon after construction because blasting and excavation leave loose rocks on the slope above the road. But rockfalls may continue long after construction, for mechanical and chemical weathering weakens slopes over time (see Interlude B). In fact, in temperate climates, rockfalls are common in the spring, after winter ice, which may cause frost wedging, melts.

FIGURE 13.6 Examples of avalanches.

(a) Aftermath of a 1999 avalanche in the Austrian Alps. Masses of snow buried several homes.



(b) A dry-snow avalanche in Alaska. It's a turbulent cloud.

Submarine Mass Movements

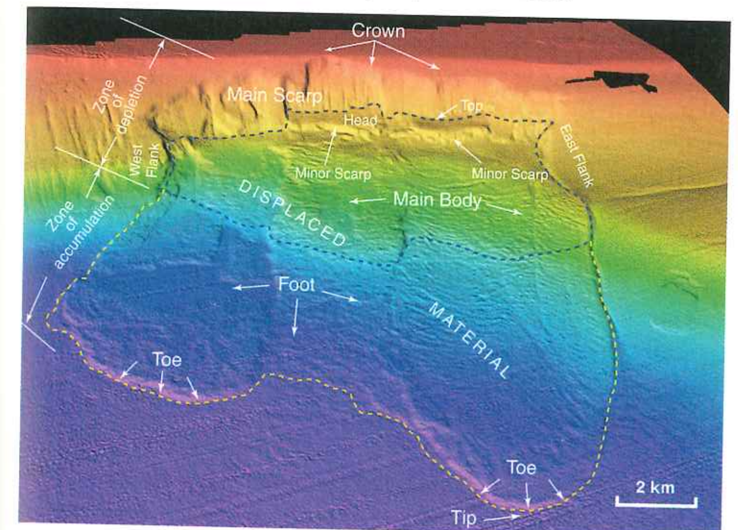
So far, we've focused on mass movements that occur subaerially, for these are the ones we can see most easily and that affect us the most. But mass wasting also happens underwater. Geologists distinguish three types of submarine mass movements, according to whether the mass remains coherent or disintegrates as it moves. In *submarine slumps*, semi-coherent blocks slip downslope on weak detachments. In some cases, the layers constituting the blocks become contorted as they move, like a tablecloth that has slid off a table. In submarine *debris flows*, the moving mass breaks apart to form a slurry containing larger clasts (pebbles to boulders) suspended in a mud matrix. And in *turbidity currents*, sediment disperses in water to create a turbulent cloud of suspended sediment that rushes downslope like an underwater avalanche (**Fig. 13.8a**).

FIGURE 13.7 Examples of rockfalls.

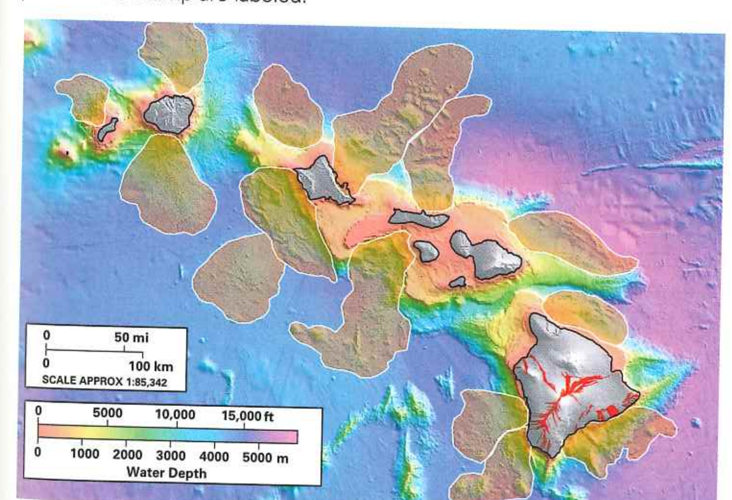
(a) Successive rockfalls have littered the base of this sandstone cliff with boulders. Note the talus at the base of the cliff.

(b) A large rockslide buried a portion of the forest bordering a lake in the Uinta Mountains, Utah.

(a) A laboratory model of a turbidity current. The cloud is entirely underwater and consists of fine clay suspended in water.



(b) A digital bathymetric map of a slip along the coast of California. The parts of the slump are labeled.



(c) A bathymetric map of the area around Hawaii shows several huge slumps, shaded in tan. The islands are grey.

FIGURE 13.8 Examples of huge submarine slumps and debris flows.

In recent years, geologists have used satellites as well as sonar to map out the extent of submarine landslides. The shapes of slumps and landslide deposits stand out on the resulting new generation of high-resolution sea-floor maps (**Fig. 13.8b**). Geologists have found that submarine slopes bordering both hot-spot volcanoes and active plate boundaries are scalloped by many immense slumps, because tectonic activity frequently jars these areas with earthquakes that set masses of material in motion. Debris from countless slumps over millions of years has substantially modified the flanks of the Hawaiian Islands (**Fig. 13.8c**). Significantly, passive-margin coasts are not immune to slumping, and immense slumps have been mapped along the coasts of the Atlantic Ocean.

Since a submarine slump can develop fairly quickly, and since its movement can displace a large area of the sea floor, it can trigger a tsunami. A huge slump called the Storegga Slide occurred west of Norway, along the Atlantic passive margin, thousands of years ago. The area affected by the slump is about 100 km wide, and the slump debris traveled underwater for over 600 km. Tsunamis generated by the slump may have wiped out Stone-Age villages all around the coast of the North Sea.

Take-Home Message

Mass movements differ from one another based on speed and character. Creep, slumping, and solifluction are slow. Mudflows and debris flows move faster, and avalanches and rockfalls move the fastest. Movements occur on land and underwater.

13.3 Why Do Mass Movements Occur?

We've seen that mass movements travel at a range of different velocities, from slow (creep) to faster (slumps, mudflows and debris flows, and rockslides and debris slides) to fastest (snow avalanches, and rock and debris falls—see **Geology at a Glance**, pp. 408–409). The velocity depends on the steepness of the slope and the water or air content of the mass. For these movements to take place, the stage must be set by the following phenomena: fracturing and weathering, which weaken materials at Earth's surface so that they cannot hold up against the pull of gravity; and the development of relief, which provides slopes down which masses move.

Weakening the Substrate by Fragmentation and Weathering

If the Earth's surface were covered by intact (unbroken) rock, mass movements would be of little concern, for intact rock has great strength and could form stalwart mountain faces that would rarely tumble. But the rock of the Earth's upper crust has been fractured by jointing and faulting (**Fig. 13.9**), and in many locations the surface has a cover of regolith resulting from the weathering of rock. Regolith and fractured rock are much weaker than intact rock and can indeed collapse in

FIGURE 13.9 Jointing broke up this thick sandstone bed along a cliff in Utah. Blocks of sandstone break free along joints and tumble downslope.

response to gravitational pull. Thus jointing, faulting, and weathering ultimately make mass movements possible.

Why are regolith and fractured rocks weaker than intact bedrock? The answer comes from looking at the strength of the attachments holding materials together. A mass of intact bedrock is relatively strong because the chemical bonds within its interlocking grains, or within the cements between grains, can't be broken easily. A mass of loose rocks or of regolith, in contrast, is relatively weak because the grains are held together only by friction, electrostatic attraction, and/or surface tension of water. All of these forces combined are weaker than chemical bonds holding together the atoms in the minerals of intact rock. To picture this contrast, think about how much easier it is to bust up a sand castle (whose strength comes primarily from the surface tension of water films on the sand grains) than it is to bust up a granite sculpture of a castle.

Slope Stability

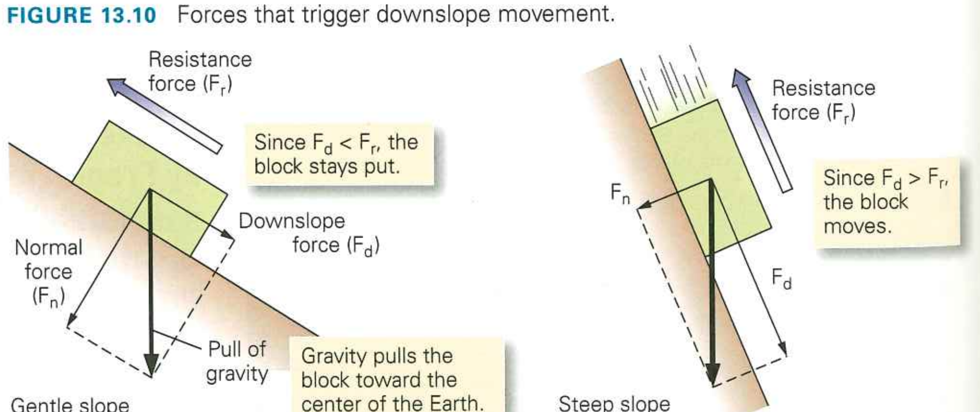
Mass movements do not take place on all slopes, and even on slopes where such movements are possible, they occur only occasionally. Geologists distinguish between *stable* slopes, on which sliding is unlikely, and *unstable* slopes, on which sliding will likely happen. When material starts moving on an unstable slope, we say that *slope failure* has occurred. Whether a slope fails or not depends on the balance between two forces—the downslope force, caused by gravity, and the resistance force, which inhibits sliding. If the downslope force exceeds the resistance force, the slope fails and mass movement results.

Let's examine this phenomenon more closely by imagining a block sitting on a slope. We can represent the gravitational attraction between this block and the Earth by an arrow (a vector) that points straight down, toward the Earth's center of gravity. This arrow can be separated into two components—the downslope force parallel to the slope and the normal force perpendicular to the slope. We can symbolize the resistance force by an arrow pointing uphill. If the downslope force is larger than the resistance force, then the block moves; otherwise, it stays in place (**Fig. 13.10a, b**). Note that for a given mass, downslope forces are greater on steeper slopes.

What produces a resistance force? As we saw above, chemical bonds in mineral crystals or cement hold intact rock in place, friction holds an unattached block in place, electrical charges and friction hold dry regolith in place, and surface tension holds wet regolith in place. Because of resistance force, granular debris tends to pile up to produce the steepest slope it can without collapsing. The angle of this slope is called the **angle of repose**, and for most dry, unconsolidated materials (such as dry sand) it typically has a value of between 30° and 37°. The angle depends partly on the shape and size of grains, which determine the amount of friction across grain boundaries. For example, steeper angles of repose (up to 45°) tend to form on slopes composed of large, irregularly shaped grains (**Fig. 13.11**).

In many locations, the resistance force is less than might be expected because a weak surface exists at some depth below ground level. If downslope movement begins on the weak surface, we can say that the weak surface has become a failure surface. Geologists recognize several different kinds of weak surfaces that are likely to become failure surfaces (**Fig. 13.12a–c**). These include wet clay layers; wet, unconsolidated sand layers; joints; weak bedding planes (shale beds and evaporite beds are particularly weak); and metamorphic foliation planes. Weak surfaces that dip parallel to the land surface slope are particularly likely to fail. An example of such failure occurred in Madison Canyon, southwestern Montana, on August 17, 1959.

FIGURE 13.10 Forces that trigger downslope movement.



(a) Gravity can be divided into a normal force and a downslope force. If the resistance force, caused by friction, is greater than the downslope force, the block does not move.

(b) If the slope angle increases, the downslope force due to gravity increases. If the downslope force becomes greater than the resistance force, the block starts to move.

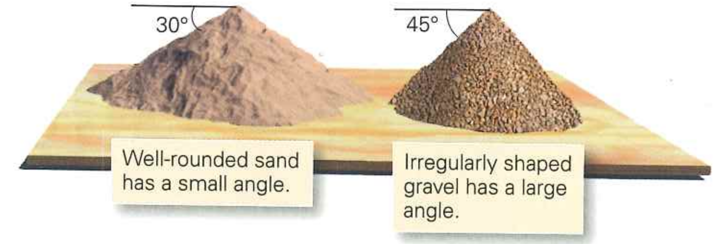


FIGURE 13.11 The angle of repose is the steepest slope that a pile of unconsolidated sediment can have and remain stable. The angle depends on the shape and size of grains.

That day, vibrations from a strong earthquake jarred the region. Metamorphic rock with a strong foliation that could serve as weak surfaces formed the bedrock of the canyon's southern wall. When the ground vibrated, rock detached along a foliation plane and tumbled downslope. Unfortunately, 28 campers lay sleeping on the valley floor. They were probably awakened by the hurricane-like winds blasting in front of the moving mass, but seconds later were buried under 45 m of rubble.

Fingers on the Trigger: What Causes Slope Failure?

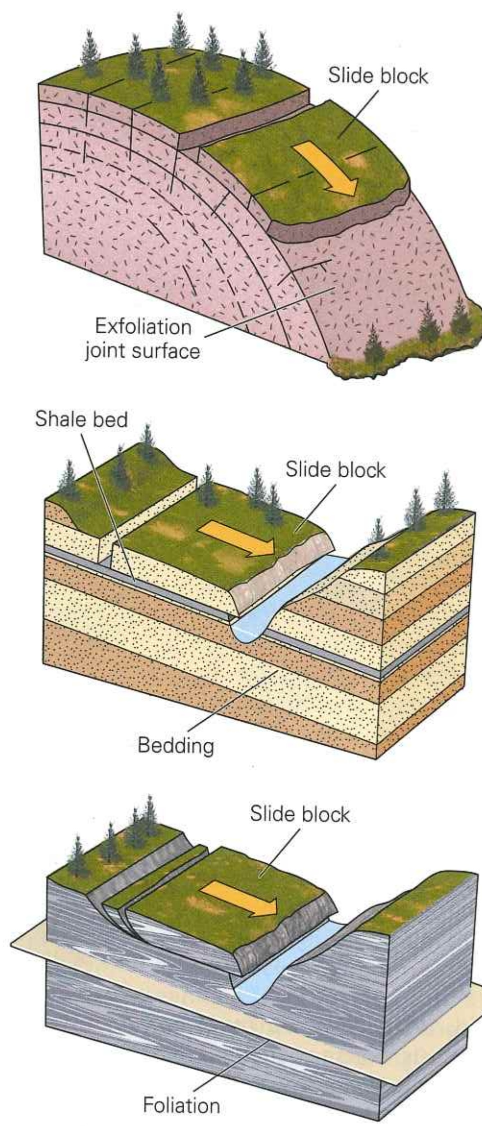
What triggers an individual mass-wasting event? In other words, what causes the balance of forces to change so that the downslope force exceeds the resistance force, and a slope suddenly fails? Here, we look at various phenomena—natural and human-made—that trigger slope failure.

Shocks, vibrations, and liquefaction. Earthquake tremors, storms, the passing of large trucks, or blasting in construction sites may cause a mass that was on the verge of moving actually to start moving. For example, an earthquake-triggered slide dumped debris into Lituya Bay, in southeastern Alaska, in 1958. The debris displaced the water in the bay, creating a 300-m-high (1,200 ft) splash that washed forests off the slopes bordering the bay and carried fishing boats anchored in the bay many kilometers out to sea. The vibrations of an earthquake break bonds that hold a mass in place and/or cause the mass and the slope to separate slightly, thereby decreasing friction. As a consequence, the resistance force decreases, and the downslope force sets the mass in motion. Shaking can also cause **liquefaction** of wet sediment by either increasing water pressure in spaces between grains so that the grains are pushed apart, or by breaking the cohesion between the grains.

Changing slope loads, steepness, and support. As we have seen, the stability of a slope at a given time depends on the balance between the downslope force and the resistance force. Factors that change one or the other of these forces can lead to failure. Examples include changes in slope loads, failure-surface strength, slope steepness, and the support provided by material at the base of the slope.

Slope loads change when the weight of the material above a potential failure plane changes. If the load increases, due to construction of buildings on top of a slope or due to saturation of regolith with water due to heavy rains, the downslope force increases and may exceed the resistance force. Seepage of water into the ground may also weaken underground failure surfaces, further decreasing resistance force. An example of such failure triggered the largest observed landslide in U.S. history, the Gros Ventre Slide, which took place in 1925 on the flank of Sheep Mountain, near Jackson Hole, Wyoming (**Fig. 13.13**). Almost 40 million cubic meters of rock, as well as the overlying soil and forest, detached from the side of the mountain and slid 600 m downslope, filling a valley and forming a 75-m-high natural dam across the Gros Ventre River.

Removing support at the base of a slope due to river or wave erosion or to construction efforts plays a major role in triggering many slope failures. In effect, the material at the base of a slope acts like a dam holding back the material farther up the slope.



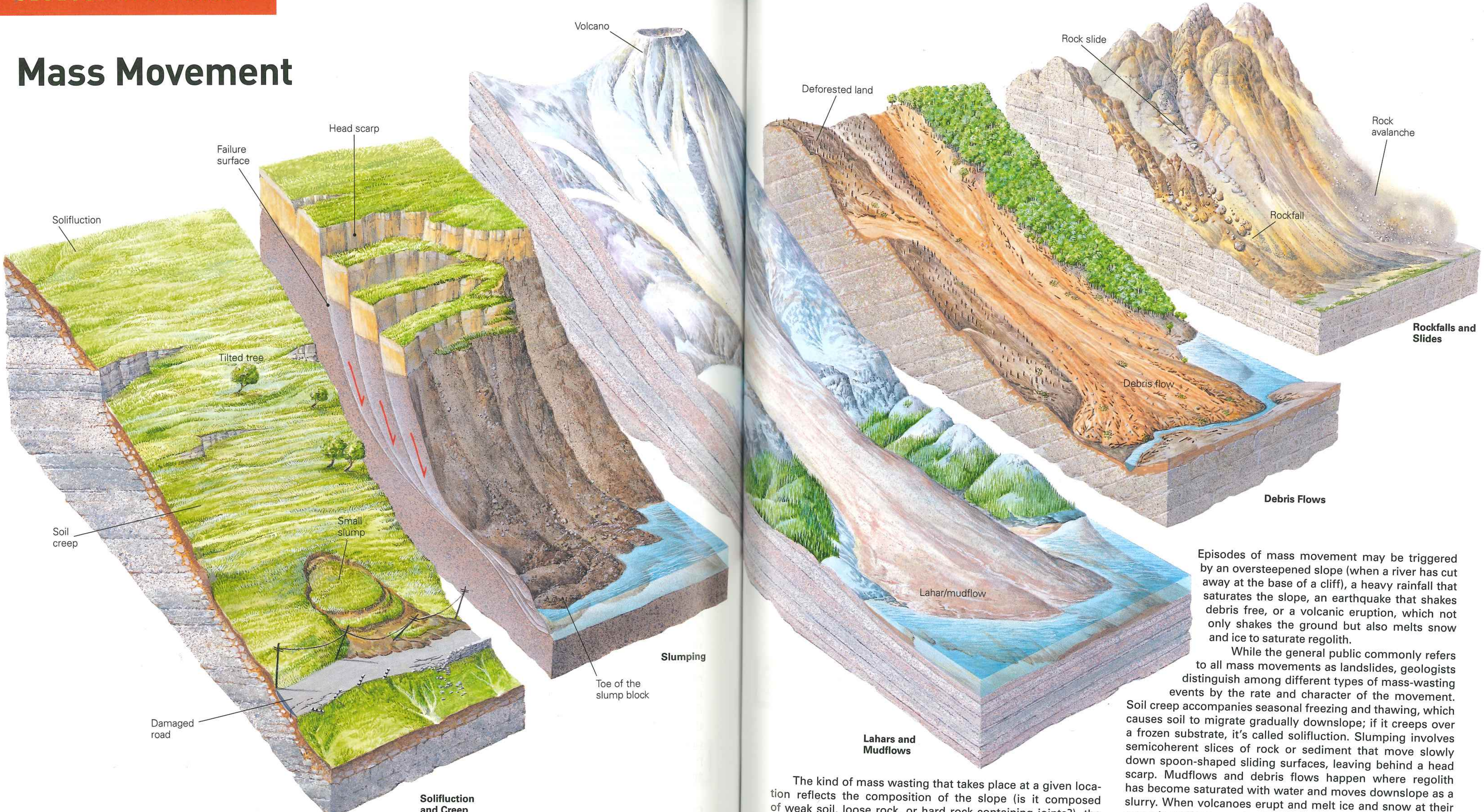
(a) Exfoliation joints form parallel to slope surfaces in granite and become failure surfaces.

(b) In sedimentary rock, bedding planes (particularly in weak shale) become failure surfaces.

(c) In metamorphic rock, foliation planes (particularly in mica-rich schist) become failure surfaces.

FIGURE 13.12 Different kinds of weak surfaces can become failure surfaces.

Mass Movement



In Earth's gravity field, what goes up must come down—sometimes with disastrous consequences. Rock and regolith are not infinitely strong, so every now and then slopes or cliffs give way in response to gravity, and materials slide, tumble, or career downslope. This downslope movement, called mass movement, or mass wasting, is the first step in the process of erosion and sediment formation. The resulting debris may eventually be carried away by water, ice, or wind.

The kind of mass wasting that takes place at a given location reflects the composition of the slope (is it composed of weak soil, loose rock, or hard rock containing joints?), the steepness of the slope, and the climate (is the slope wet or dry, frozen or unfrozen?). Stronger rocks can hold up steep cliffs, but with time, rock breaks free along joints and tumbles or slides down weak surfaces. Coherent regolith may slowly slide down slopes, whereas water-saturated regolith may flow rapidly.

Episodes of mass movement may be triggered by an oversteepened slope (when a river has cut away at the base of a cliff), a heavy rainfall that saturates the slope, an earthquake that shakes debris free, or a volcanic eruption, which not only shakes the ground but also melts snow and ice to saturate regolith.

While the general public commonly refers to all mass movements as landslides, geologists distinguish among different types of mass-wasting events by the rate and character of the movement. Soil creep accompanies seasonal freezing and thawing, which causes soil to migrate gradually downslope; if it creeps over a frozen substrate, it's called solifluction. Slumping involves semicoherent slices of rock or sediment that move slowly down spoon-shaped sliding surfaces, leaving behind a head scarp. Mudflows and debris flows happen where regolith has become saturated with water and moves downslope as a slurry. When volcanoes erupt and melt ice and snow at their summit, or if heavy rains fall during an eruption, water mixes with ash, creating a fast-moving lahar. Steep, rocky cliffs may suddenly give way in rockfalls. If the rock breaks up into a cloud of debris that rushes downslope at high velocity, it is a rock avalanche. Snow avalanches are similar, but the debris consists only of snow.

In some cases, erosion by a river or by waves eats into the base of a cliff and produces an overhang. When such **undercutting** has occurred, rock making up the overhang eventually breaks away from the slope and falls (**Fig. 13.14a, b**).

Changing the slope strength. The stability of a slope depends on the strength of the material constituting it. If the material weakens with time, the slope becomes weaker and eventually collapses. Three factors influence the strength of slopes:

(1) *Weathering*: With time, chemical weathering produces weaker minerals, and physical weathering breaks rocks apart. Thus, a formerly intact rock composed of strong minerals is transformed into a weaker rock or into regolith.

(2) *Vegetation cover*: In the case of slopes underlain by regolith, vegetation tends to strengthen the slope because the roots hold otherwise unconsolidated grains together. Also, plants absorb water from the ground, thus keeping it from turning into slippery mud. The removal of vegetation therefore has the net result of making slopes more susceptible to downslope mass movement. Deforestation in tropical rainforests, similarly, leads to catastrophic mass wasting of the forest's substrate.

(3) *Water content*: Water affects materials comprising slopes in many ways. Surface tension, due to the film of water on grain surfaces, may help hold regolith together. But if the water content increases, water pressure may push grains apart so that regolith liquefies and can begin to flow. Water infiltration may make weak surfaces underground more slippery, or may push surfaces apart and decrease friction. Some kinds of clays absorb water and expand, causing the ground surface to rise and, as a consequence, break up.

FIGURE 13.13 Stages leading to the 1925 Gros Ventre Slide in Wyoming.

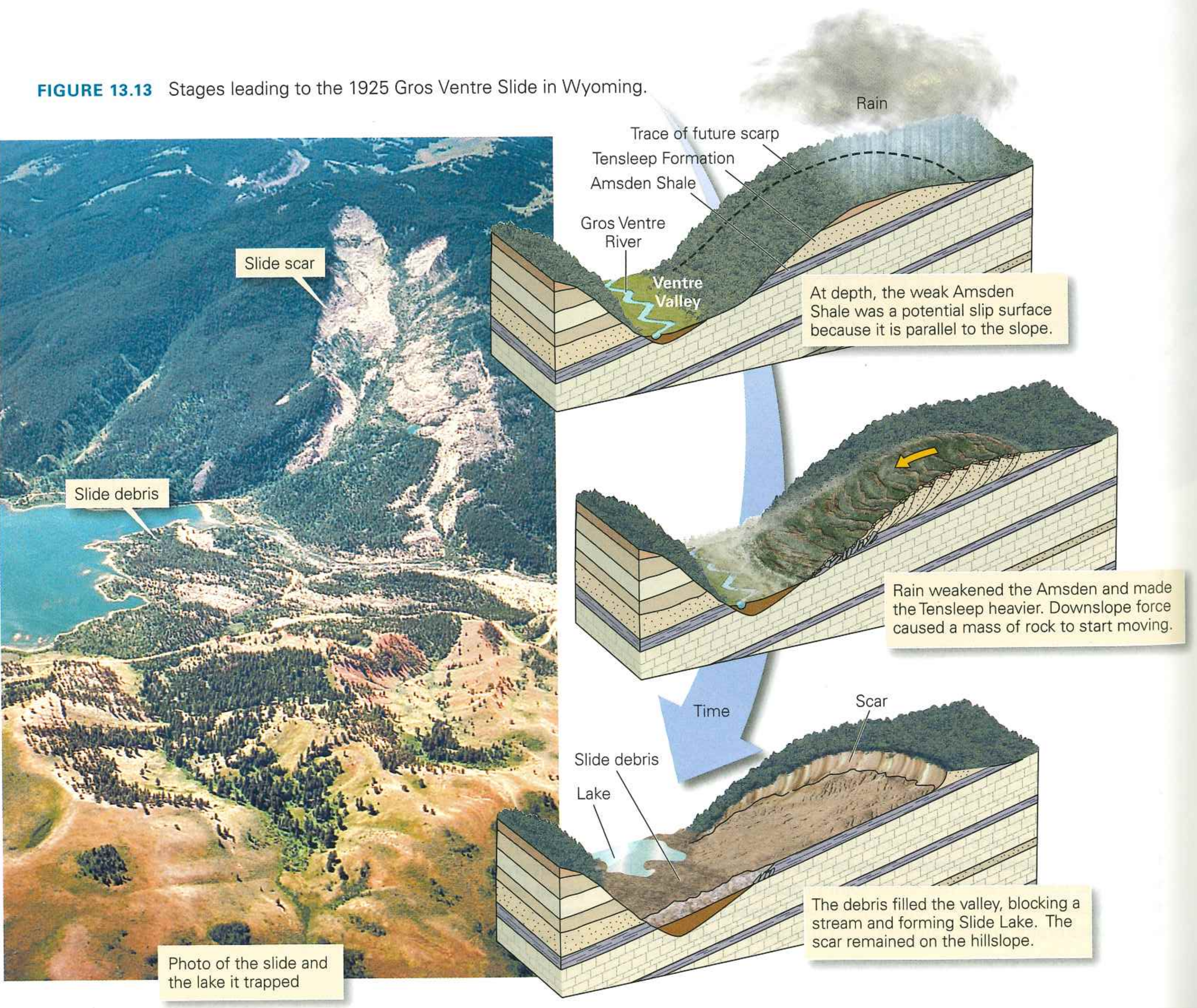
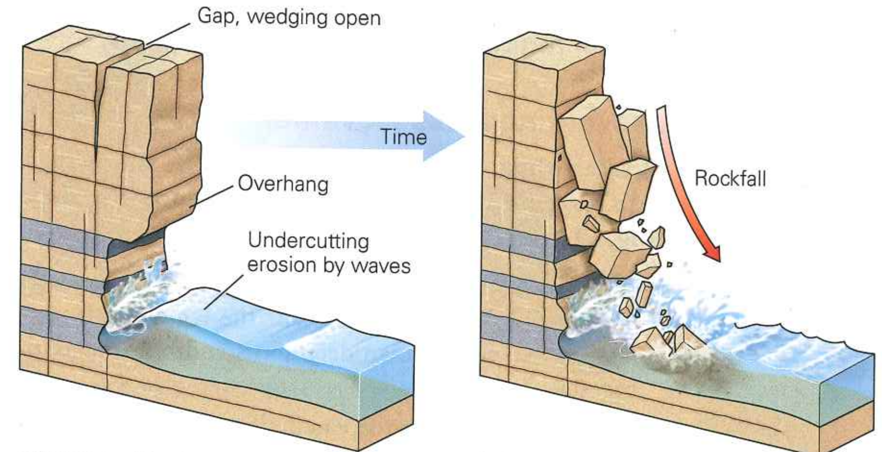


FIGURE 13.14 Undercutting and collapse of a sea cliff.



(a) Undercutting by waves removes the support beneath an overhang.

(b) Eventually, the overhang breaks off along joints, and a rockfall takes place.

> **Take-Home Message**
>
> **Weathering and fragmentation weaken slope materials and make them more susceptible to mass movement. Failure occurs when downslope pull exceeds resistance force due to shocks, changing slope angles and strength, changing water content, and changing slope support.**

13.4 How Can We Protect Against Mass-Movement Disasters?

Identifying Regions at Risk

Clearly, landslides, mudflows, and slumps are natural hazards we cannot ignore. Too many of us live in regions where mass wasting has the potential to kill people and destroy property. In many cases, the best solution is avoidance: don't build, live, or work in an area where mass movement can take place. But avoidance is possible only if we know where the hazards are.

To pinpoint dangerous regions, geologists look for landforms known to result from mass movements, for where these movements have happened in the past, they might happen again in the future. Features such as slump head scarps, swaths of forest in which trees have been tilted, piles of loose debris at the base of hills, and hummocky land surfaces all indicate recent mass wasting.

FIGURE 13.15 Surface features warn that a large slump is beginning to develop. Cracks that appear at the head scarp may drain water and kill trees. Power-line poles tilt and the lines become tight. Fences, roads, and houses on the slump begin to crack.

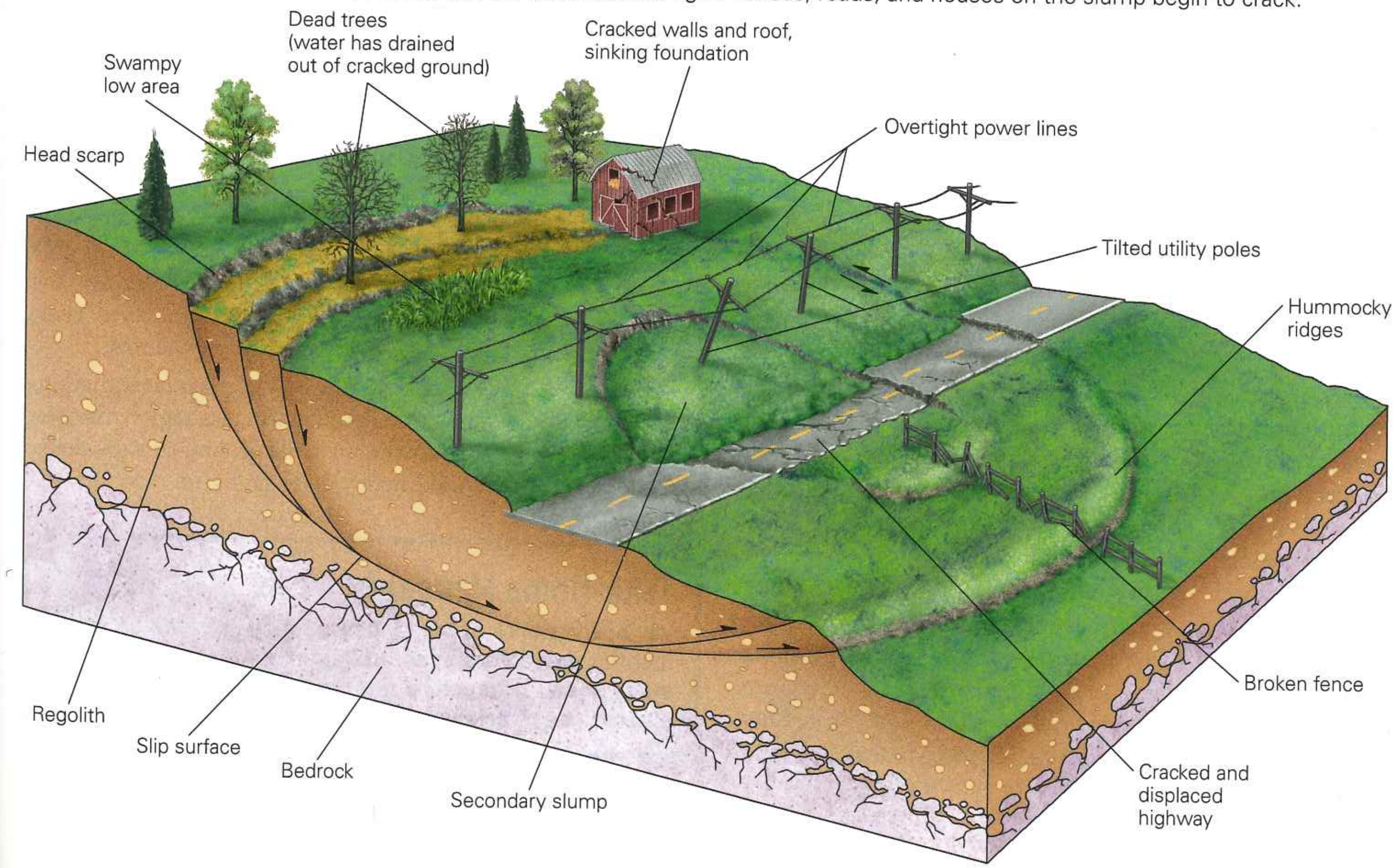


FIGURE 13.16 A landslide hazard map of the Seattle area.

In some cases, geologists may also be able to detect regions that are *beginning to move* (**Fig. 13.15**). For example, roads, buildings, and pipes begin to crack over unstable ground. Power lines may be too tight or too loose because the poles to which they are attached move together or apart. Visible cracks form on the ground at the potential head of a slump, and the ground may bulge up at the toe of the slump. In some cases, subsurface cracks may drain the water from an area and kill off vegetation, whereas in other areas land may sink and form a swamp. Slow movements cause trees to develop pronounced curves at their base. More recently, new extremely precise surveying technologies have permitted geologists to detect the beginnings of mass movements that may not yet have visibly affected the land surface.

Even if there is no evidence of recent movement, a danger may still exist: just because a steep slope hasn't collapsed in the recent past doesn't mean it won't in the future. In recent years, geologists have begun to identify such potential hazards by using computer programs that evaluate factors that trigger mass wasting. These factors include the following: slope steepness; strength of substrate; degree of water saturation; orientation of bedding, joints, or foliation relative to the slope; nature of vegetation cover; potential for heavy rains; potential for undercutting to occur; and likelihood of earthquakes. From such hazard-assessment studies, geologists compile **landslide-potential maps**, which rank regions according to the likelihood that a mass movement will occur (**Fig. 13.16**). In any case, common sense suggests that you should avoid building on or below particularly dangerous slide-prone slopes.

Preventing Mass Movements

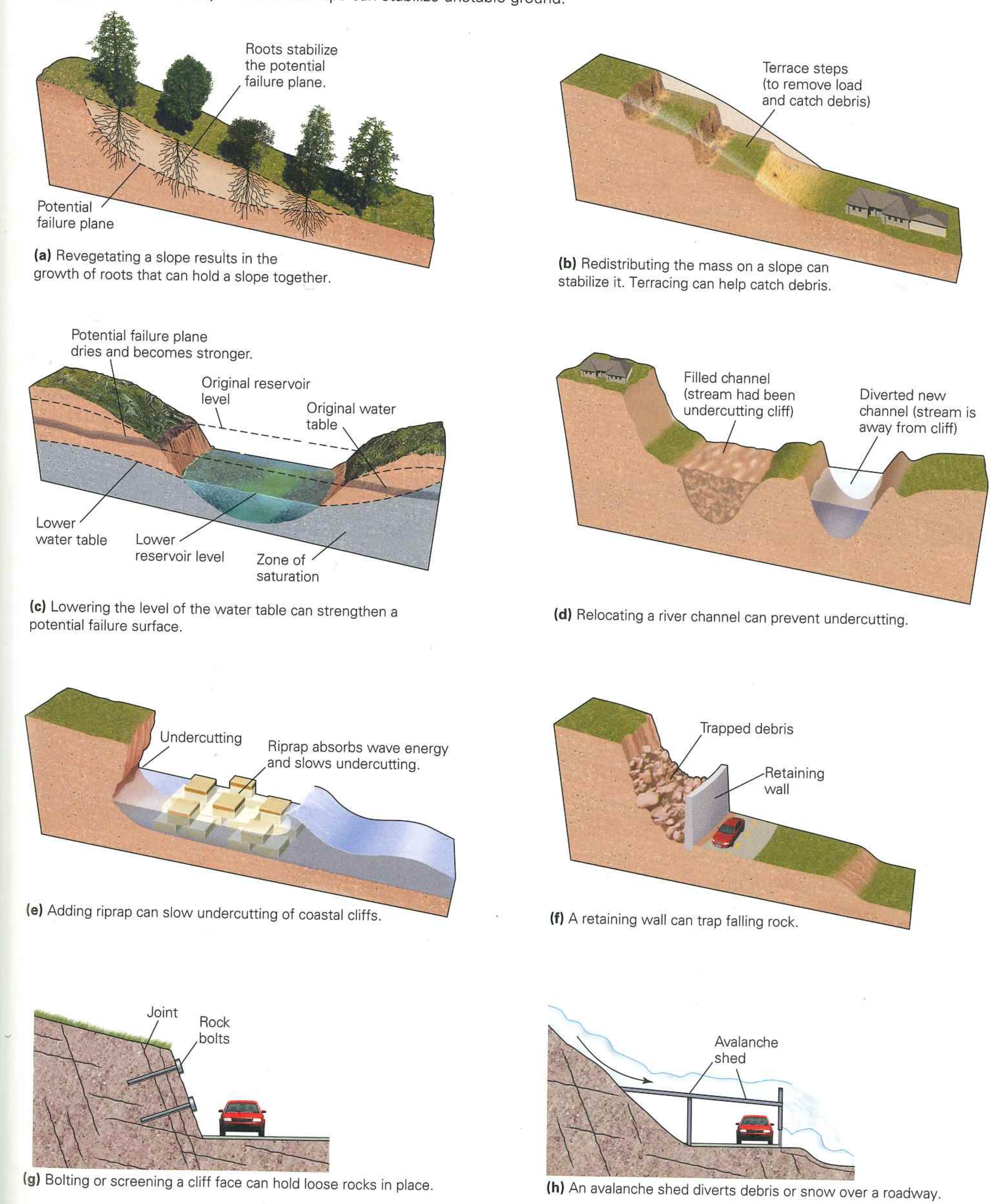
In areas where a hazard exists, people can take certain steps to remedy the problem and stabilize the slope (**Fig. 13.17a–h**).

- *Revegetation*: Stability in deforested areas will be greatly enhanced if land owners replant the region with vegetation that sends down deep roots and binds regolith together.
- *Regrading*: An oversteepened slope can be regraded or terraced so that it does not exceed the angle of repose.
- *Reducing subsurface water*: Because water weakens material beneath a slope and adds weight to the slope, an unstable situation may be remedied either by improving drainage so that water does not enter the subsurface in the first place, or by removing water from the ground.
- *Preventing undercutting*: In places where a river undercuts a cliff face, engineers can divert the river. Similarly, along coastal regions they may build an offshore breakwater or pile riprap (loose boulders or concrete) along the beach to absorb wave energy before it strikes the cliff face.
- *Constructing safety structures*: In some cases, the best way to prevent mass wasting is to build a structure that stabilizes a potentially unstable slope or protects a region downslope from debris if a mass movement does occur. For example, civil engineers can build retaining walls or bolt loose slabs of rock to more coherent masses in the substrate in order to stabilize highway embankments. The danger from rockfalls can be decreased by covering a roadcut with chain link fencing or by spraying roadcuts with concrete. Highways at the base of an avalanche-prone slope can be covered by an avalanche shed, whose roof keeps debris off the road.
- *Controlled blasting of unstable slopes*: When it is clear that unstable ground or snow threatens a particular region, the best solution may be to blast the unstable ground or snow loose at a time when its movement can do no harm.

Take-Home Message

Various features of the landscape may help geologists to identify unstable slopes and estimate risk. Systematic study allows production of landslide-potential maps. Engineers use a variety of techniques to stabilize slopes.

FIGURE 13.17 A variety of remedial steps can stabilize unstable ground.



(a) Revegetating a slope results in the growth of roots that can hold a slope together.

(b) Redistributing the mass on a slope can stabilize it. Terracing can help catch debris.

(c) Lowering the level of the water table can strengthen a potential failure surface.

(d) Relocating a river channel can prevent undercutting.

(e) Adding riprap can slow undercutting of coastal cliffs.

(f) A retaining wall can trap falling rock.

(g) Bolting or screening a cliff face can hold loose rocks in place.

(h) An avalanche shed diverts debris or snow over a roadway.

Chapter Summary

- Rock or regolith on unstable slopes has the potential to move downslope under the influence of gravity. This process, called mass movement, or mass wasting, plays an important role in the erosion of hills and mountains.
- Slow mass movement, caused by the freezing and thawing of regolith, is called creep. In places where slopes are underlain with permafrost, solifluction causes a melted layer of regolith to flow down slopes. During slumping, a semicoherent mass of material moves down a spoon-shaped failure surface. Mudflows and debris flows occur where regolith has become saturated with water and moves downslope as a slurry.
- Rock and debris slides move very rapidly down a slope; the rock or debris breaks apart and tumbles. During avalanches, snow or debris mixes with air and moves downslope as a turbulent cloud. And in a debris fall or rockfall, the material free-falls down a vertical cliff.
- Large mass movements can take place on underwater slopes. Some generate tsunamis.
- Intact, fresh rock is usually too strong to undergo mass movement. Thus, for mass movement to be possible, rock must be weakened by fracturing or weathering.
- Unstable slopes start to move when the downslope force exceeds the resistance force that holds material in place. The steepest angle at which a slope of unconsolidated material can remain without collapsing is the angle of repose.
- Downslope movement can be triggered by shocks and vibrations, changes in the steepness of a slope, removal of support from the base of the slope, changes in the strength of a slope, deforestation, weathering, or heavy rain.
- Geologists can sometimes detect unstable ground before it begins to move, and they produce landslide-potential maps to identify areas susceptible to mass movement.
- Engineers can help prevent mass movements by using a variety of techniques to stabilize slopes.

Key Terms

angle of repose (p. 406)
creep (p. 398)
debris fall (p. 403)
debris flow (debris slide) (pp. 400, 401)
failure surface (p. 399)
head scarp (p. 399)
lahar (p. 401)
landslide-potential map (p. 412)
liquefaction (p. 407)
mass movement (wasting) (p. 398)
mudflow (mudslide) (p. 400)
natural hazard (p. 398)
rockfall (p. 403)
rockslide (p. 401)
slump (p. 399)
snow avalanche (p. 403)
solifluction (p. 398)
talus (p. 403)
undercutting (p. 410)

Review Questions

1. What factors do geologists use to distinguish among various types of mass movements?
2. Explain how soil creep operates.
3. Identify the key differences between a slump, a debris flow, a lahar, an avalanche, a rockslide, and a rockfall.
4. Why is intact bedrock stronger than fractured bedrock? Why is it stronger than regolith?
5. Explain the difference between a stable and an unstable slope. What factors determine the angle of repose of a material? What features are likely to serve as failure surfaces?
6. Discuss the variety of phenomena that can cause a stable slope to become so unstable that it fails.
7. How can ground shaking cause fairly solid layers of sand or mud to become weak slurries capable of flowing?
8. Discuss the role of vegetation and water in slope stability. Why can fires and deforestation lead to slope failure?
9. What factors do geologists take into account when producing a landslide-potential map, and how can geologists detect the beginning of mass movement in an area?
10. What steps can people take to avoid landslide disasters?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on the identification of mass movements.
- Animation-based exercises on debris flows and cliff retreat.
- Questions that help students understand the concept of slope stability.

On Further Thought

11. Imagine that you have been asked by the World Bank to determine whether it makes sense to build a dam in a steep-sided, east-west-trending valley in a small central Asian nation. The local government has lobbied for the dam because the climate of the country has gradually been getting drier, and the farms of the area are running out of water. The World Bank is considering making a loan to finance construction of the dam, a process that would employ thousands of now-jobless people. Initial investigation shows that the rock of the valley wall consists of schist containing a strong foliation that dips toward the valley and is parallel to the slope of the valley wall. Outcrop studies reveal that abundant fractures occur in the schist along the valley floor; the surface of most fractures are coated with slickensides. Moderate earthquakes have rattled the region. What would you advise the bank? Explain the hazards and what might happen if the reservoir were filled.

SEE FOR YOURSELF M... Mass Movements

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet M of our **Geotours Workbook**.

Portuguese Bend, California
Latitude 33°44′46.94″N,
Longitude 118°22′7.83″W

As seen from 7 km, housing covers much of the land in southern California, but not on a 3.5-km-wide spoon-shaped depression at Portuguese Bend slump. In the 1950s, developers built on the hummocky land, but water infiltration weakened a failure surface and reactivatied the slump, destroying 150 houses.

Canyonlands, Utah
Latitude 38°29′50.07″N,
Longitude 110°0′15.63″W

As seen from 5 km, the Green River has carved a deep valley through horizontal layers of strata. Shale forms the slopes, and sandstone forms the top ledge. Erosion of the shale undercuts the sandstone, which breaks away at joints and tumbles downslope to build a talus pile.

La Conchita Mudslide, California
Latitude 34°21′50.29″N,
Longitude 119°26′46.85″W

Tectonic activity has uplifted the coast of California to form a terrace bordered on the ocean side by a steep escarpment. Looking NE from 250 m, you can see a mudflow that overran houses built at the base of the escarpment. Note the head scarp.

Debris Fall, Yungay, Peru
Latitude 9°7′21.42″S,
Longitude 77°39′44.86″W

Looking NE from 6.4 km, you can see the steep, glaciated face of Nevado Huascarán. In 1970, a debris fall from the mountain rushed down the valley in the foreground and buried the landscape. More recent, smaller debris flows have accumulated on top of the larger one.