3.3 Slope processes

Introduction and definitions

The term 'slope' refers to:

- an inclined surface or hillslope
- an angle of inclination or slope angle.

Slopes therefore include any part of the solid land surface, including level surfaces of 0° (Figure 3.15). These can be sub-aerial (exposed) or sub-marine (underwater), aggradational (depositional), degradational (erosional), transportational or any mixture of these. Given the large scope of this definition, geographers generally study the hillslope. This is the area between the watershed (or drainage-basin divide) and the base. It may or may not contain a river or stream.

Slope processes

Many slopes vary with climate. In humid areas, slopes are frequently rounder, due to chemical weathering, soil creep and fluvial transport. By contrast, in arid regions slopes are jagged or straight owing to mechanical weathering and sheetwash (Figure 3.16). Climatic geomorphology is a branch of geography that studies how different processes operate in different climatic zones, and produce different slope forms or shapes (see Table 3.3 in Section 3.2).

Geological structure is another important control on slope development. This includes faults, angle of dip and vulcanicity. These factors influence the strength of a rock and create lines of potential weakness within it. In addition, rock type and character affect vulnerability to weathering and the degree of resistance to downslope movement.

Geological structure can also influence the occurrence of landslips. Slopes composed of many different types of rock are often more vulnerable to landslides due to differential erosion; that is, less resistant rocks are worn away and can lead to the undermining of more resistant rocks.

Figure 3.15 Rounded slopes at Wytham, Oxfordshire, UK – a temperate region

Figure 3.16 Silent Valley, Dolomites, Italy

Soil can be considered as part of the regolith. Its structure and texture will largely determine how much water it can hold. Clay soils can hold more water than sandy soils. A deep clay on a slope where vegetation has been removed will offer very little resistance to mass movement.

Aspect refers to the direction in which a slope faces. In some areas, past climatic conditions varied depending on the direction a slope faced. During the cold periglacial period in the northern hemisphere, in an east–west valley, the southern slope which faced north, remained in the shade. Temperatures rarely rose above freezing. By contrast, the northern slope, facing south, was subjected to many more cycles of freeze–thaw. Solifluction and overland runoff lowered the level of the slope, and streams removed the debris from the valley. The result was an asymmetric valley.

Vegetation can decrease overland runoff through the interception and storage of moisture. Deforested slopes are frequently exposed to intense erosion and gullying. However, vegetation can also increase the chance of major landslips. Dense forests reduce surface wash, causing a build-up of soil between the trees, thus deepening the regolith and increasing the potential for failure.

Section 3.3 Activities

1 Briefly describe **two** ways in which climate affects slope development. What does the term *climatic geomorphology* mean?
2 Briefly describe **two** ways in which geology affects slope development.

Mass movements

Mass movements include any large-scale movement of the Earth's surface that are not accompanied by a moving agent such as a river, glacier or ocean wave. They include:

- **very slow movements**, such as soil creep
- **fast movement**, such as avalanches
- **dry movement**, such as rockfalls
- **very fluid movements**, such as mudflows (Figure 3.17).

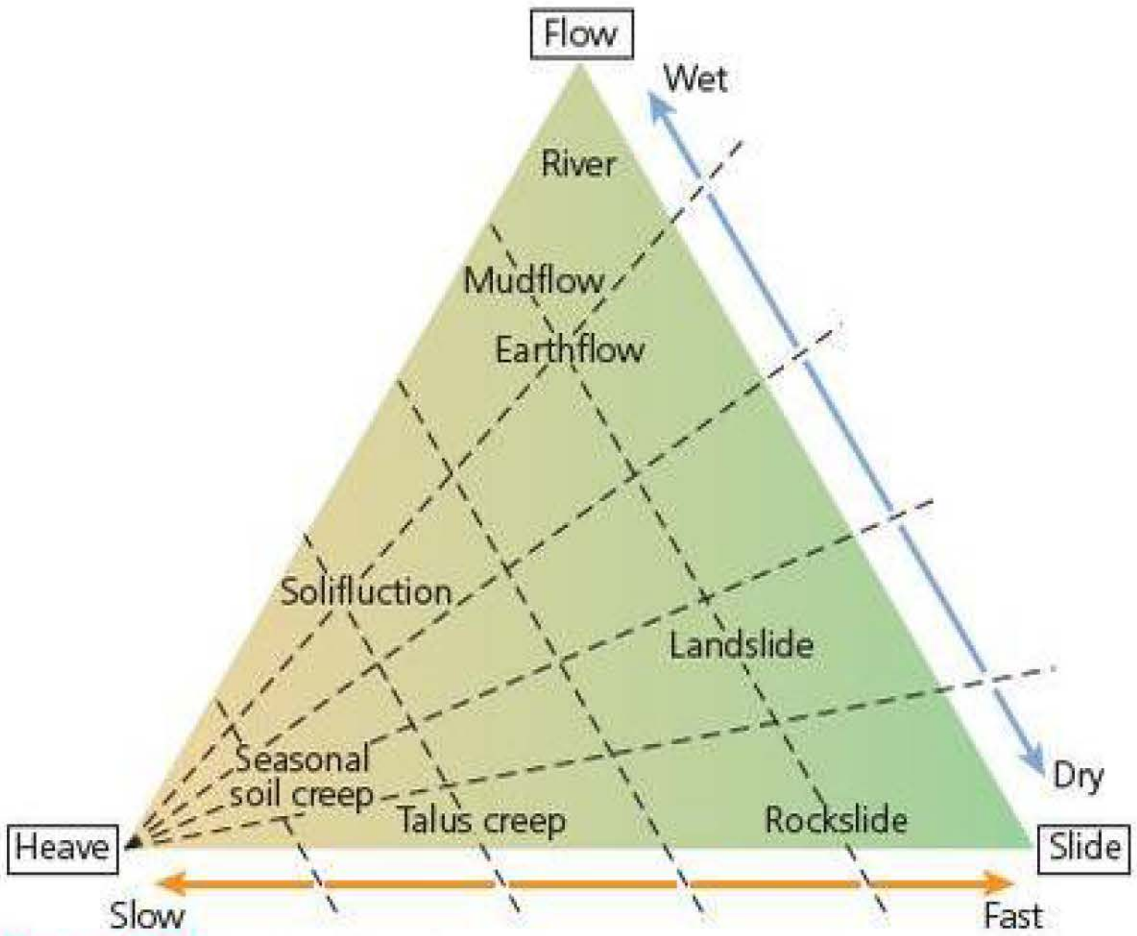

Figure 3.17 A classification of mass movements

A range of slope processes occur that vary in terms of magnitude, frequency and scale. Some are large and occur infrequently, notably rockfalls, whereas others are smaller and more continuous, such as soil creep.

The types of processes can be classified in a number of different ways:

- speed of movement (Figure 3.18)
- water content
- type of movement: flows, slides, slumps
- material.

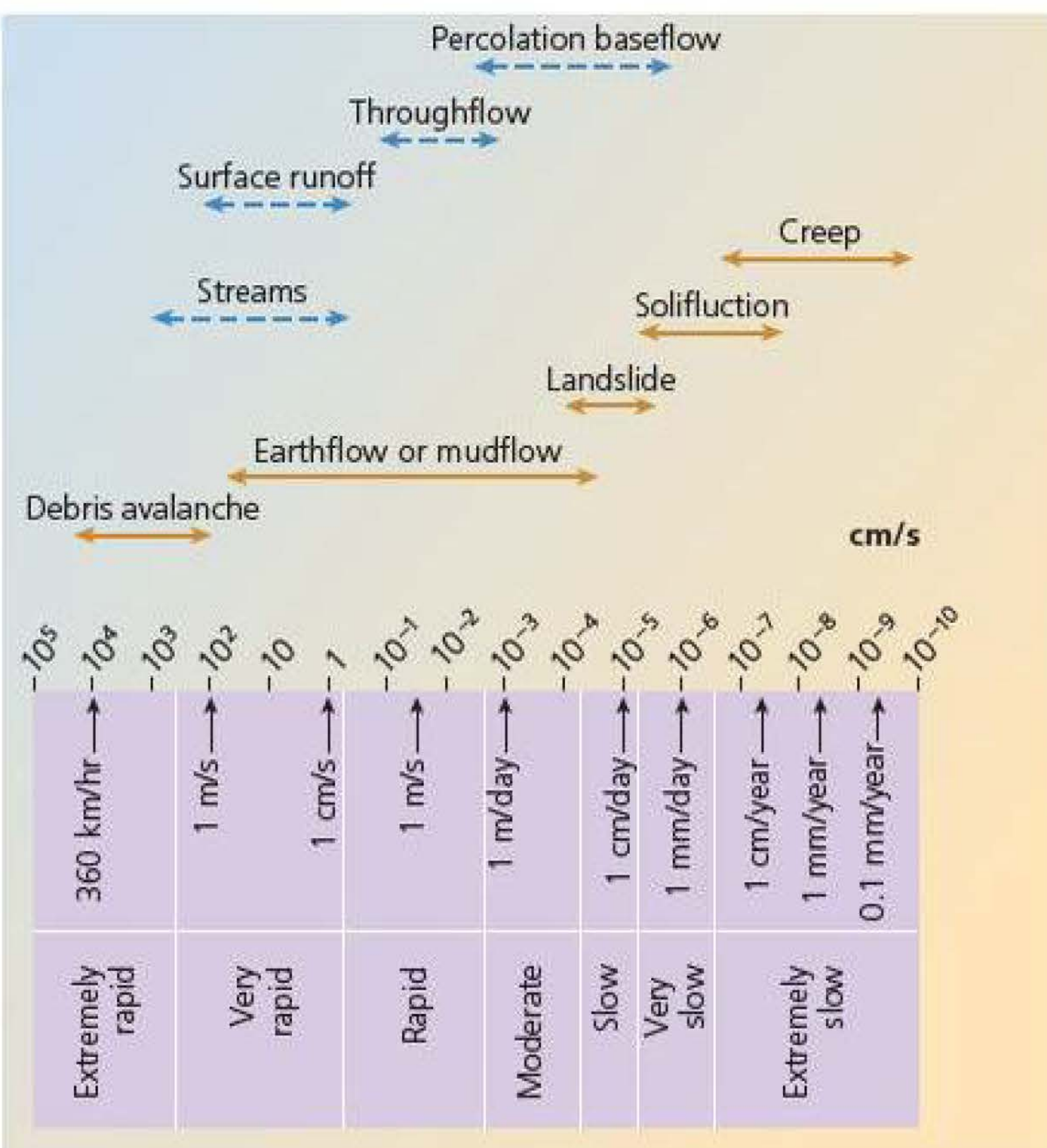

Figure 3.18 Speed of mass movements

Causes of mass movements

The likelihood of a slope failing can be expressed by its safety factor. This is the relative strength or resistance of the slope, compared with the force that is trying to move it. The most important factors that determine movement are gravity, slope angle and pore pressure.

Gravity has two effects. First, it acts to move the material downslope (a slide component). Second, it acts to stick the particle to the slope (a stick component). The downslope movement is proportional to the weight of the particle and slope angle. Water lubricates particles and in some cases fills the spaces between the particles. This forces them apart under pressure. Pore pressure will greatly increase the ability of the material to move. This factor is of particular importance in movements of wet material on low-angle slopes.

Shear strength and shear resistance

Slope failure is caused by two factors:

1. a reduction in the internal resistance, or shear strength, of the slope, or
2. an increase in shear stress; that is, the forces attempting to pull a mass downslope.

Both can occur at the same time.

Increases in shear stress can be caused by a multitude of factors (Table 3.5). These include material

Table 3.5 Increasing stress and decreasing resistance

Factor	Example
Factors that contribute to increased shear stress	
Removal of lateral support through undercutting or slope steepening	Erosion by rivers and glaciers, wave action, faulting, previous rockfalls or slides
Removal of underlying support	Undercutting by rivers and waves, subsurface solution, loss of strength by extrusion of underlying sediments
Loading of slope	Weight of water, vegetation, accumulation of debris
Lateral pressure	Water in cracks, freezing in cracks, swelling (especially through hydration of clays), pressure release
Transient stresses	Earthquakes, movement of trees in wind
Factors that contribute to reduced shear strength	
Weathering effects	Disintegration of granular rocks, hydration of clay minerals, dissolution of cementing minerals in rock or soil
Changes in pore-water pressure	Saturation, softening of material
Changes of structure	Creation of fissures in shales and clays, remoulding of sand and sensitive clays
Organic effects	Burrowing of animals, decay of tree roots

characteristics, weathering processes and changes in water availability. Weaknesses in rocks include joints, bedding planes and faults. Stress may be increased by:

- steepening or undercutting of a slope
- addition of a mass of regolith
- dumping of mining waste
- sliding from higher up the slope
- vibrational shock
- earthquakes.

Weathering may reduce cohesion and resistance. Consequently, material may be more susceptible to movement on slopes, even though the original material was stable.

Water can weaken a slope by increasing shear stress and decreasing shear resistance. The weight of a potentially mobile mass is increased by:

- an increase in the volume of water
- heavy or prolonged rain
- a rising water table
- saturated surface layers.

Moreover, water reduces the cohesion of particles by saturation. Water pressure in saturated soils (pore-water pressure) decreases the frictional strength of the solid material. This weakens the slope. Over time the safety factor for a particular slope will change. These changes may be gradual, for example percolation carrying away finer material. By contrast, some changes are rapid.

There are a number of ways that downslope movement can be opposed:

- **Friction** will vary with the weight of the particle and slope angle. Friction can be overcome on gentle slope angles if water is present. For example, solifluction can occur on slopes as gentle as 3°.
- Cohesive forces act to bind the particles on the slope. Clay may have high cohesion, but this may be reduced if the water content becomes so high that the clay liquefies, when it loses its cohesive strength.
- Pivoting occurs in the debris layers which contain material embedded in the slope.
- **Vegetation** binds the soil and thereby stabilises slopes. However, vegetation may allow soil moisture to build up and make landslides more likely (see pages 75–77).

Section 3.3 Activities

1 a Define the term *mass movement*.
  b Suggest how mass movements can be classified.
2 Define the terms *strength* and *shear stress*.
3 With the use of examples, explain why mass movements occur.

Types of mass movement

Heave or creep is a slow, small-scale process that occurs mostly in winter. It is one of the most important slope processes in environments where flows and slides are not common. Talus creep is the slow movement of fragments on a scree slope.

Individual soil particles are pushed or heaved to the surface by **a** wetting, **b** heating or **c** freezing of water (Figure 3.19). About 75 per cent of the soil-creep movement is induced by moisture changes and associated volume change. Nevertheless, freeze–thaw and normal temperature-controlled expansion and contraction are important in periglacial and tropical climates.

Particles move at right-angles to the surface (2) as it is the zone of least resistance. They fall under the influence of gravity (5) once the particles have dried, cooled, or the water has thawed. Next movement is downslope.

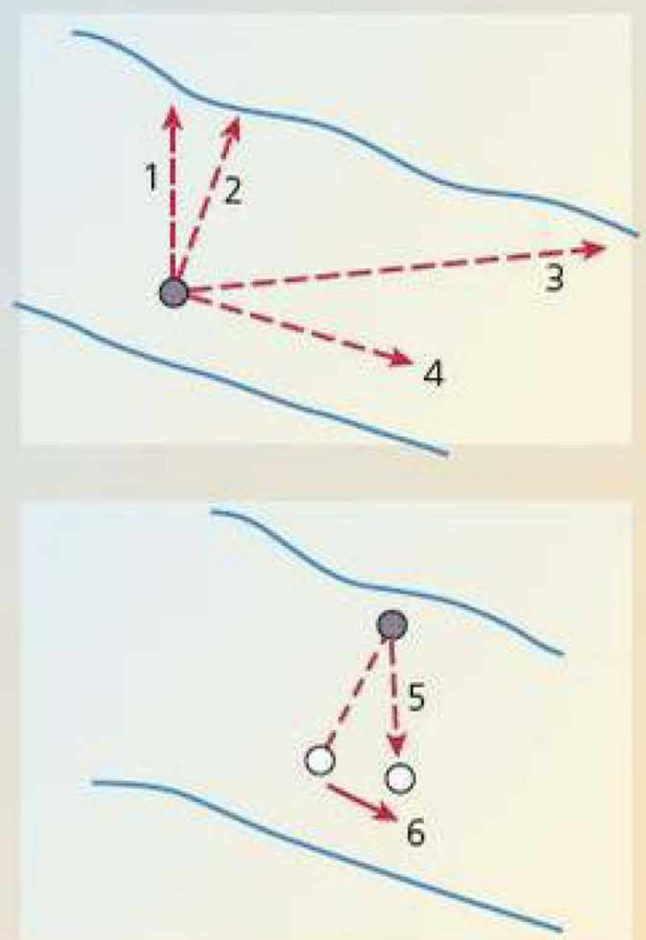

Figure 3.19 Soil creep

Rates of soil creep are slow, at 1–3 millimetres per year in temperate areas and up to 10 millimetres per year in tropical rainforest. They form terracettes. In well-vegetated humid temperate areas, soil creep can be ten times more important than slope wash. In periglacial areas, it can be as much as 300 millimetres per year. By contrast, in arid environments slope wash is more important. Small-scale variations in slope, compaction, cohesion and vegetation will have a significant effect on the rate of creep.

Observation of soil creep is difficult. Traditional qualitative evidence such as bent trees (Figure 3.20) is misleading and now largely discredited. The slow rate of movement may mean that measurement errors are serious.

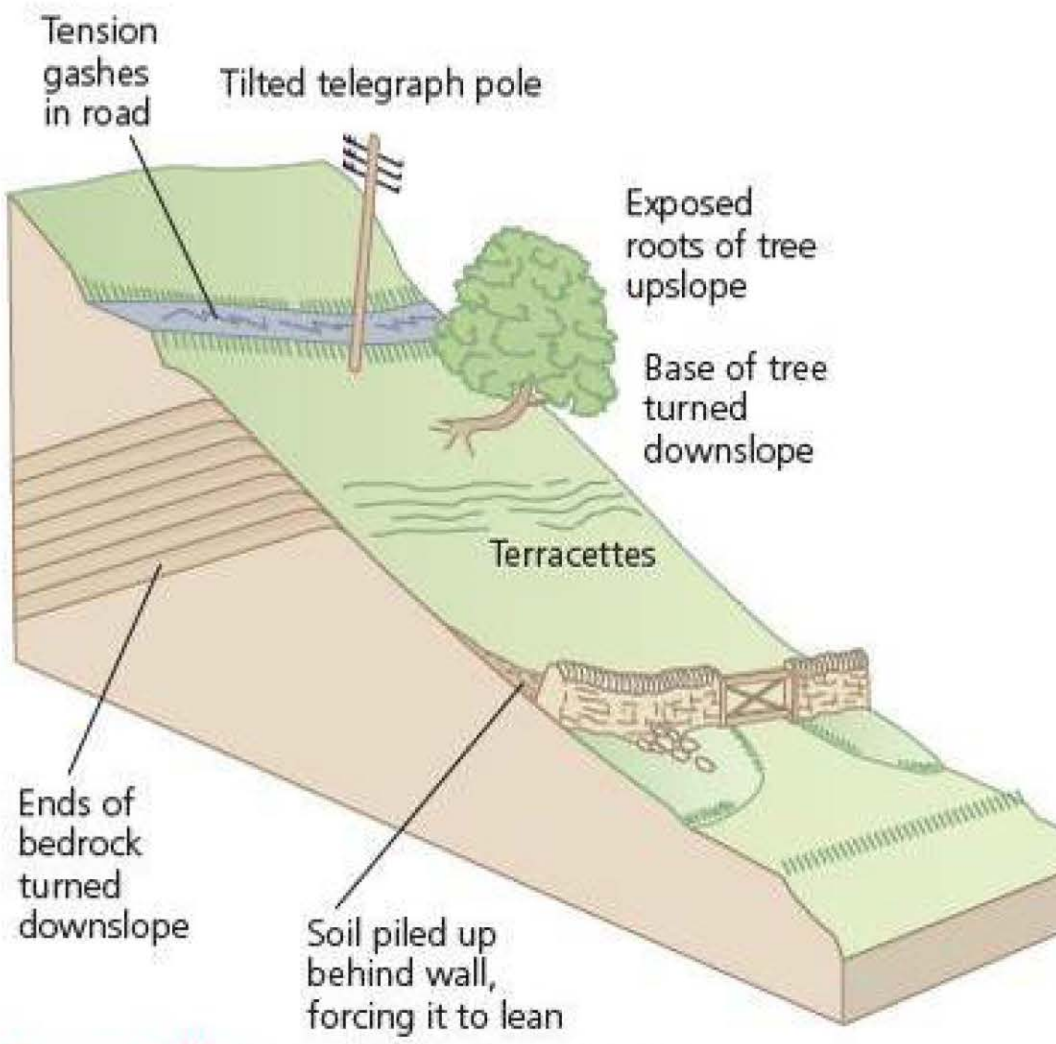

Figure 3.20 The evidence for soil creep

Slumps and flows

Slumps occur on weaker rocks, especially clay, and have a rotational movement along a curved slip plane (Figure 3.21). Clay absorbs water, becomes saturated and exceeds its liquid limit. It then flows along a slip plane. Frequently the base of a cliff has been undercut and weakened by erosion, thereby reducing its strength. By contrast, flows are more continuous, less jerky, and are more likely to contort the mass into a new form (Figure 3.22). Material is predominantly of a small size, such as deeply weathered clays. Particle size involved in flows is generally small, for example sand-sized and smaller.

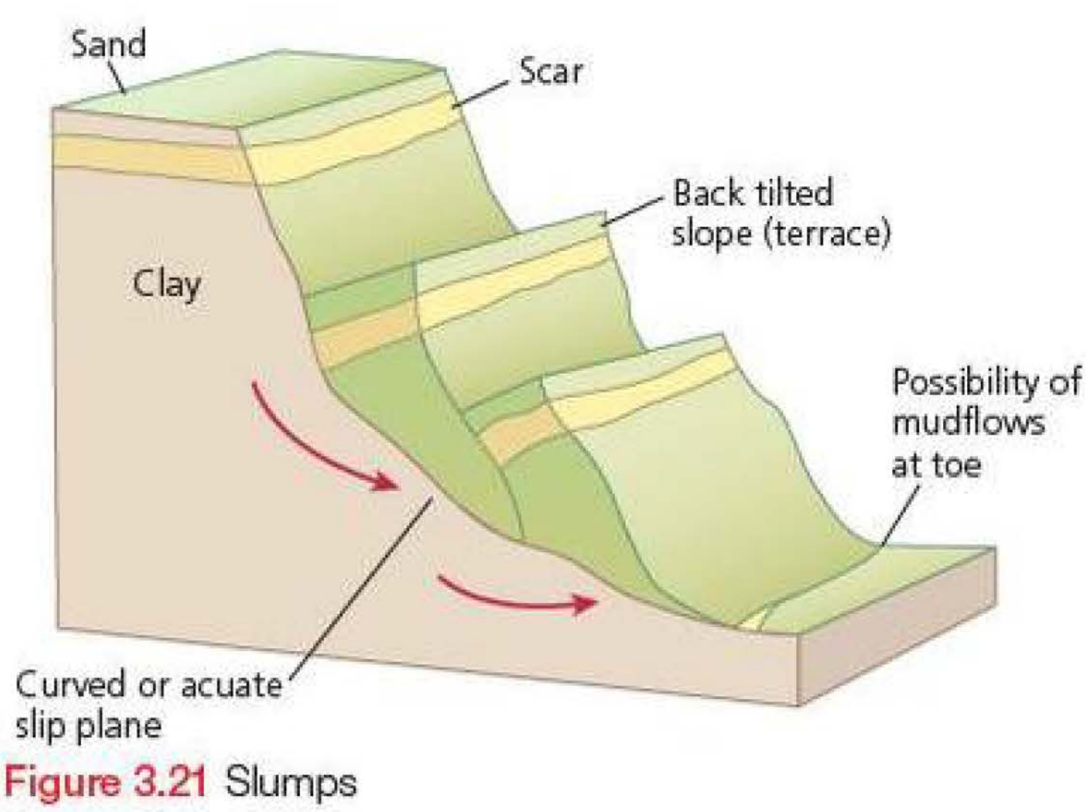

Figure 3.21 Slumps

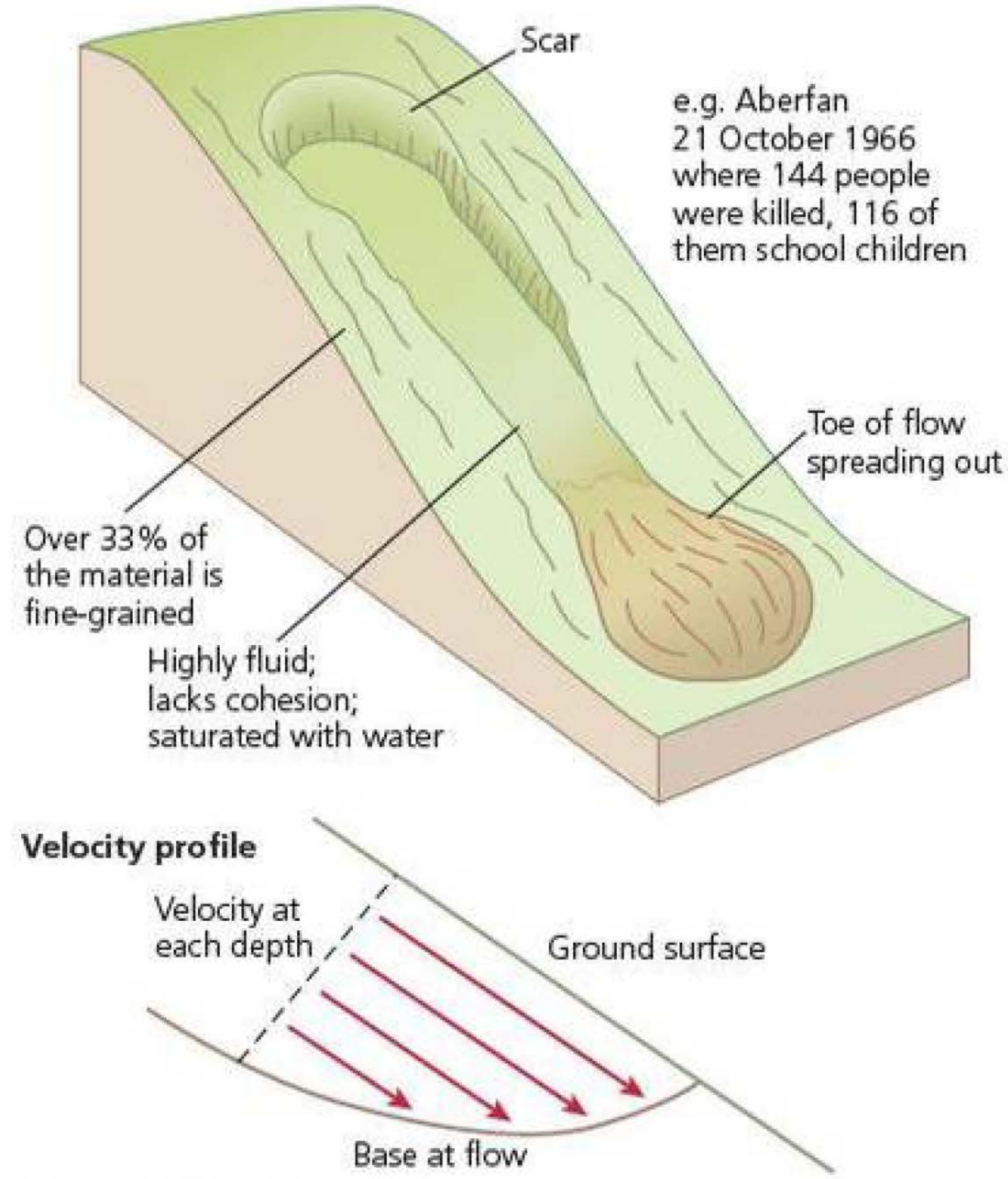

Figure 3.22 Flows

The speed of a flow varies: mudflows are faster and more fluid than earthflows, which tend to be thicker and deeper. A higher water content will enable material to flow across gentle angles.

Earthflows and mudflows can occur on the saturated toe (end) of a landslide, or may form a distinctive type of mass movement in their own right. Small flows may develop locally, whereas others may be larger and more rapid. In theory, mudflows give way to sediment-laden rivers – but the distinction is very blurred.

Case Study: Sidoarjo mudflow

Since May 2006, more than 50 000 people in Porong District, Indonesia, have been displaced by hot mud flowing from a natural well. Gas and hot mud began spewing out when a drill penetrated a layer of liquid sediment. The amount of material spilling out peaked at 135 000 m^3/day in September 2006. By 2010, the main thoroughfare in Porong was raised 80 cm to avoid further mudflows. The Sidoarjo mudflow is an ongoing eruption of gas and mud.

Slides

Slides occur when an entire mass of material moves along a slip plane. These include:

- **rockslides and landslides** of any material, rock or regolith
- **rotational slides**, which produce a series of massive steps or terraces.

Slides commonly occur where there is a combination of weak rocks, steep slopes and active undercutting. Slides are often caused by a change in the water content of a slope or by very cold conditions. As the mass moves along the slip plane, it tends to retain its shape and structure until it hits the bottom of a slope (Figure 3.23). Slides range from small-scale slides close to roads, to large-scale movements that kill thousands of people.

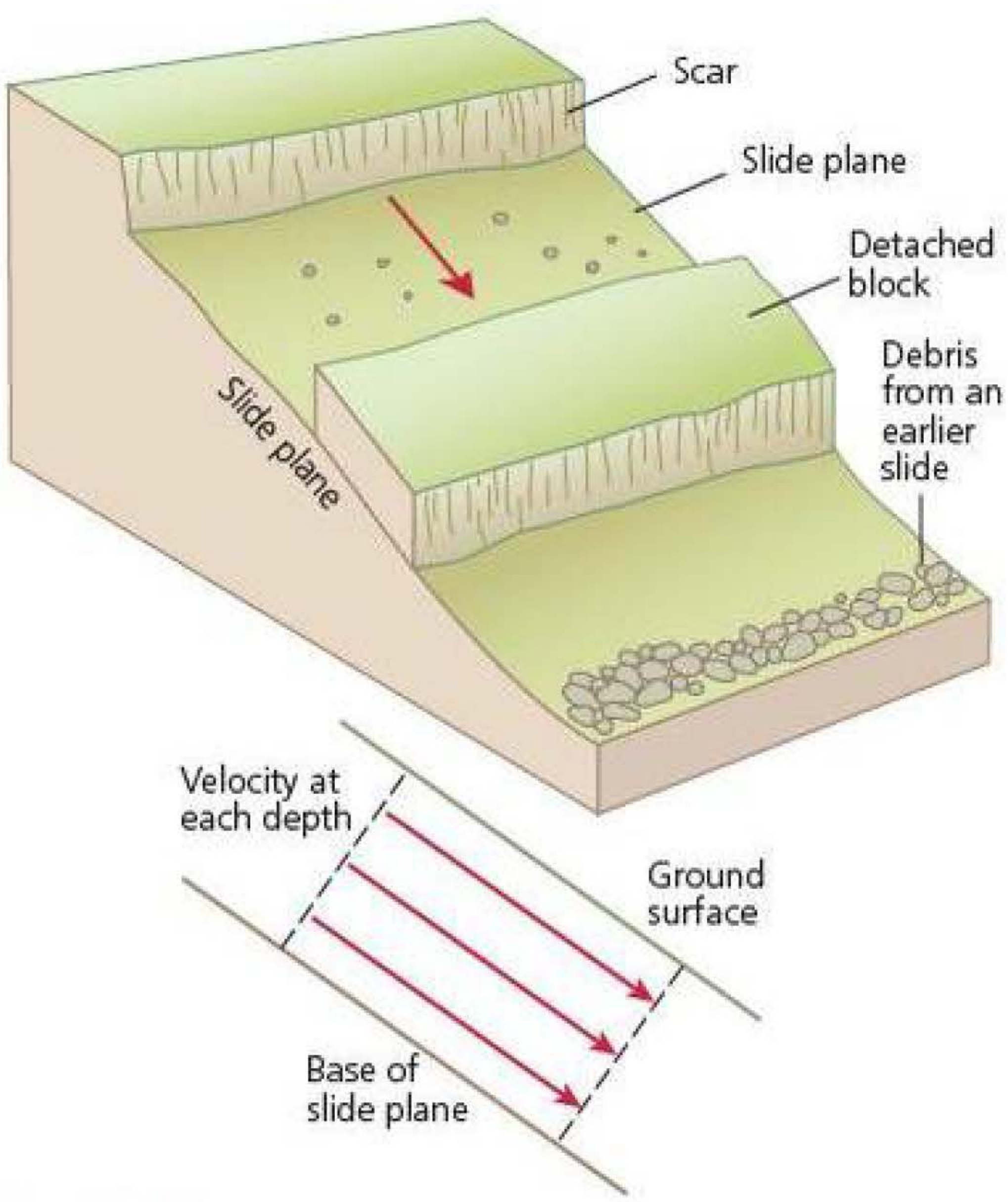

Figure 3.23 Slides

Slip planes occur for a variety of reasons:

- at the junction of two layers
- at a fault line
- where there is a joint
- along a bedding plane
- at the point beneath the surface where the shear stress becomes greater than the shear strength.

Weak rocks such as clay have little shear strength to start with, and are particularly vulnerable to the development of slip planes. The slip plane is typically a concave curve and as the slide occurs the mass will be rotated backwards.

Rockslides

In 1959, the sixth strongest earthquake ever to affect the USA occurred in Montana. Close to the epicentre of the earthquake, in the Madison River valley, a slope of schists and gneiss with slippery mica and clay was supported by a base of dolomite. The earthquake cleanly broke the dolomite. A huge volume of rock, 400 metres high and 1000 metres long, slid into the valley; 80 million tonnes of material moved in less than a minute! The Madison River was dammed and a lake 60 metres deep and 8 kilometres long was created.

Landslides

Loose rock, stones and soil all have a tendency to move downslope. They will do so whenever the downward force exceeds the resistance produced by friction and cohesion. When the material moves downslope as a result of shear failure at the boundary of the moving mass, the term 'landslide' is applied. This may include a flowing movement as well as straightforward sliding. Landslides are very sensitive to water content, which reduces the strength of the material by increasing the water pressure. This effectively pushes particles apart, thereby weakening the links between them. Moreover, water adds weight to the mass, increasing the downslope force.

Case Study: The Abbotsford landslide, Dunedin, New Zealand

The landslide that took place in East Abbotsford, South Island, New Zealand is a very good example of how human and physical factors can interact to produce a hazardous event. It also shows clearly how such hazards can be managed.

From 1978, several families in Abbotsford noticed hairline cracks appearing in their homes – in the brickwork, concrete floors and driveways. During 1979, workmen discovered that a leaking water main had been pulled apart. Geologists discovered that water had made layers of clay on the hill soft, and the sandstone above it was sliding on this slippery surface.

As a result, an early warning system was put in place. A civil defence emergency was declared on 6 August, although the situation wasn't thought to be urgent as geologists believed that landslip would continue to move only slowly. However, on 8 August a 7 hectare section of Abbotsford started down the hill at a rate of over 3 metres a minute (Figure 3.24), with houses and 17 people on board. No-one was killed, although 69 homes were destroyed or damaged and over 200 people were displaced. The total cost from the destruction of the homes, infrastructure and relief operation amounted to over £7 million. An insurance scheme designed to cope with such disasters, and government and voluntary relief measures, meant that many of the residents were compensated for their loss. However, other costs, such as depressed house prices in the surrounding area, psychological trauma and the expense of a prolonged public enquiry, were not immediately appreciated.

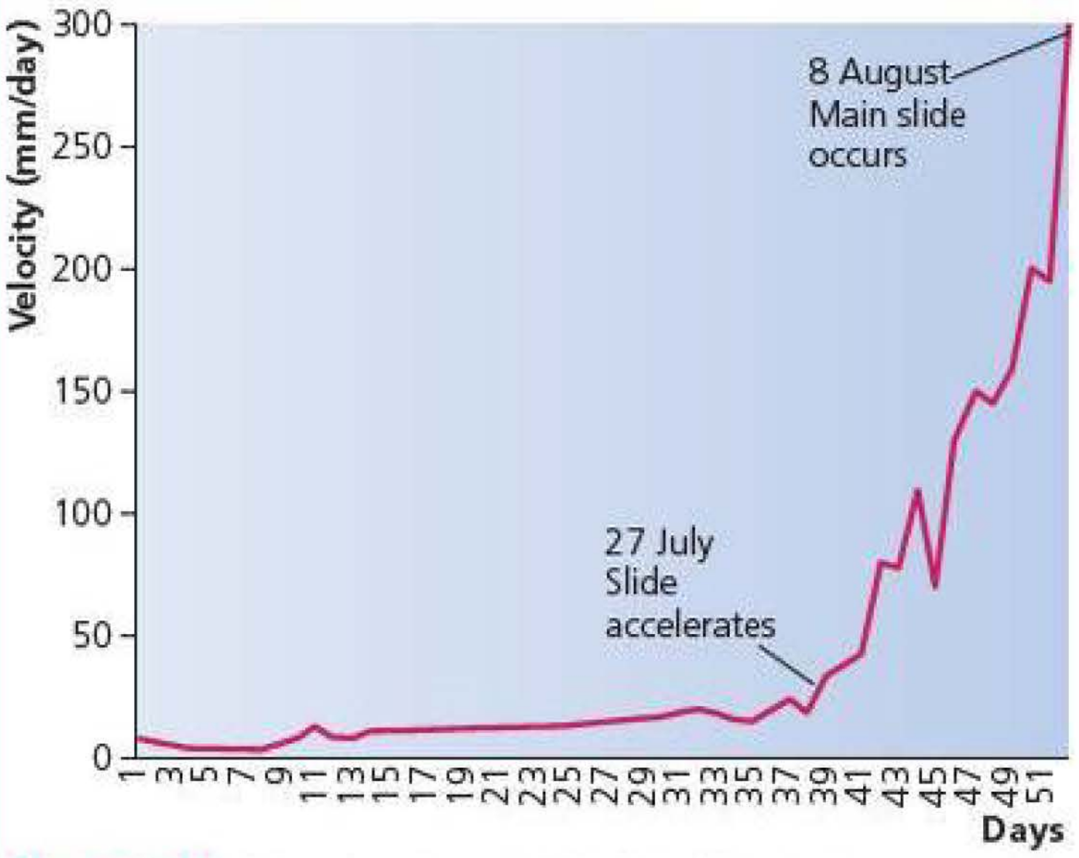

Figure 3.24 Abbotsford landslide, New Zealand

The landslide was essentially a block slide of sandstone resting on a bed of weaker clay. Displacement of 50 metres took place in about 30 minutes, leaving a small rift 30 metres deep at the head of the slope. Such geological conditions – in which a permeable hard rock rests on an impermeable soft rock – are commonly associated with landslides. In addition, the slope was dipping at an angle of 7°. Water collected in the impermeable clay, reduced its strength and cohesion, and caused the sandstone to slip along the boundary of the two rocks.

The landslide involved 5.4 million m^3 of material. At first, the land moved as a slow creep, followed by a rapid movement with speeds of 1.7 metres per minute. Rapid sliding lasted for about 30 minutes. An area of about 18 hectares was affected.

However, other factors are also believed to have made a contribution. Deforestation in the area, even over a century before, had reduced evapotranspiration in the area and there was less binding of the soil by plant roots. Urbanisation in the previous 40 years had modified the slopes by cutting and infilling, and had altered surface drainage (speeding up the removal of surface water). Quarrying of material at the toe of the slope in the 1960s and 1970s had removed support from the base of the slope. The trigger of the landslide is believed to have been a combination of leaking water pipes and heavy rainfall.

A number of lessons can be learnt from the Abbotsford landslide:

- Dangerous landslides can occur on relatively gentle slopes if the right conditions exist.
- Attention to early warning can help preparedness and reduce the loss of life.
- Human activity can destabilise slopes.
- Low-frequency, high-magnitude events may be hard to predict, but mapping and dating of old hazards may indicate areas of potential risk – a regional landslide **hazard assessment** should be made where there is evidence of previous landslide activity.
- A landslide insurance scheme eased the cost of the event – however, money was available only after the event rather than beforehand, and the insurance only covered houses, not land damage.

Section 3.3 Activities

1 What were the causes of the Abbotsford landslide?
2 Describe the impacts of the Abbotsford landslide.
3 What lessons can be learnt from the Abbotsford landslide?

Case Study: Mexican landslides, 2010

In October 2010, mud buried part of a remote town in the southern Mexican state of Oaxaca when a large chunk of a nearby mountain collapsed after three days of relentless rain. Initially, it was thought that the landslide had caused a massive tragedy with up to 1000 people killed. However, the number of deaths was believed to be less than ten. The landslide happened at about four o'clock in the morning. The authorities were unsure how many houses had been buried because it was dark, so they estimated.

The rescue progress along the unpaved mountain road was hampered by smaller landslides and a collapsed bridge. Heavy cloud cover prohibited helicopters from getting a clear view of the situation on the ground. When the first rescue workers and soldiers eventually reached the town, they found considerable destruction in one relatively small part of the town. Two houses were completely interred, two partially buried and thirty more in serious danger because they lay within the path of the still-unstable mudflow.

In 2010, Mexico experienced one of the most intense rainy seasons on record, with large areas under water in lowland regions of Oaxaca as well as in other southern states. Landslides are a major danger in mountainous parts of the country – particularly those, such as Oaxaca, that have long suffered from severe deforestation.

Falls

Falls occur on steep slopes (greater than 40°), especially on bare rock faces where joints are exposed. The initial cause of the fall may be weathering, such as freeze–thaw or disintegration, or erosion prising open lines of weakness. Once the rocks are detached, they fall under the influence of gravity (Figure 3.25). If the fall is short, it produces a relatively straight scree. If it is long, it forms a concave scree. Falls are significant in producing the retreat of steep rock faces and in providing debris for scree slopes and talus slopes.

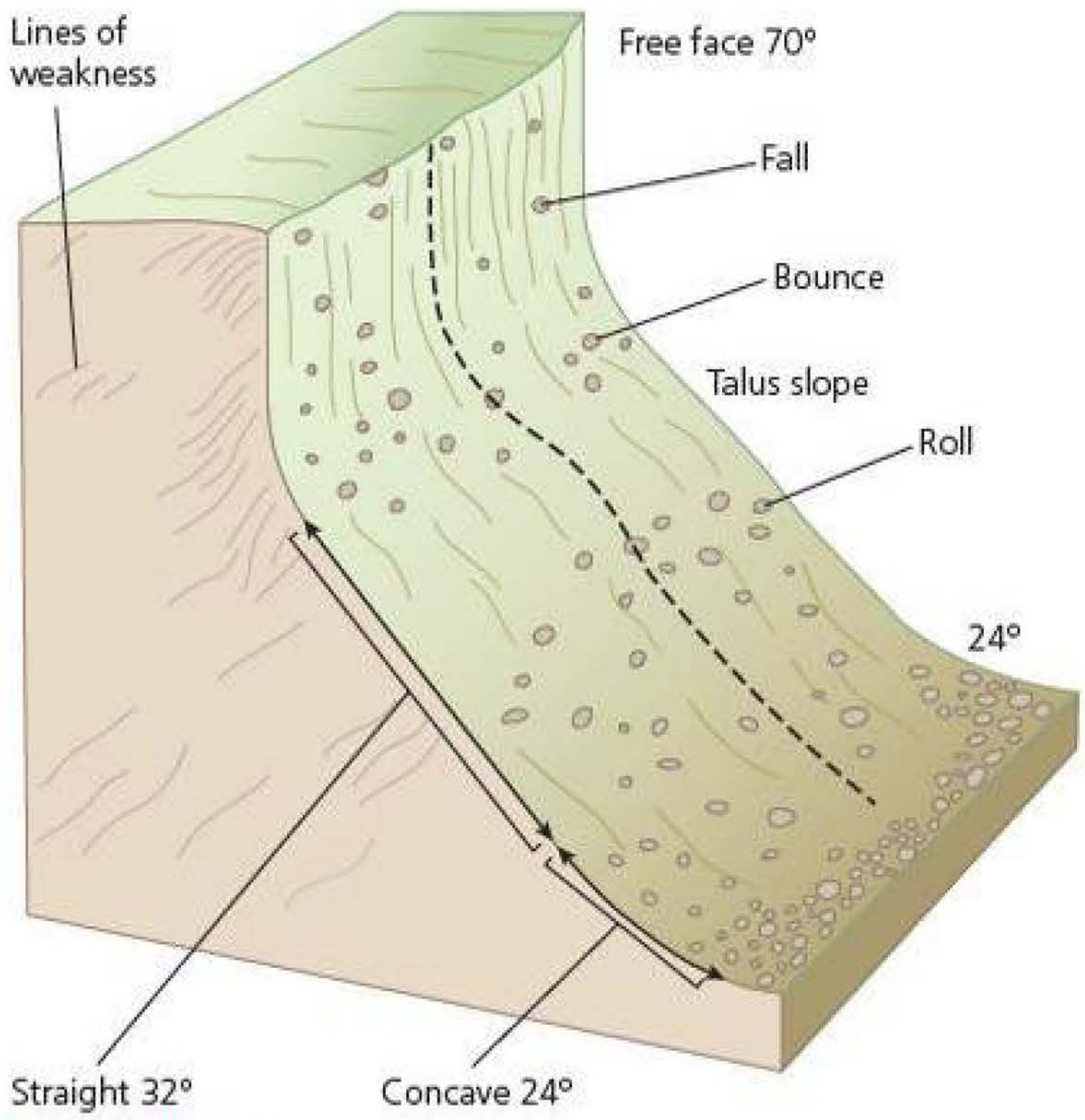

Figure 3.25 Falls

Section 3.3 Activities

1 Explain the terms *mass movement*, *soil creep* and *rotational slide*.
2 Outline the main characteristics of slumps and flows.

Water and sediment movement on hillslopes

Surface wash occurs when the soil's infiltration capacity is exceeded. In the UK, this commonly occurs in winter as water drains across saturated or frozen ground, following prolonged or heavy downpours or the melting of snow. It is also common in arid and semi-arid regions where particle size limits percolation.

Sheetwash is the unchannelled flow of water over a soil surface. On most slopes, sheetwash breaks into areas of high velocity separated by areas of lower velocity. It is capable of transporting material dislodged by rainsplash (see the following section). Sheetwash occurs in the UK on footpaths and moorlands. For example, during the Lynmouth floods of 1952, sheetwash from the shallow moorland peat caused gullies 6 metres deep to form. In the semi-arid areas of south-west USA, it lowers surfaces by 2–5 millimetres per year compared with 0.01 millimetres per year on vegetated slopes in a temperate climate.

Sheetwash erosion of soil occurs through raindrop impact and subsequent transport by water flowing overland rather than in channels. The result is a relatively uniform layer of soil being eroded. A **rill** is a relatively shallow channel, generally less than tens of centimetres deep and carrying water and sediment for only a short period. Rills are common in agricultural areas, following the removal of vegetation during the harvest season, and the ground subsequently being left bare. They are also common in areas following deforestation or land-use changes. Ground compaction by machinery may also lead to the generation of rills during rainfall events.

Throughflow refers to water moving down through the soil. It is channelled into natural pipes in the soil. This gives it sufficient energy to transport material, and added to its solute load, may amount to a considerable volume.

Rainsplash erosion

Raindrops can have an erosive effect on hillslopes (Figure 3.26). On a 5° slope, about 60 per cent of the movement is downslope. This figure increases to 95 per cent on a 25° slope. The amount of erosion depends on the rainfall intensity, velocity and raindrop distribution. It is most effective on slopes of between 33° and 45° and at the start of a rainfall event when the soil is still loose.

On flat surfaces **a** raindrops compact the soil and dislodge particles equally in all directions. On steep slopes **b** the downslope component is more effective than the upslope motion due to gravity. Erosion downslope increases with slope angle.

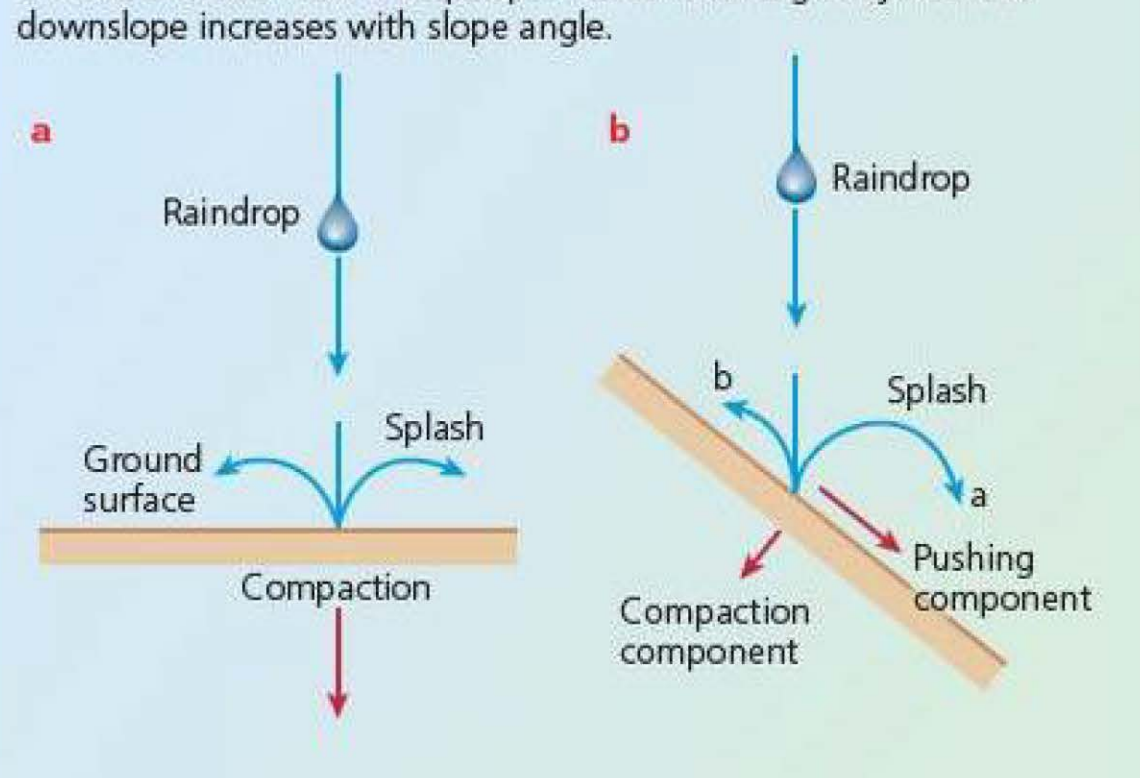

Figure 3.26 Rainsplash erosion

Section 3.3 Activities

1 Briefly explain how rainsplash erosion occurs.
2 Define the term *sheetwash*.
3 Under what conditions do rills occur?