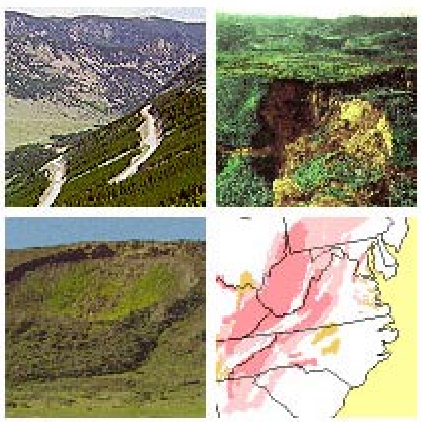
Slope Failure



Introduction

Slope Failure Factors

Slope Failure Processes

Summary

The whole black earth is oppressed beneath the storm . . . all the rivers flow in flood, and many hillsides are furrowed deeply by the torrents, and they rush to the purple sea from the mountains, roaring mightily, and the fields of men are wasted.

Homer

Introduction

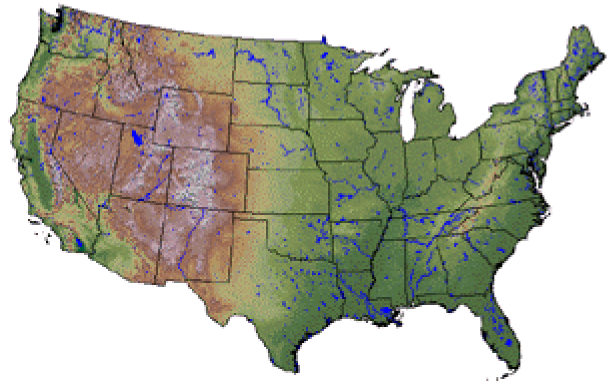
- Weathering can produce a thick mantle of unconsolidated material on slopes that may fail as a result of human activity or natural processes.
- Mass wasting is the downslope movement of material under the influence of gravity and mass wasting phenomena can be linked to weathering processes.
- Mass wasting processes may be slow and gradual or swift and deadly.

Weathered debris may collect on slopes or form new slopes in areas with relatively rapid weathering rates. This unconsolidated material is susceptible to collapse resulting in slope failure. The downslope movement of material under the influence of gravity is termed **mass wasting** and represents one of the most active processes in modifying the landscape in areas of significant relief (Fig. 1). Mass wasting involves material other than weathered debris (notably in rock slides) but most mass wasting phenomena occur in a thick mantle of regolith, the rock and mineral fragments produced by weathering. The general term **landslide** is used to describe all rapid forms of mass wasting.

Figure 1. Steep terrain with significant relief (change in elevation) suitable for slope failure in the Beartooth Mountains, southern Montana.

The national map of mass wasting activity (http:// geohazards.cr.usgs.gov/html_files/landslides/nationalmap/national.html) shows areas with greatest potential for landslides and other slope failure events (in red and pink colors). The areas at greatest risk are in mountainous regions (Fig. 2) with relatively steep slopes such as the Appalachians, Rockies, and mountain ranges of California.

Figure 2. U.S. painted relief map. Tan and brown colors show areas of higher elevations. Note areas of high relief in the western states and along the northeast trending Appalachian Mountains in the east.



However, the potential for mass wasting is not determined by slope angle alone. For example, we might expect the greatest hazards to be associated with the highest peaks in western states. However, the largest area at risk from landslides is in the eastern Appalachian states. **Water** plays a significant role in mass wasting and is much more plentiful in the eastern U.S. than in the West (with the exception of the Pacific Northwest). Finally, miscellaneous factors such as **earthquakes**, the presence or absence of **vegetation**, and **human activities** can also influence the potential for mass wasting (Fig. 3). In the next section we consider the factors affecting slope failure, including slope angle and the presence of water. We will also discuss how we can attempt to prevent such hazards by stabilizing slopes.

Figure 3. The result of a landslide triggered by the 1994 Northridge earthquake, southern California. Some steep hillsides collapsed destroying homes. Image courtesy of USGS Geohazards website.

Mass wasting processes may be slow and gradual or swift and deadly. The final section in this part of the chapter describes a classification system for mass wasting phenomena.

Slope Failure Factors

- Gravity can be divided into components acting parallel to a slope and perpendicular to the slope.
- Failure is more likely to occur if the effect of friction on the potential sliding surface is reduced.
- The physical properties of the slope materials such as cohesion between grains may reduce the potential for slope failure.
- The angle of repose is the maximum slope generated when loose unconsolidated material is formed into a pile.
- The addition of excess water may destabilize slopes by adding weight, destroying cohesion between grains, and reducing friction.

Gravity acts on all objects on Earth's surface. Gravity can be divided into two components for objects resting on sloping surfaces (Fig. 4). One component is parallel to the slope (g_s) and one is perpendicular to the slope (g_p). On steep slopes (>45 degrees) the component parallel to the slope will be greatest and will act to pull objects downhill. On gentle slopes the component perpendicular to the slope will be greatest and will act to hold the object in place.

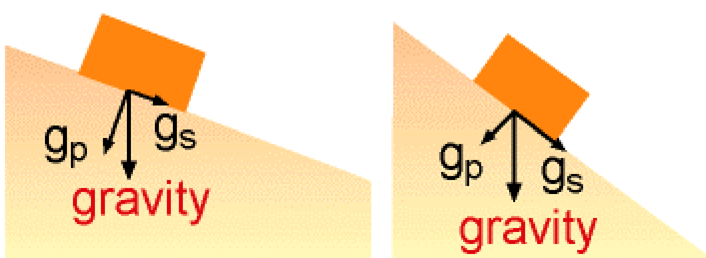


Figure 4. Components of gravity oriented parallel (g_s) and perpendicular (g_p) to the slope for gentle and steep slopes

However, gravity alone does not determine if the object will move downslope. There are numerous steep slopes that are not currently undergoing mass wasting. A physical trigger is often required to initiate slope failure.

The **properties of the surface** between the object and the slope (e.g., friction) and the **physical properties** of the sliding object itself all contribute to the potential for mass wasting. The object is more likely to move if **friction** between the object and the slope is reduced. In contrast, a slope will be less likely to fail if the **cohesion between the grains** in the material is increased. For example, no matter how much dry sand is added to a pile, it can never form a slope that is steeper than 35 degrees inclination. This angle is termed the material's **angle of repose**. In contrast, by adding a little water, the cohesion between the sand grains (surface tension) increases dramatically allowing us to sculpt sand castles with vertical walls. Irregularly shaped objects may form steeper slopes than dry sand; large angular blocks may have an angle of repose of around 45 degrees. In contrast, spherical marbles are almost impossible to form into a pile with sloping sides.

The addition of **excess water** to a slope may also be the precursor for a disaster. Not only does excess water saturate the material and reduce cohesion between grains but water-saturated pore spaces will support the weight of overlying material thus reducing the effect of friction. Finally, the addition of water may promote instability by adding weight to a slope.

Figure 5. Two views of a landslide area in southwest Montana before and after supports were added to the road above the slide area and the slide area was graded to reduce risk of future mass wasting

The addition of extra weight to a slope may be attributed to natural processes (e.g., rainfall) but may also be the result of human activity that adds water to the slope (e.g., leaking septic systems, overzealous irrigation) or adds new structures. Furthermore, human activity such as logging may remove vegetation that shelters the slope and provides a network of roots to hold slope material in place. Over 100 people were killed when devastating mudslides destroyed parts of two Italian villages in May 1998. The mudslides followed heavy rains and were blamed on poor land management practices, including **deforestation** of slopes.

Stabilizing Slopes

One obvious solution to the problem of landslides is to avoid building structures on steep slopes. However, such pragmatic advice may not deter a homeowner in search of a spectacular view and is of little use to engineers who must build roads on steep slopes in mountainous terrain (Fig. 5). Instead, efforts focus on improving slope drainage (to reduce the role of water) or attaching the slope material to bedrock with physical restraints. Such restraints may be as mundane as covering slope material with chicken wire or cement, or bolting rock panels to the underlying bedrock (Fig. 6).

Figure 6. Slope-stabilization methods. Chicken wire (top left) and concrete (top right) cover exposed slopes and a retaining wall with drainage pipes protects the road (below). All images from the Rocky Mountains.

The Beartooth highway climbs up the side of the Beartooth Mountains, Montana (Fig. 7). The route connects the northeast entrance to Yellowstone National Park (Wyoming) with the city of Red Lodge, Montana. Persistent failure of the steep slopes requires that the road be repaired every few years.

Elsewhere, efforts to prevent mass wasting have involved supporting the base of the slope to prevent it from failing (Fig. 8). Wire baskets filled with rocks are often used for such retaining walls.

Figure 7. View of Beartooth Highway along the east side of the Beartooth Mountains, near Red Lodge, Montana.

Figure 8. Retaining wall made up of rock-filled wire baskets below restaurant on a hillside in Pennsylvania. (Right: a close up of the contents of the wire baskets).

Think about it . . .
Examine the National Landslide Hazards Map located at the end of the chapter and answer the questions about the distribution of mass wasting in the U.S.

Slope Failure Processes

- Rock fall occurs when ice wedging loosens angular boulders from rocky cliffs.
- Rockslides occur where sheets of rock move downslope on a planar sliding surface such as a bedding plane or fracture surface.

- A slump is the downslope movement of material on a curved surface.
- Mudflows and debris flows represent a chaotic mixture of water and unconsolidated slope materials.
- Arid and temperate areas may be marked by rockfall and rockslides whereas humid regions will show greater frequency of slumps, mudslides, and debris flows.

Mass wasting phenomena can be directly linked to weathering processes. Physical weathering processes that cause the breakdown of rocks at Earth's surface will result in **rockfalls** at high elevations (ice wedging) and may create suitable conditions for **rockslides** along sheeting joints (unloading). Rockslides may occur preferentially on surfaces that have been weakened by chemical weathering. Bare rock surfaces are less likely to occur in areas of rapid chemical weathering. The thick regolith of these regions may fail by **slumping** where moisture is relatively low or by **mudflows** or **debris flows** where water is plentiful. Rockfall may still occur in high elevations but rockslides are less likely where rock is covered by a thick mantle of regolith.

Climate	Weathering	Mass wasting
Arid	Physical weathering only	Rockfalls, rockslides
Temperate	Physical weathering and slow-moderate chemical weathering	Rockfalls, rockslides, slumps
Humid	Rapid chemical weathering and physical weathering in high elevations	Mudflows, debris flows, slumps, rockfalls

Mass wasting phenomena are classified on the basis of the type of material moving downslope and the movement mechanism. Rocks fall or slide downslope whereas unconsolidated regolith slumps on curved surfaces or flows where water is plentiful.

Material	Type of Movement		
	Fall	Slip	Flow
Rock	Rockfall	Rockslide	---
Regolith	---	Slump	Mudflow Debris flow

Rockfall

Rockfall occurs when physical weathering (ice wedging) loosens angular boulders from rocky cliffs in mountainous terrain. The boulders break off and fall downslope producing an apron of coarse debris (**talus**) at the base of the slope (Fig. 9). Rockfall is rarely hazardous because it occurs in relatively isolated locations. However, activities that place people on or near rock slopes in mountainous areas can occasionally prove dangerous. Rockfall claimed the life of a climber in Yosemite National Park in the summer of 1999 when a slab of rock broke off from the near-vertical face of an exfoliation dome along one side of the Yosemite Valley.

Figure 9. Talus piles formed by rockfall along base of cliff, Beartooth Mountains, Montana.

Rockslides

Rockslides occur where a sheets of rock move downslope on a **planar sliding surface**. The sliding surface is typically a suitably oriented bedding plane or a fracture surface (Figs. 10, 11). The 1925 **Gros Ventre slide**, northwest Wyoming, occurred when a sandstone layer moved downslope on an slip plane overlying weak shales (Fig. 10). The slide was triggered by an earthquake and followed weeks of heavy rains that had saturated the slope. Fifty million cubic yards of rock moved downslope, crossed the river, and moved 130 meters up the opposite slope. The whole event took just three minutes and formed a natural dam across the valley. The dam failed nearly two years later causing a flood that killed six people. The rocks exposed by the slide are still visible today (Fig. 10).

Rockslides generate relatively thin sheets of rock that are broken into smaller blocks as they move downslope. The toe of a rockslide is characterized by a jumbled collection of blocks, some up to hundreds of meters across, at the base of the slide plane (Fig. 11).

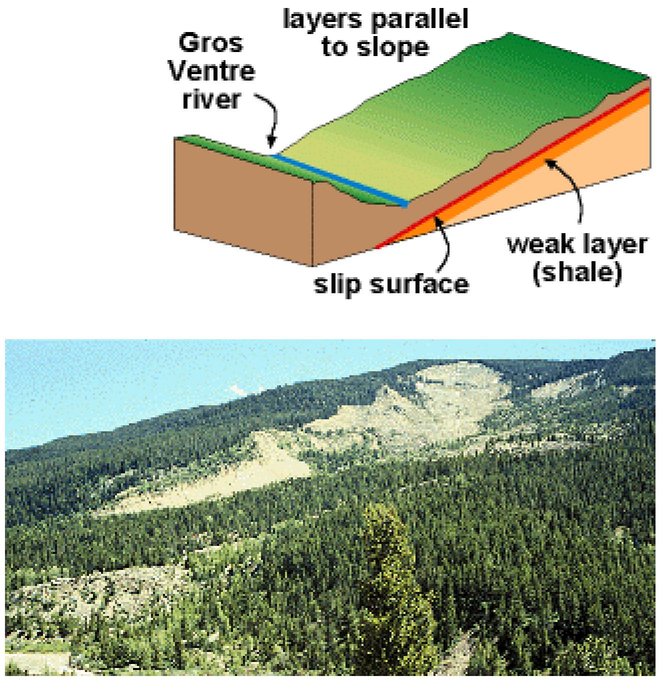


Figure 10. Above: Diagram of geology of Gros Ventre slide area prior to slide. Below: View of Gros Ventre slide (tan area on slope) with Gros Ventre River in the foreground.

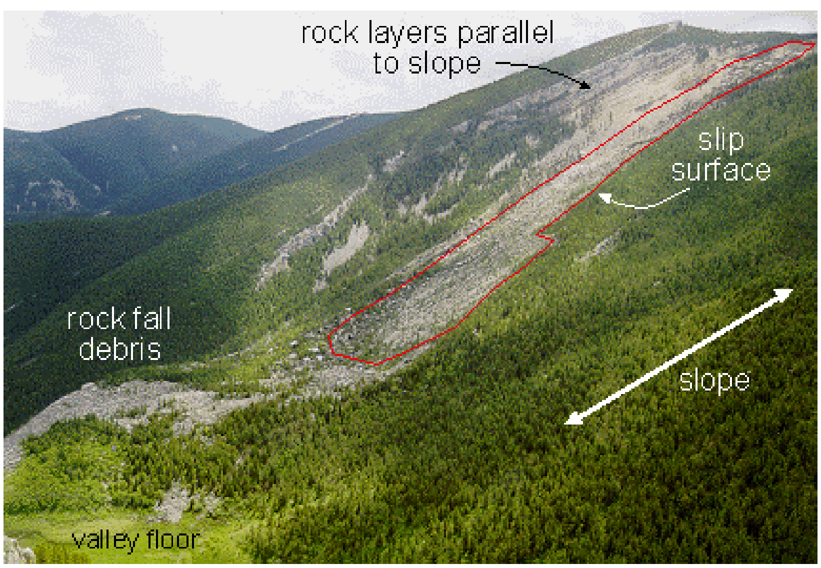


Figure 11. Rockslide formed when limestone slipped downslope above a layer of shale, Bighorn Mountains, Wyoming. Cliff near top of slope is approximately 100 meters high.

Slump

A **slump** is the downslope movement of material on a **curved** (concave-upward) **slip surface**. Slumping typically involves unconsolidated regolith that becomes saturated with water. The curved sliding surface results in rotation of overlying slump blocks. A clifflike scarp is left behind at the head of the slump (Fig. 12).

Slumps frequently occur in association with saturated slope material that may be the result of heavy precipitation or inadvertent human activity.

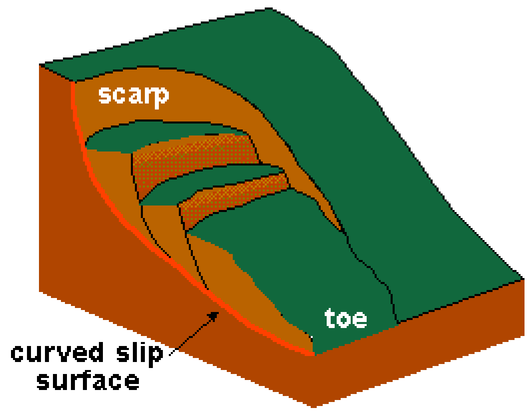


Figure 12. Elements of a slump. The slump may break into separate blocks, each with their own scarp surface. Unconsolidated material breaks away from the top of the slope leaving a scarp surface. The toe of the slump overrides structures at base of slope.

The La Conchita slump (Fig. 13), California, occurred in March 1995 following a series of heavy rainstorms and warnings by geologists of the potential for slope failure. Six hundred thousand tons of material buried nine homes and damaged several others. Property values in the small community plummeted following the slump and the homeowners sued the La Conchita Ranch, a landowner that irrigated crops on top of the collapsed slope (Fig. 13). The residents claimed that persistent overwatering by the ranch owners had destabilized the slope and increased the risk for landslides. The owners eventually settled out of court for unspecified damages.

Figure 13. La Conchita slump, California. The slump was attributed to overwatering of the flat area above the slope. Image courtesy of USGS Geohazards website.

Flows

Sediment flows occur when there is a relatively **large volume of water** present in a mixture of coarse and/or fine-grained sediment. Rather than moving downslope as a coherent mass (slump, rockslide) the material flows downhill as a chaotic mixture. Flows are differentiated on the basis of their velocity and the type of sediment involved.

Following a series of storms in January 1997, USGS geologists flew an aerial survey of the Sierra Nevada Mountains, California, to observe landslide damage (Fig. 14). A **debris flow** approximately 100 meters wide and stretching for nearly five kilometers was observed near Dorrington, California. The flow began near a ridge crest and descended 700 meters downslope before ending in the valley of the Stanislaus River. Debris flows may travel with velocities of 15 to50 kilometers per hour and involve unconsolidated regolith (most of which is coarser than sand).

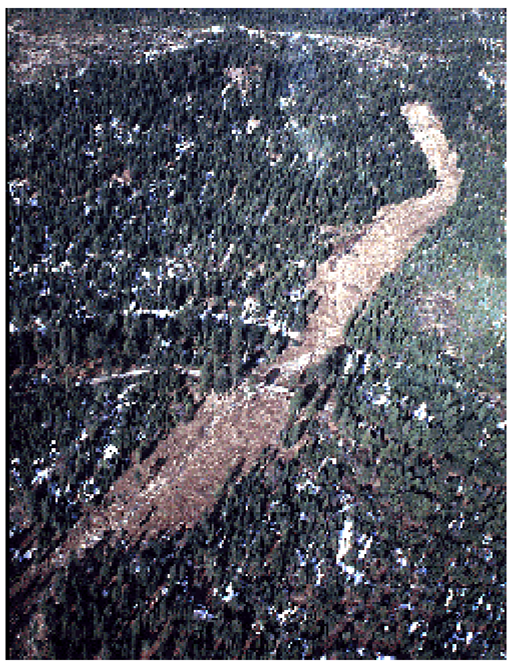


Figure 14. Dorrington debris flow, 1997, Sierra Nevada Mountains, California. Inset shows close up of debris flow path with road (State Route 4) for scale. Images courtesy of USGS, original photographs by Mark Reid, USGS.

Highly fluid **mudflows** incorporate fine-grained sediment and typically follow stream channels. These fast-flowing, high-density flows are common following volcanic eruptions producing substantial volumes of volcanic ash. Mudflows involving volcanic debris are termed **lahars**.

Think about it . . .

1. Create a concept map that illustrates the characteristics of slope failure processes.
2. Select any two of the landslides from the list of Web addresses found at the end of the chapter and complete the Venn diagram to illustrate the similarities and differences between these mass wasting events.

Summary

1. What is mass wasting and where is it most active?

Mass wasting is failure of slopes by the downslope movement of material under the influence of gravity. Mass wasting is one of the most significant processes in sculpting the landscape. It is most active in areas of slopes with plentiful water supply.

2. What is the relationship between weathering and slope failure?

Physical weathering results in rockfalls at high elevations (ice wedging) and may create suitable conditions for rockslides along sheeting joints (unloading). Rockslides may occur preferentially on surfaces that have been weakened by chemical weathering. Slopes in regions of rapid chemical weathering may fail by slumping where moisture is relatively low or by mudflows or debris flows where water is plentiful. Rockfall may still occur in high elevations but rockslides are less likely where rock is covered by a thick mantle of regolith.

3. What factors lead to mass wasting?

Gravity acts to pull objects on Earth's surface downslope and is especially significant on steep slopes (>45 degrees). However, the properties of the surface (friction) and the object itself (cohesion) both contribute to the potential for mass wasting. Processes that reduce friction or cohesion between grains will promote slope failure. The addition of excess water to the slope may accomplish both these goals.

4. How can slopes be protected to prevent slope failure?

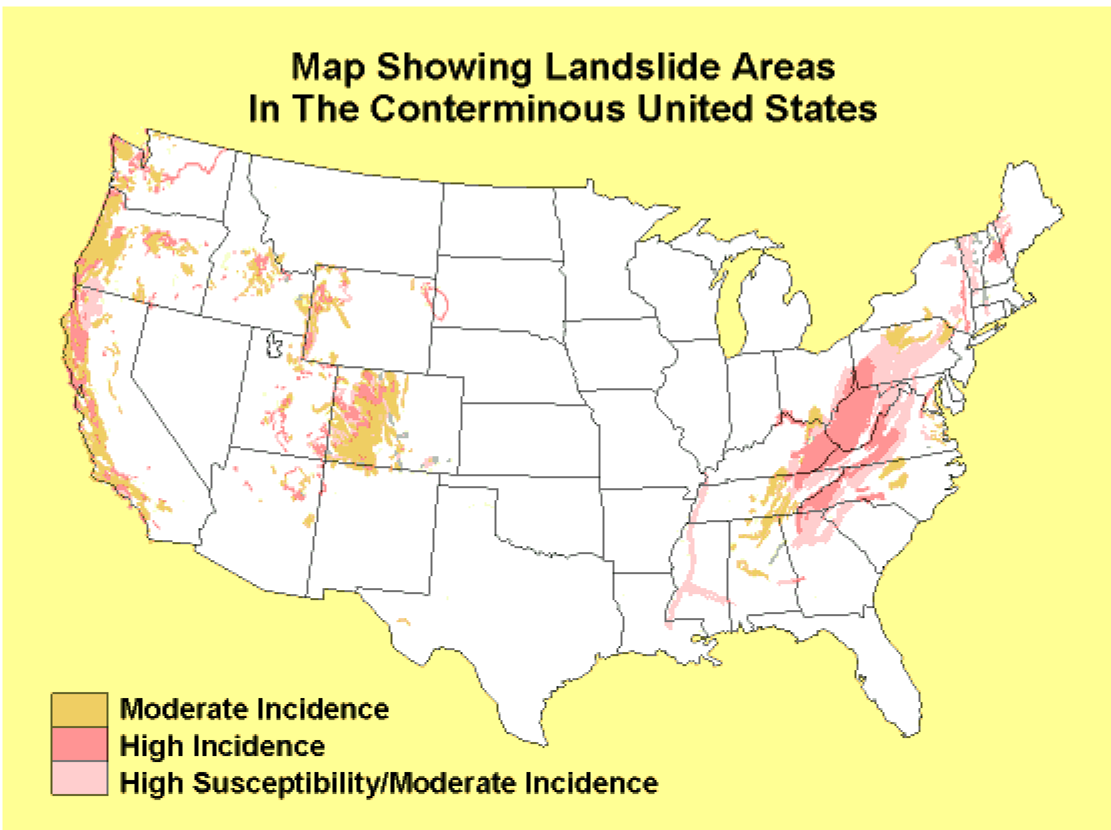
Efforts to stabilize slopes include improving slope drainage or attaching the slope material to bedrock with physical restraints (e.g., chicken wire, cement, or rock bolts). Alternatively, supporting the base of the slope with retaining walls or planting vegetation on the slope will inhibit failure.

5. What are the different types of mass wasting?
The four major forms of mass wasting may be classified by the type of material involved (bedrock or regolith) and the type of movement (fall, slip, flow). There are no significant slope failure mechanisms involving the fall of regolith or the flow of rocks but rockfall, rockslides, slumps, and debris flows/mudflows are relatively common.

6. What is the difference between slumps and rockslides?
Both occur on slip surfaces. Slumps involve regolith and occur above curved surfaces that result in the rotation of slope material. In contrast, rockslides occur on planar surfaces (bedding) that lie parallel to the slope.

U.S. Slope Failure (Mass Wasting)

The National Landslide Hazards Map (below) is produced by the U.S. Geological Survey. It shows areas where there have been a moderate or high incidence of landslides (where landslides have actually occurred) and areas with a high susceptibility to landslides (few recent landslides but potential for future events). The areas colored pink represent places where there is a high incidence of landslides (covering greater than 15% of the area). Examine the map and answer the questions that follow.



1. Identify three geographic regions (e.g., Midwest) where there is a high incidence of landslides.

2. Why are landslides more frequent in these regions than elsewhere?

3. West Virginia has a larger area with a high incidence of landslides than Colorado. What difference in the physical environments of these states may account for this?

Venn Diagram: Characteristics of Landslides

Select any two of the landslides described at the Web addresses below and identify their physical characteristics. Compare and contrast the features of these mass wasting phenomena using the Venn diagram below.

Anaheim Hills, California (http://anaheim-landslide.com/).
Blue Ridge, Virginia (http://landslides.usgs.gov/html_files/nlic/blueridge.htm).
Sleeping Bear Dunes, Michigan (http://geology.wr.usgs.gov/fact-sheet/fs020-98/).
Tully Valley, New York (http://pubs.usgs.gov/factsheet/fs13-98/).

Landslide 1 ____________________ Landslide 2 ____________________