2

Weathering and slopes

'Every valley shall be exalted, and every mountain and hill shall be made low: and the crooked shall be made straight, and the rough places plain.'

The Bible, Isaiah 40:4

Weathering

The majority of rocks have been formed at high temperatures (igneous and many metamorphic rocks) and/or under great pressure (igneous, metamorphic and sedimentary rocks), but in the absence of oxygen and water. If, later, these rocks become exposed on the Earth's surface, they will experience a release of pressure, be subjected to fluctuating temperatures, and be exposed to oxygen in the air and to water. They are therefore vulnerable to **weathering**, which is the disintegration and decomposition of rock *in situ* – i.e. in its original position. Weathering is, therefore, the natural breakdown of rock and can be distinguished from erosion because it need not involve any movement of material. Weathering is the first stage in the **denudation** or wearing down of the landscape; it loosens material which can subsequently be transported by such agents of erosion as running water (Chapter 3), ice (Chapter 4), the sea (Chapter 6) and the wind (Chapter 7). The degree of weathering depends upon the structure and mineral composition of the rocks, local climate and vegetation, and the length of time during which the weathering processes operate.

There are two main types of weathering:

1 **Mechanical** (or **physical**) **weathering** is the disintegration of rock into smaller particles by mechanical processes but without any change in the chemical composition of that rock. It is more likely to occur in areas devoid of vegetation, such as deserts, high mountains and arctic regions. Physical weathering usually produces sands.

2 **Chemical weathering** is the decomposition of rock resulting from a chemical change. It produces changed substances and solubles, and usually forms clays. Chemical weathering is more likely to take place in warmer, more moist climates where there is an associated vegetation cover.

It should be appreciated that although in any given area either mechanical or chemical weathering may be locally dominant, both processes usually operate together rather than in isolation.

Mechanical weathering

Frost shattering

This is the most widespread form of mechanical weathering. It occurs in rocks that contain crevices and joints (e.g. joints formed in granite as it cooled, bedding planes found in sedimentary rocks, and pore spaces in porous rocks), where there is limited vegetation cover and where temperatures fluctuate around 0°C (page 134). In the daytime, when it is warmer, water enters the joints, but during cold nights it freezes. Frost leads to mechanical breakdown in two ways:

1 As ice occupies 9 per cent more volume than water, it exerts pressure within the joints.

2 When water freezes within the rock it attracts small particles of water, creating increasingly large ice crystals.

In each case the alternating **freeze–thaw process**, or **frost shattering**, slowly widens the joints and, in time, causes pieces of rock to shatter from the main body. Where this **block disintegration** occurs on steep slopes, large angular rocks collect at the foot of the slope as **scree** or **talus** (Figure 2.1); if the slopes are gentle, however, large **blockfields** (felsenmeer) tend to develop. Frost shattering is more common in upland regions of Britain where temperatures fluctuate around freezing point for several months in winter, than in polar areas where temperatures rarely rise above 0°C.

Salt crystallisation

If water entering the pore spaces in rocks is slightly saline then, as it evaporates, salt crystals are likely to form. As the crystals become larger, they exert stresses upon the rock, causing it to disintegrate. This process occurs in hot deserts where capillary action draws water to the surface and where the

Figure 2.1

The formation of screes resulting from frost shattering: Moraine Lake, Banff National Park, Canada

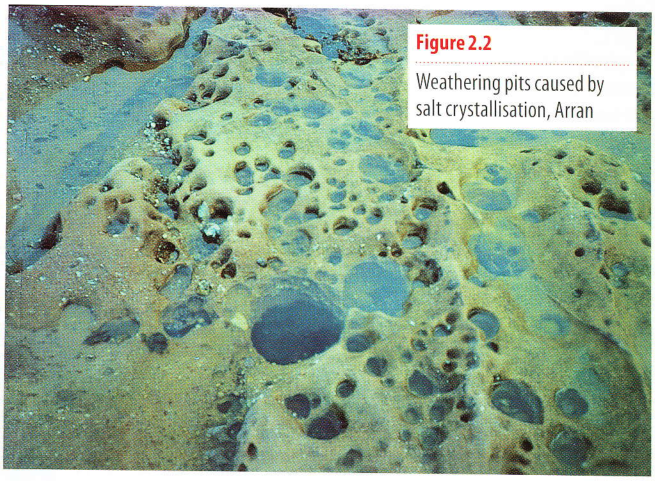


Figure 2.2

Weathering pits caused by salt crystallisation, Arran

rock is sandstone (page 182). Individual grains of sand are broken off by **granular disintegration**. Salt crystallisation also occurs on coasts where the constant supply of salt can lead to the development of weathering pits (Figure 2.2).

Pressure release

As stated earlier, many rocks, especially intrusive jointed granites, have developed under considerable pressure. The confining pressure increases the strength of the rocks. If these rocks, at a later date, are exposed to the atmosphere, then there will be a substantial release of pressure. (If you had 10 m of bedrock sitting on top of you, you would be considerably relieved were it to be removed!) The release of pressure weakens the rock allowing other agents to enter it and other processes to develop. Where cracks develop parallel to the surface, a process called **sheeting** causes the outer layers of rock to peel away. This process is now believed to be responsible for the formation of large, rounded rocks called **exfoliation domes** (Figures 2.3 and 7.6) and, in part, for the granite tors of Dartmoor and the Isle of Arran (Figures 8.14 and 8.15). Jointing, caused by pressure release, has also accentuated the characteristic shapes of glacial cirques and troughs (Figures 2.4, 4.14 and 4.15).

Figure 2.3

An exfoliation dome: Sugar Loaf Mountain in Rio de Janeiro, Brazil

Thermal expansion or insolation weathering

Like all solids, rocks expand when heated and contract when cooled. In deserts, where cloud and vegetation cover are minimal, the diurnal range of temperature can exceed 50°C. It was believed that, because the outer layers of rock warm up faster and cool more rapidly than the inner ones, stresses were set up that would cause the outer thickness to peel off like the layers of an onion – the process of **exfoliation** (page 181). Initially, it was thought that it was this expansion–contraction process which produced exfoliation domes. Changes in temperature will also cause different minerals within a rock to expand and contract at different rates. It has been suggested that this causes **granular disintegration** in rocks composed of several minerals (e.g. granite which consists of quartz, feldspar and mica), whereas in homogeneous rocks it is more likely to cause block disintegration.

Laboratory experiments (e.g. by Griggs in 1936 and Goudie in 1974) have, however, cast doubt on the effectiveness of insolation weathering (page 181).

Biological weathering

Tree roots may grow along bedding planes or extend into joints, widening them until blocks of rock become detached (Figure 2.5). It is also claimed that burrowing creatures, such as worms and rabbits, may play a minor role in the excavation of partially weathered rocks.

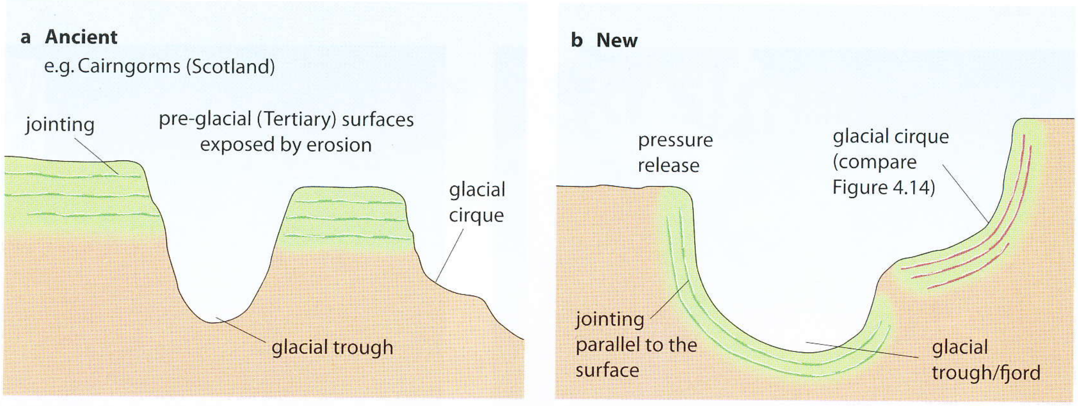


Figure 2.4

The process of pressure release tends to perpetuate landforms: as new surfaces are exposed, the reduction in pressure causes further jointing parallel to the surface

Chemical weathering

Chemical weathering tends to:

- attack certain minerals selectively
- occur in zones of alternate wetting and drying, e.g. where the level of the water table fluctuates
- occur mostly at the base of slopes where it is likely to be wetter and warmer.

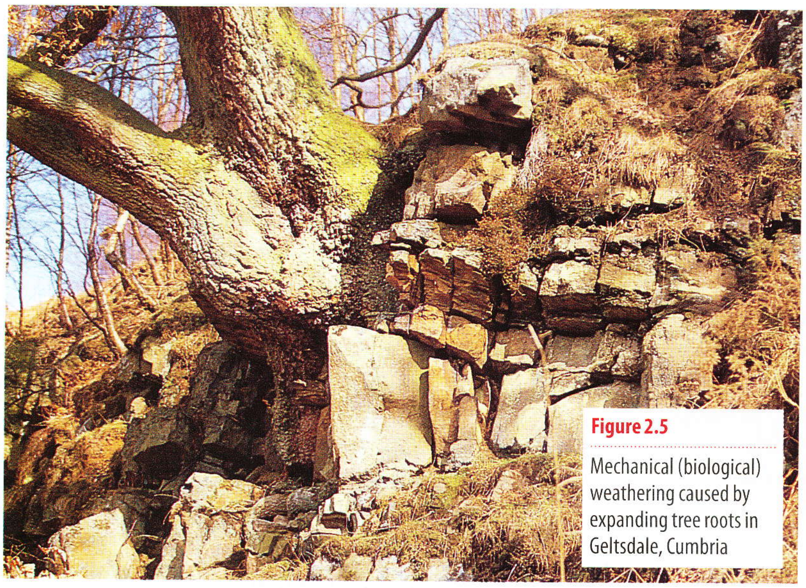


Figure 2.5

Mechanical (biological) weathering caused by expanding tree roots in Geltsdale, Cumbria

Figure 2.6

Oxidation in Geltsdale, Cumbria

This type of weathering involves a number of specific processes which may operate in isolation but which are more likely to be found in conjunction with one another. Formulae for the various chemical reactions are listed at the end of the chapter, page 57.

Oxidation

This occurs when rocks are exposed to oxygen in the air or water. The simplest and most easily recognised example is when iron in a **ferrous** state is changed by the addition of oxygen into a **ferric** state. The rock or soil, which may have been blue or grey in colour (characteristic of a lack of oxygen), is discoloured into a reddish-brown – a process better known as **rusting** (Figure 2.6). Oxidation causes rocks to crumble more easily.

In waterlogged areas, oxidation may operate in reverse and is known as **reduction**. Here, the amount of oxygen is reduced and the soils take on a blue/green/grey tinge (see **gleying**, page 272).

Hydration

Certain rocks, especially those containing salt minerals, are capable of absorbing water into their structure, causing them to swell and to become vulnerable to future breakdown. For example, gypsum is the result of water having been added to anhydrite ($CaSO_4$). This process appears to be most active following successive periods of wet and dry weather and is important in forming clay particles. Hydration is in fact a physio-chemical process as the rocks may swell and exert pressure as well as changing their chemical structure.

Hydrolysis

This is possibly the most significant chemical process in the decomposition of rocks and formation of clays. Hydrogen in water reacts with minerals in the rock or, more specifically, there is a combination of the $H+$ and $OH-$ ions in the water and the ions of the mineral (i.e. the water combines with the mineral rather than dissolving it).

The rate of hydrolysis depends on the amount of H+ ions, which in turn depends on the composition of air and water in the soil (Figure 10.4), the activity of organisms (page 268), the presence of organic acids (page 271) and the cation exchange (page 269). An example of hydrolysis is the breakdown of feldspar (Figure 2.7), a mineral found in igneous rocks such as granite, into a residual clay deposit known as kaolinite (china clay). Granite consists of three minerals – quartz, mica and feldspar (Figure 8.2c) – and, as the table below shows, each reacts at a different rate with water.

Quartz	Mica	Feldspar
Not affected by water, remains unchanged as sand (Figure 2.7)	May be affected by water under more acid conditions releasing aluminium and iron	Readily attracts water producing a chemical change which turns the feldspar into clay (kaolin or china clay)

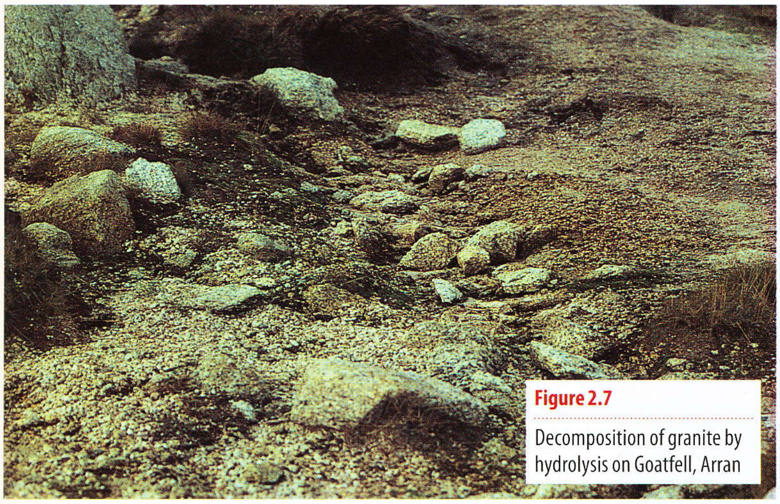


Figure 2.7

Decomposition of granite by hydrolysis on Goatfell, Arran

Figure 2.8

Carbonation of limestone near Ingleton, North Yorkshire

Carbonation

Rainwater contains carbon dioxide in solution which produces carbonic acid (H_2CO_3). This weak acid reacts with rocks that are composed of calcium carbonate, such as limestone. The limestone dissolves and is removed in solution (calcium bicarbonate) by running water. Carboniferous limestone is well-jointed and bedded (Chapter 8), which results in the development of a distinctive group of landforms (Figure 2.8).

Solution

Some minerals, e.g. rock salt, are soluble in water and simply dissolve *in situ*. The rate of solution can be affected by acidity since many minerals become more soluble as the pH of the solvent increases (page 269).

Organic weathering

Humic acid, derived from the decomposition of vegetation (humus), contains important elements such as calcium, magnesium and iron. These are released by a process known as **chelation** (page 271). The action of bacteria and the respiration of plant roots tends to increase carbon dioxide levels which helps accelerate solution processes, especially carbonation. Lichen can also extract iron from certain rocks through the process of reduction. Recent research suggests that lichen and blue-green algae, which form the pioneer community in the development of a lithosere (page 288), play a far greater weathering role than was previously thought. However, it should be remembered that the presence of a vegetation cover dramatically reduces the extent of mechanical weathering.

Acid rain

Human economic activities (such as power generation and transport) release increasingly more carbon dioxide, sulphur dioxide and nitrogen oxide into the atmosphere. These gases then form acids in solution in rainwater (page 222). Acid rain readily attacks limestones and, to a lesser extent, sandstones, as shown by crumbling buildings and statues (Figure 2.9). The increased level of acidity in water passing through the soil tends to release more hydrogen and so speeds up the process of hydrolysis. An indirect consequence of acid rain is the release from certain rocks of toxic metals, such as aluminium, cadmium, copper and zinc, which can be harmful to plants and soil biota (page 268).

Some authorities, including Andrew Goudie, prefer to divide weathering into three categories rather than the two described here. Their alternative classification includes, as a third category, **biological weathering**. Instead of including 'biological' under mechanical weathering and 'organic' under chemical weathering, they would group these two types together under the heading 'biological weathering'.

Climatic controls on weathering

Mechanical weathering

Frost shattering is important if temperatures fluctuate around 0°C, but will not operate if the climate is too cold (permanently frozen), too warm (no freezing), too dry (no moisture to freeze), or too wet (covered by vegetation). Mechanical weathering will not take place at X on Figure 2.10a where it is too warm and there is insufficient moisture, while at Y, the high temperature and heavy rainfall will give a thick protective vegetation cover against insolation.

Figure 2.9

Acid rain damage to stone statues, Exeter Cathedral

Chemical weathering

This increases as temperatures and rainfall totals increase. It has been claimed that the rate of chemical weathering doubles with every 10°C temperature increase. Recent theories suggest that, in humid tropical areas, direct removal by solution may be the major factor in the lowering of the landscape, due to the continuous flow of water through the soil. Chemical weathering will be rapid at **S** (Figure 2.10b) due to humic acid from the vegetation. It will be limited at **P**, because temperatures are low, and at **R**, where there is insufficient moisture for the chemical decomposition of rocks. Carbon dioxide is an exception in that, being more soluble at lower as opposed to higher temperatures, it can accelerate rates of solution in cold climates.

Weathering regions

Peltier, an American physicist and climatologist, attempted to predict the type and rate of weathering at any given place in the world from its mean annual temperature and mean annual rainfall (Figure 2.10c). It should be realised that mechanical and chemical weathering usually operate together at the same time and at the same place, but it is likely that in each situation one type or the other will be the more significant.

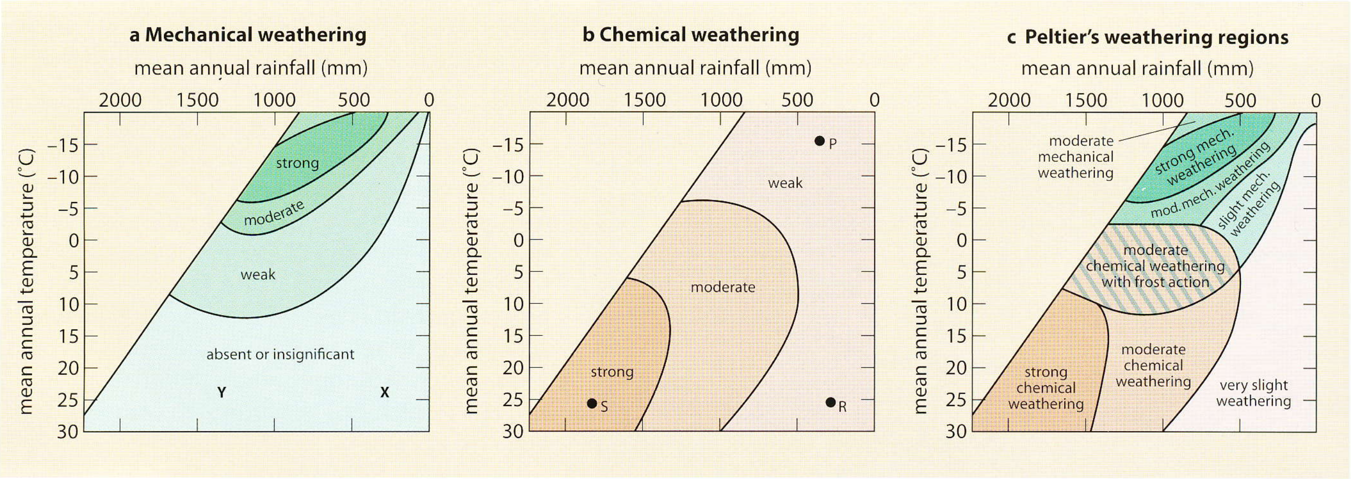


Figure 2.10

Climatic controls on weathering (*after* Peltier)

Framework 3 A systems approach

One type of model (Framework 12, page 352) widely adopted by geographers to help explain phenomena is the **system**. The system is a method of analysing relationships within a unit and consists of a number of components between which there are linkages. The model is usually illustrated schematically as a flow diagram.

Systems may be described in three ways:

- **Isolated:** there is no input or output of energy or matter. Some suggest the universe is the sole example of this type; others claim the idea is not applicable in geography.
- **Closed:** there is input, transfer and output of energy but not of matter (or mass).
- **Open:** most environmental systems are open and there are inputs and outputs of both energy and matter.

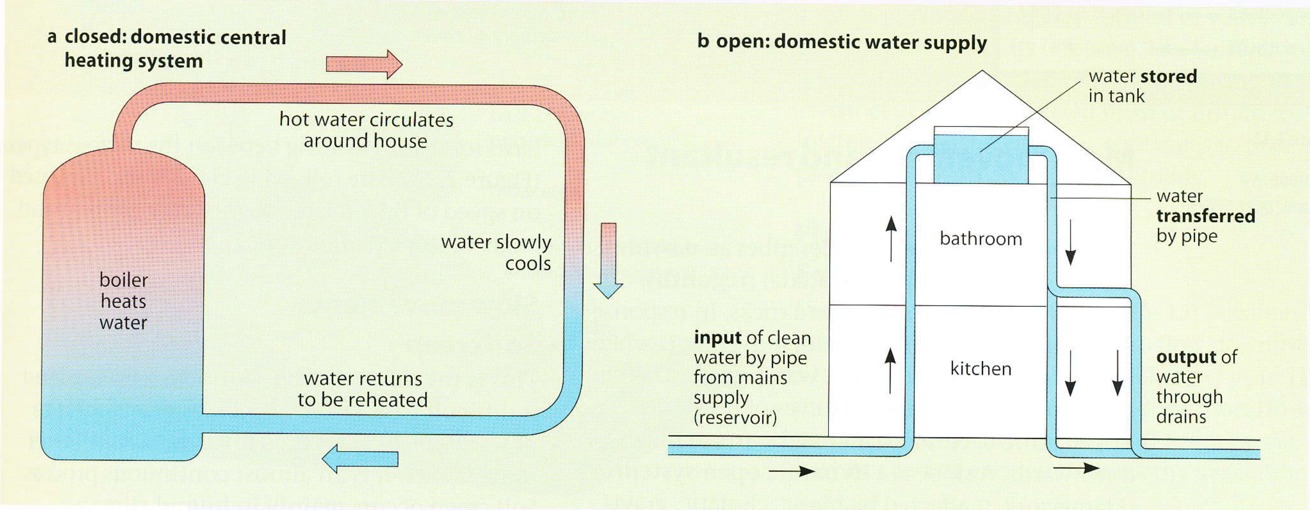


Figure 2.11

Closed and open systems in the house

Examples of the systems approach used and referred to in this book (chapter number is given in brackets):

Geomorphological	Climate, soils and vegetation	Human and economic
Slopes (2)	Atmosphere energy budget (9)	Population change (13)
Drainage basins (3)	Hydrological cycle (9)	Farming (16)
Glaciers (4)	Soils (10)	Industry (19)
	Ecosystems (11)	
	Nutrient cycle (12)	

When opposing forces, or inputs and outputs, are balanced, the system is said to be in a state of **dynamic equilibrium**. If one element in the system changes because of some outside influence, then it upsets this equilibrium and affects the other components. For example, equilibrium is upset when:

- prolonged heavy rainfall causes an increase in the discharge and velocity of a river or a lowering of base level (page 81), both of which lead to an increase in the rate of erosion
- an increase in carbon dioxide into the atmosphere causes global temperatures to rise (global warming, Case Study 9)
- drought affects the carrying capacity of animals (or people) grazing (living) in an area as the water shortage reduces the availability of grass (food supplies) (page 378)
- an increase in the number of tourists to places of scenic attraction harms the environment (especially where it is fragile) that was the original source of the attraction (page 591).

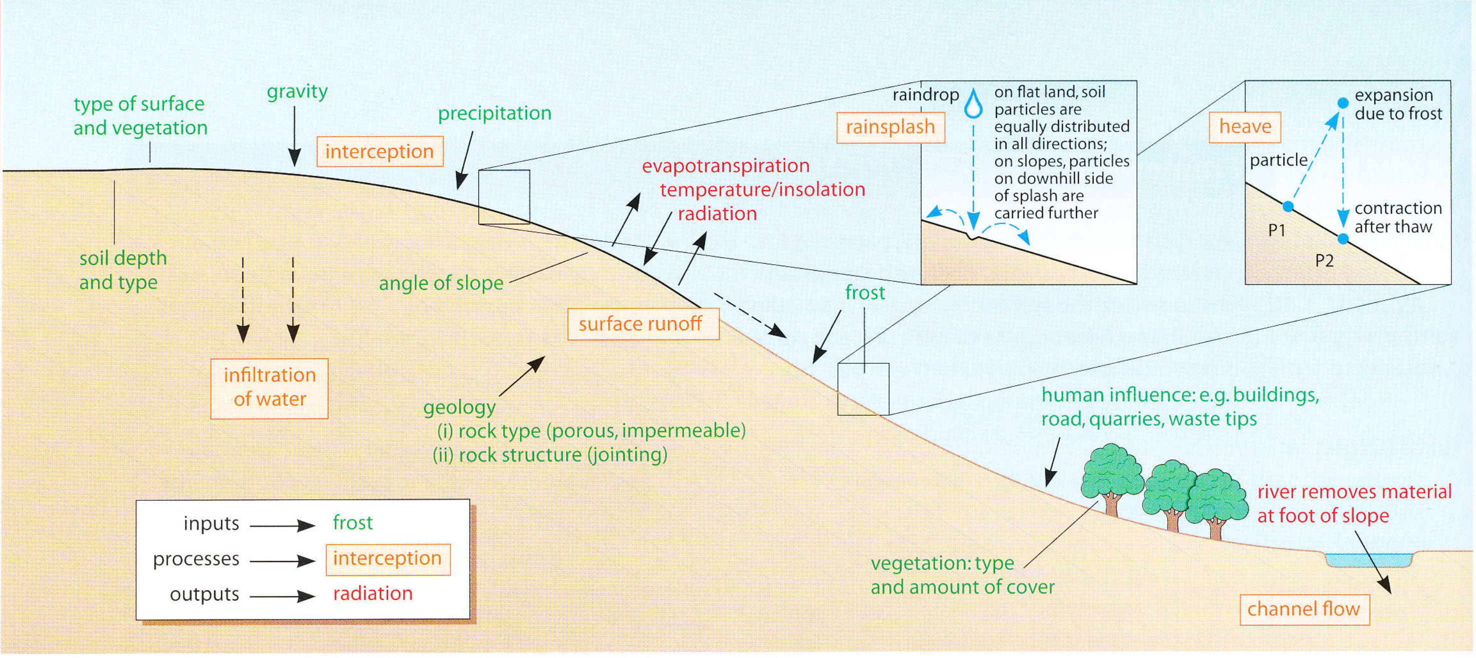


Figure 2.12

The slope as a dynamic open system

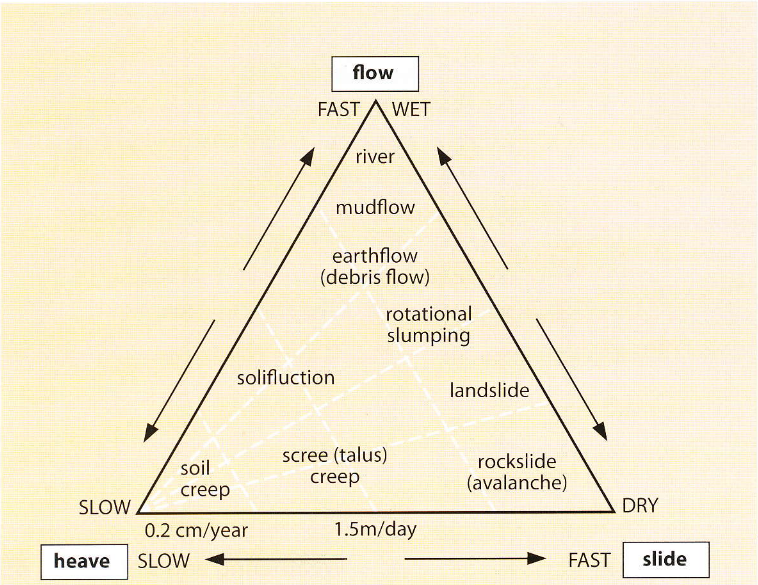
Mass movement and resultant landforms

The term **mass movement** describes all downhill movements of weathered material (**regolith**), including soil, loose stones and rocks, in response to gravity. However, it excludes movements where the material is carried by ice, water or wind. When gravitational forces exceed forces of resistance, slope failure occurs and material starts to move downwards. A slope is a **dynamic open system** (Framework 3) affected by biotic, climatic, gravitational, groundwater and tectonic inputs which vary in scale and time. The amount, rate and type of movement depend upon the degree of slope failure (Figure 2.12).

Although by definition mass movement refers only to the movement downhill of material under the force of gravity, in reality water is usually present and assists the process. When Carson and Kirkby (1972) attempted to group mass movements, they used the speed of movement and the amount of moisture present as a basis for distinguishing between the various types (Figure 2.13). The following classification is based on speed of flow related to moisture content and angle of slope (Framework 7, page 167).

Figure 2.13

A classification of mass movement processes (*after* Carson and Kirkby, 1972)



Slow movements

Soil creep

This is the slowest of downhill movements and is difficult to measure as it takes place at a rate of less than 1 cm a year. However, unlike faster movements, it is an almost continuous process. Soil creep occurs mainly in humid climates where there is a vegetation cover. There are two major causes of creep, both resulting from repeated expansion and contraction.

1 **Wet–dry periods** During times of heavy rainfall, moisture increases the volume and weight of the soil, causing expansion and allowing the regolith to move downhill under gravity. In a subsequent dry period, the soil will dry out and then contract, especially if it is clay. An extreme case of contraction in clays occurred in south-east England during the 1976 drought when buildings sited on almost imperceptible slopes suffered major structural damage.

2 **Freeze–thaw** When the regolith freezes, the presence of ice crystals increases the volume of the soil by 9 per cent. As the soil expands, particles are lifted at right-angles to the slope in a process called **heave** (Figure 2.12 and page 132). When the ground later thaws and the regolith contracts, these particles fall back vertically under the influence of gravity and so move downslope.

Figure 2.14

Terracettes in Wharfedale, Yorkshire Dales

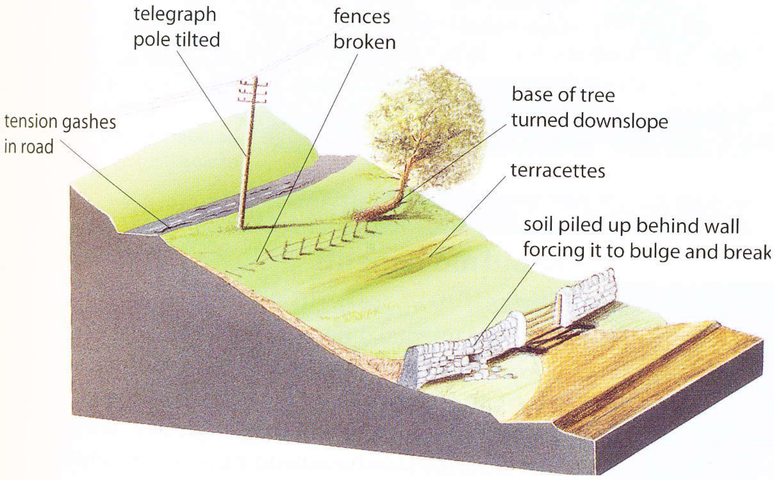


Figure 2.15

The effects of soil creep

Soil creep usually occurs on slopes of about 5° and produces **terracettes** (Figure 2.14). These are step-like features, often 20–50 cm in height, which develop as the vegetation is stretched and torn: they are often used and accentuated by grazing animals, especially sheep. The effects of soil creep are shown in Figure 2.15.

Solifluction

This process, meaning 'soil flow', is a slightly faster movement usually averaging between 5 cm and 1 m a year. It often takes place under periglacial conditions (Chapter 5) where vegetation cover is limited. During the winter season, both the bedrock and regolith are frozen. In summer, the surface layer thaws but the underlying layer remains frozen and acts like impermeable rock. Because surface meltwater cannot infiltrate downwards and temperatures are too low for much effective evaporation, any topsoil will soon become saturated and will flow as an **active layer** over the frozen subsoil and rock (page 131). This process produces **solifluction sheet** or **lobes** (Figure 5.12), rounded, tongue-like features reaching up to 50 m in width, and **head**, a mixture of sand and clay formed in valleys and at the foot of sea cliffs (Figure 5.13). Solifluction was widespread in southern Britain during the Pleistocene ice age; covered most of Britain following the Pleistocene; and continues to take place in the Scottish Highlands today.

Flow movements

Earthflows

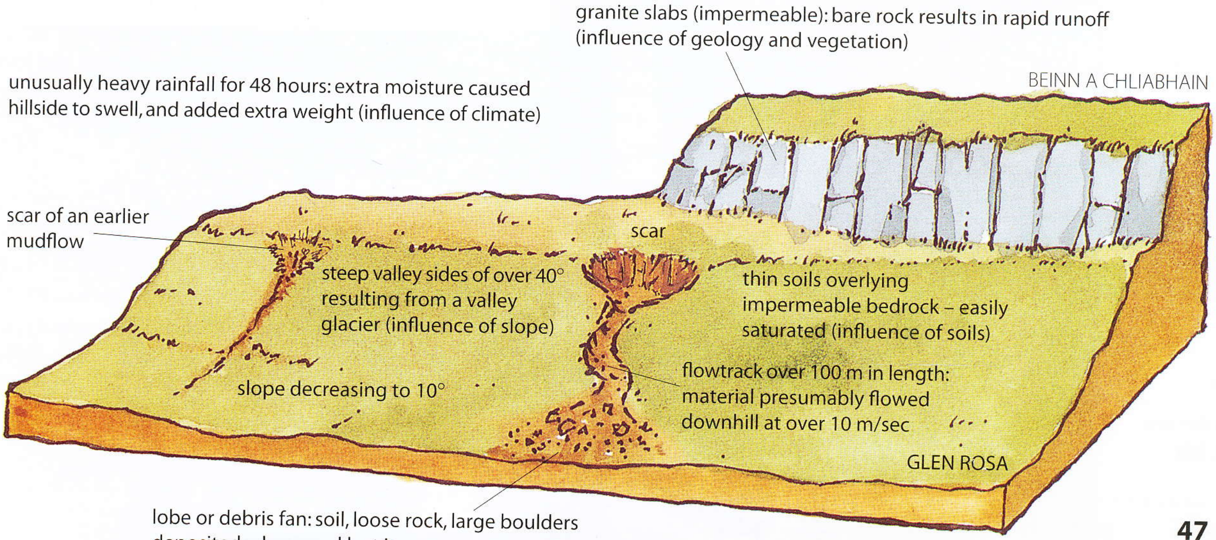
When the regolith on slopes of 5–15° becomes saturated with water, it begins to flow downhill at a rate varying between 1 and 15 km per year. The movement of material may produce short **flow tracks** and small bulging lobes or tongues, yet may not be fast enough to break the vegetation.

Mudflows

These are more rapid movements, occurring on steeper slopes, and exceeding 1 km/hr. When Nevado del Ruiz erupted in Colombia in 1985, the resultant mudflow reached the town of Armero at an estimated speed of over 40 km/hr (Case Study 2A). Mudflows are most likely to occur following periods of intensive rainfall, when both volume and weight are added to the soil giving it a higher water content than an earthflow. Mudflows may result from a combination of several factors (Figure 2.16).

Figure 2.16

Fieldsketch showing the causes of a mudflow, Glen Rosa, Arran



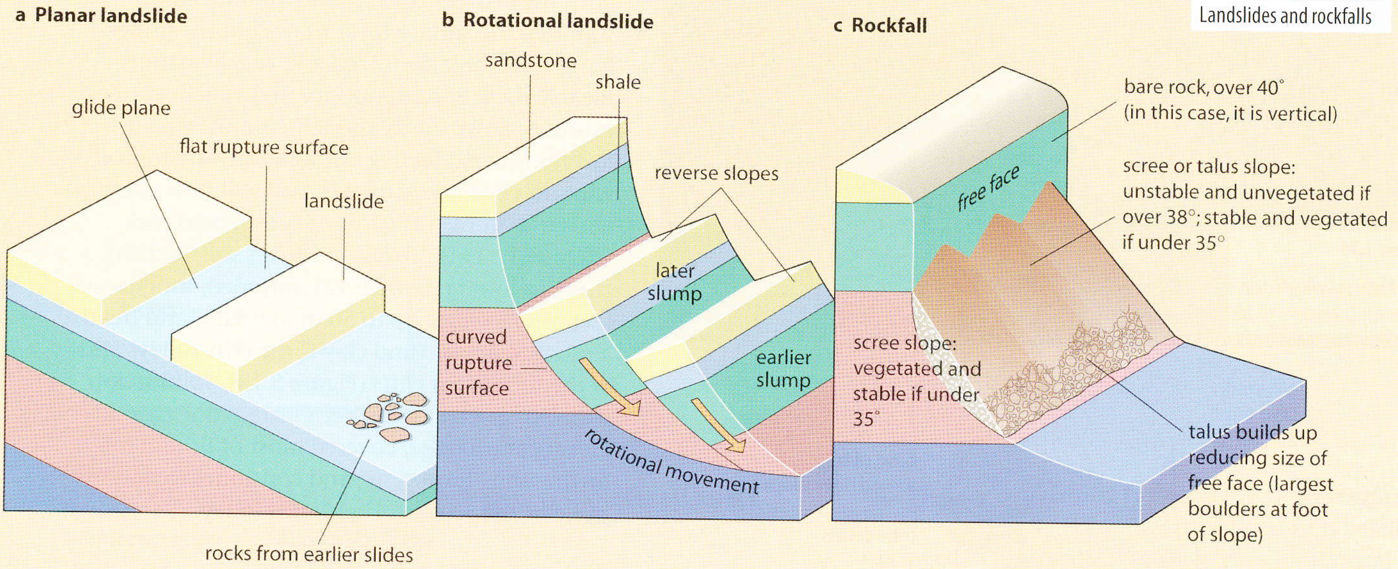


Figure 2.17

Landslides and rockfalls

Figure 2.18

Landslides on the Norfolk coast

Figure 2.19

Rockfalls in the crater of Vesuvius, Italy

Rapid movements

Slides

The fundamental difference between slides and flows is that flows suffer internal derangement whilst, in contrast, slides move 'en masse' and are not affected by internal derangement. Rocks that are jointed or have bedding planes roughly parallel to the angle of slope are particularly susceptible to landslides. Slides may be planar or rotational (Figure 2.17a and b). In a planar slide, the weathered rock moves downhill leaving behind it a flat rupture surface (Figure 2.17a). Where rotational movement occurs, a process sometimes referred to as **slumping**, a curved rupture surface is produced (Figure 2.17b). Rotational movement can occur in areas of homogeneous rock, but is more likely where softer materials (clay or sands) overlie more resistant or impermeable rock (limestone or granite). Slides are common in many coastal areas of southern and eastern England. In Figure 2.18, the cliffs, composed of glacial deposits, are retreating rapidly due to frequent slides. The slumped material can be seen at the foot of the cliff.

Very rapid movements

Rockfalls

These are spontaneous, though relatively rare, debris movements on slopes that exceed 40°. They may result from extreme physical or chemical weathering in mountains, pressure release, storm-wave action on sea cliffs, or earthquakes. Material, once broken from the surface, will either bounce or fall vertically to form scree, or talus, at the foot of a slope (Figures 2.17c and 2.19).

Places 8 South-east Brazil: landslides

Petropolis

The town of Petropolis, named after a former king of Brazil, lies in the Serro do Mar Mountains some 60 km north of Rio de Janeiro (Figure 2.21). Today, with a population of 300 000, it is one of Rio's two main mountain resorts to which people escape in summer to avoid the heat and humidity of the coast. But the steep-sided mountains can also prove to be a hazard, as in 2001 when 50 people were killed in a series of landslides (Figure 2.20).

As shown below, December of that year was an exceptionally wet month for Petropolis. The result was a series of more than 20 significant landsides, 14 of which were between them responsible for the 50 fatalities.

Period	Rainfall
1 to 16 December	up to 250 mm
17 to 23 December	up to 125 mm
24 December (in 12 hours)	up to 200 mm

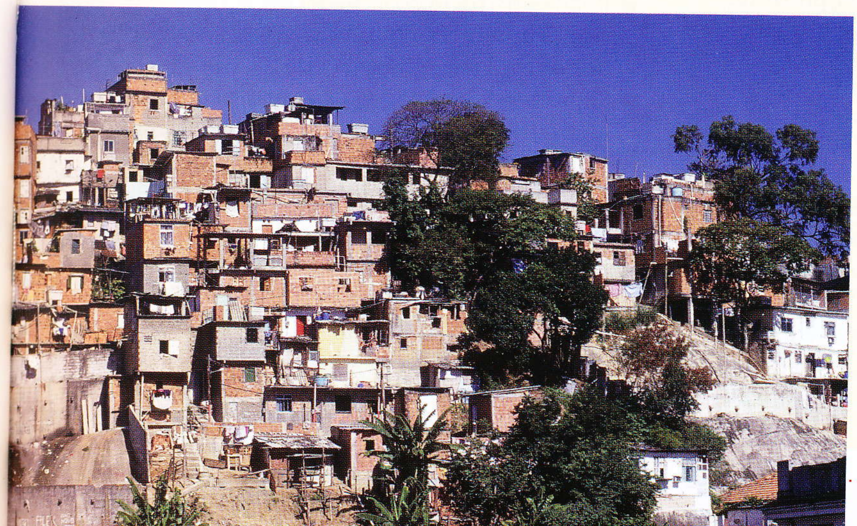
The area, with its steep hillsides and heavy seasonal rainfall, is prone to natural landslides but investigations following this event suggested that the two main causes, on this occasion at least, resulted from human activity:

1 The construction of poor-quality, unauthorised building: many of the shanty settlements had been built on steep hillsides, often where the slope was over 45° and in places even up to 80°.
2 The failure to provide rainwater drainage channels: such drains could have taken away some of the excess surface water and so reduced the hazard risk.

Of the 50 deaths, 24 were attributed to unauthorised settlements and 22 to the lack of drainage channels.

Figure 2.21

The town of Petropolis has spread up steep hillsides from the valley bottom



Rio de Janeiro

Rio de Janeiro experiences the same problems of mass movement, but on an even larger scale, as Petropolis. Figure 15.34 shows one of Rio's many favelas (shanty settlements) that have been built on the steep hillsides. One flash flood in 1988 led to mudslides which carried away many of the flimsy houses that had probably been built from waste materials such as wood, corrugated iron and broken bricks. The mudslides were responsible for the deaths of more than 200 people.

Figure 2.20

A landslide in Petropolis, 2001

Development of slopes

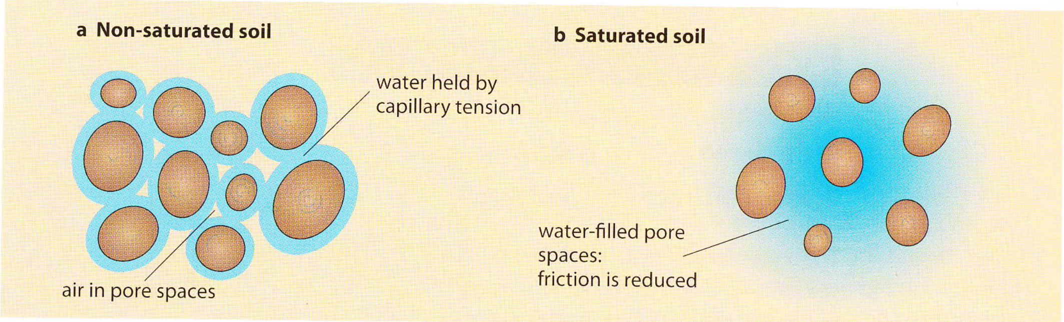
Slope development is the result of the interaction of several factors. Rock structure and lithology, soil, climate, vegetation and human activity are probably the most significant. All are influenced by the time over which the processes operate. Slopes are an integral part of the drainage basin system (Chapter 3) as they provide water and sediment for the river channel.

The effects of rock structure and lithology

- Areas of bare rock are vulnerable to mechanical weathering (e.g. frost shattering) and some chemical weathering processes.
- Areas of alternating harder/more resistant rocks and softer/less resistant rocks are more likely to experience movement, e.g. clays on limestones (Vaiont Dam, Case Study 2B).
- An impervious underlying rock will cause the topsoil to become saturated more quickly, e.g. glacial deposits overlying granite.
- Steep gradients are more likely to suffer slope failure than gentler ones. In Britain, especially in lowland areas, most slopes are under 5° and few are over 40°.
- Failure is also likely on slopes where the equilibrium (balance) of the system (Framework 3, page 45), has been disturbed, e.g. a glaciated valley.
- The presence of joints, cracks and bedding planes can allow increased water content and so lead to sliding (Vaiont Dam, Case Study 2B).
- Earthquakes (Mount Huascaran in Peru) and volcanic eruptions (Nevado del Ruiz in Colombia) can cause extreme slope movements (Case Study 2A).

Figure 2.22

The effect of pore-water pressure and capillary action on soil movement



Soil

- Thin soils tend to be more unstable. As they can support only limited vegetation, there are fewer roots to bind the soil together.
- Unconsolidated sands have lower internal cohesion than clays.
- A porous soil, e.g. sand, is less likely to become saturated than one that is impermeable, e.g. clay.
- In a non-saturated soil (Figure 2.22a), the surface tension of the water tends to draw particles together. This increases cohesion and reduces soil movement. In a saturated soil (Figure 2.22b), the pore water pressure (page 267) forces the particles apart, reducing friction and causing soil movement.

Climate

- Heavy rain and meltwater both add volume and weight to the soil.
- Heavy rain increases the erosive power of any river at the base of a slope and so, by removing material, makes that slope less stable.
- Areas with freeze–thaw or wet–dry periods are subjected to alternating expansion–contraction of the soil.
- Heavy snowfall adds weight and is thus conducive to rapid movements, e.g. avalanches, Case Study 4a.

Vegetation

- A lack of vegetation means that there are fewer roots to bind the soil together.
- Sparse vegetation cover will encourage surface runoff as precipitation is not intercepted (page 59).

Human influence

- Deforestation increases (afforestation decreases) the rate of slope movement.
- Road construction or quarrying at the foot of slopes upsets the equilibrium, e.g. during the building of the M5 in the Bristol area.
- Slope development processes may be accentuated either by building on steep slopes (Hong Kong and Rio de Janeiro, Case Study 2B) or by using them to deposit industrial or mining waste (Aberfan, Case Study 2B).
- The vibration caused by heavy traffic can destabilise slopes (Mam Tor, Derbyshire).
- The grazing of animals and ploughing help loosen soil and remove the protective vegetation cover.

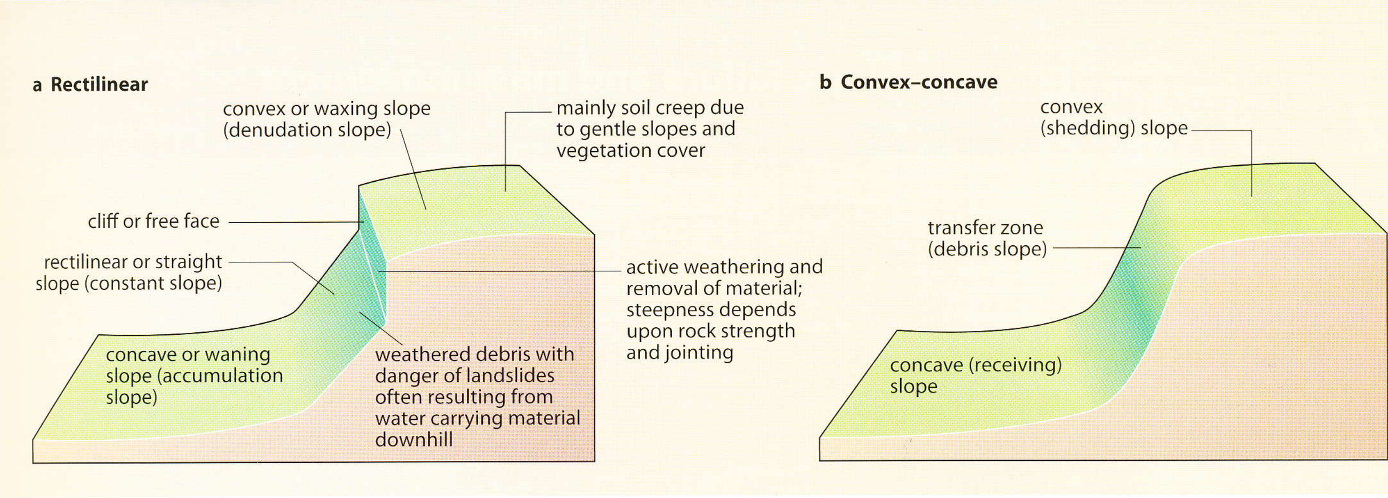


Figure 2.23

Slope element models

Slope elements

Two models try to show the shape and form of a typical slope. The first, Figure 2.23a, is more widely used than the second (Figure 2.23b) – although, in this author's view, the first is less easily seen in the British landscape. Regardless of which model is used, confusion unfortunately arises because of the variation in nomenclature used to describe the different facets of the slope.

In reality, few slopes are likely to match up perfectly with either model, and each individual slope is likely to show more elements than those in Figure 2.23.

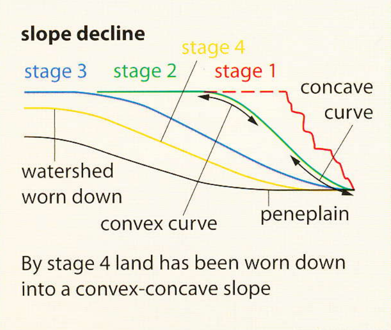
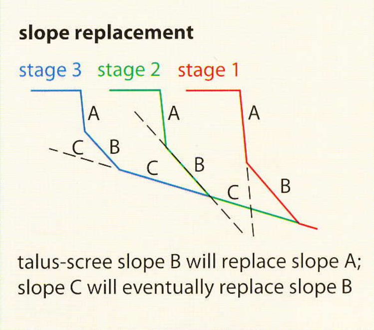
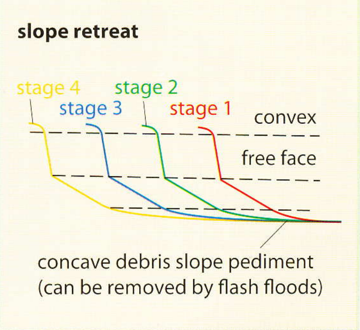
Slope development through time

How slopes have developed over time is one of the more controversial topics in geomorphology. This is partly due to the time needed for slopes to evolve and partly due to the variety of combinations of processes acting upon slopes in various parts of the world. Slope development in different environments has led to three divergent theories being proposed: **slope decline**, **slope replacement** and **parallel retreat**. Figure 2.24 is a summary of these theories.

None of the theories of slope development can be universally accepted, although each may have local relevance in the context of the climate and geology (structure) of a specific area. At the same time, two different climates or processes may produce the same type of slope, e.g. cliff retreat due to sea action in a humid climate or to weathering in a semi-arid climate.

Figure 2.24

Slope development theories

	Slope decline (W.M. Davis, 1899)	**Slope replacement (W. Penck, 1924)**	**Parallel retreat (L.C. King, 1948, 1957)**
Region of study	Theory based on slopes in what was to Davis a normal climate, north-west Europe and north-east USA.	Conclusions drawn from evidence of slopes in the Alps and Andes.	Based on slopes in South Africa.
Climate	Humid climates.	Tectonic areas.	Semi-arid landscapes. Sea cliffs with wave-cut platforms.
Description of slope	Steepest slopes at beginning of process with a progressively decreasing angle in time to give a convex upper slope and a concave lower slope.	The maximum angle decreases as the gentler lower slopes erode back to replace the steeper ones giving a concave central portion to the slope.	The maximum angle remains constant as do all slope facets apart from the lower one which increases in concavity.
	 By stage 4 land has been worn down into a convex-concave slope	 talus-scree slope B will replace slope A; slope C will eventually replace slope B	 concave debris slope pediment (can be removed by flash floods)
Changes over time	Assumed a rapid uplift of land with an immediate onset of denudation. The uplifted land would undergo a cycle of erosion where slopes were initially made steeper by vertical erosion by rivers but later became less steep (slope decline) until the land was almost flat (peneplain).	Assumed landscape started with a straight rock slope with equal weathering overall. As scree (talus) collected at the foot of the cliff it gave a gentler slope which, as the scree grew, replaced the original one.	Assumed that slopes had two facets – a gently concave lower slope or pediment and a steeper upper slope (scarp). Weathering caused the parallel retreat of the scarp slope allowing the pediment to extend in size.

2 Case Study

Slope failure and mass movement

A Natural causes

All slopes are affected by gravity and, consequently, by one or more of the several mass movement processes by which weathered material is transported downhill (pages 46–48). Where slopes are gentle (about 5°), the movement of material is slow and has relatively little effect on property, life or human activity. As slope angles increase, however, so too do the rate and frequency of slope movement and the risk of sudden slope failure. Slope failure, occurring in the form of either mudflows or landslides, is a natural event. When this failure occurs in densely populated areas, it becomes a potentially dangerous natural hazard (Framework 2, page 31). Three examples of how slope failure caused by natural events can cause serious loss of property and life (Figure 2.25) are:

(i) earthquakes
(ii) volcanic activity
(iii) excessive rainfall.

(i) Earthquakes – avalanches and rockfalls (Peru 1970)

In 1970 an offshore earthquake measuring 7.7 on the Richter scale shook parts of Peru to the north of its capital, Lima. The shock waves loosened a mass of unstable ice and snow near the summit of Huascaran, the country's highest peak (6768 m). The falling ice and snow formed a huge avalanche which rushed downhill, falling 3000 m into the Rio Santo Valley, collecting rocks and boulders en route. In its path stood the town of Yungay with a population of 20 000.

Estimates suggest that the avalanche was travelling at a speed of 480 km/hr when it hit the settlement. It took rescue workers three days to reach the town. Once there, they found very few survivors and only the tops of several 30 m palm trees, which marked the location of the former town square (Figures 2.25 and 2.26).

Figure 2.25

Sites of some recent hazardous events in South and Central America

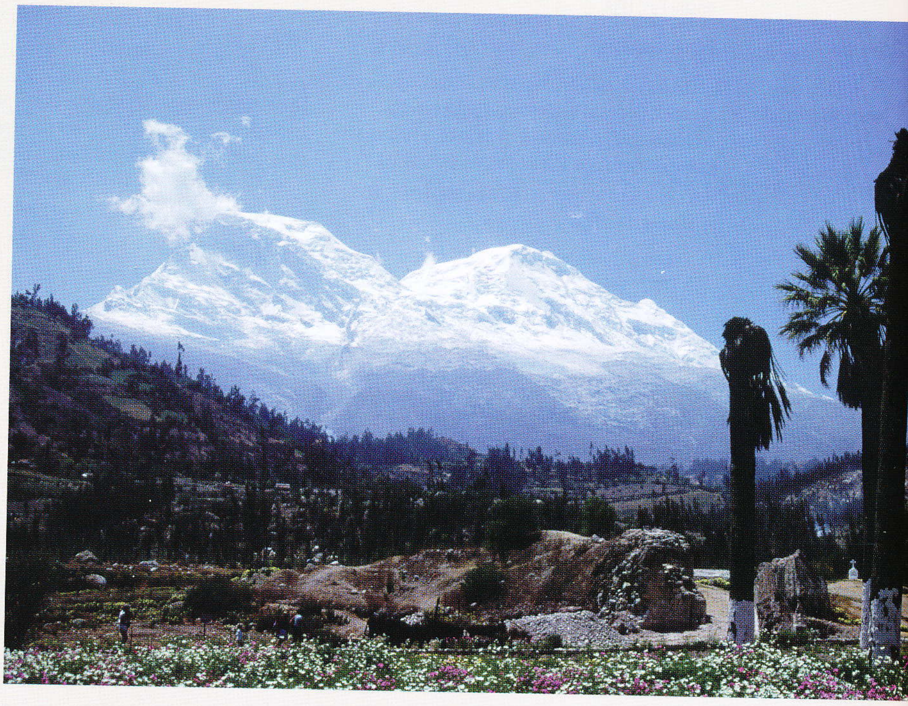


Figure 2.26

The site of Yungay after the avalanche

(ii) Volcanic eruptions – mudflows (Colombia 1985)

The Colombian volcano of Nevado del Ruiz had not erupted since 1595 until, in November 1985, it showed signs of activity by emitting gas and steam. As an increasing amount of magma welled upwards towards the crater, the whole peak must have become warmer, as was made evident by the increased melting of ice and snow around its summit. A mudflow, 20 m in height, which travelled 27 km down the Lagunillas Valley, proved an advance warning that went unheeded. Ice and snow continued to melt until, on 13 November, there was a major eruption. Although this eruption was small in comparison with other eruptions such as Mount St Helens, the lava, ash and hot rocks ejected were sufficient to melt the remaining ice and snow, releasing a tremendous volume of meltwater. This meltwater, swelled by torrential rain (often associated with volcanic eruptions), raced down the Lagunillas Valley collecting with it large amounts of ash deposited from previous eruptions. The resultant mud tidal wave (a lahar), estimated to have been 30 m in height, travelled down the valley at over 80 km/hr.

Some 50 km from the crater, the mudflow emerged onto more open ground on which was situated the town of Armero. The time was 2300 hours when the mudflow struck, and most of the 22 000 inhabitants had already gone to bed. The few survivors claimed that the first onrush of muddy water was ice-cold, but became increasingly warmer. By morning a layer of mud, up to 8 m deep, covered Armero and the surrounding area (Figures 2.25 and 2.27). The death toll was put at 21 000, making this the worst single natural disaster ever to have affected people in the western hemisphere.

Figure 2.27

Armero, Colombia

(iii) Heavy rainfall – Hurricane Stan (Guatemala 2005)

Hurricane Stan swept across Central America during September 2005. Although by hurricane standards it was not the strongest, it proved particularly lethal because it struck a region where most people lived in flimsy shanty dwellings constructed around, or at the foot of, steep mountainsides. As is often the case with hurricanes, it was not the strength of the winds that was to cause so many deaths, but rather the effects of the torrential rainfall.

The rainwater collected soil and other material as it rushed down the mountain slopes creating a mudflow 15 m deep that engulfed the town of Panabaj (Figures 2.25 and 2.28). The devastation was so complete that the authorities and relief workers soon abandoned efforts to retrieve survivors, or even bodies, and declared the area a mass grave. In all, 1400 people disappeared and all that was left of the town were the tops of the taller trees. The handful of lucky survivors described how they were awoken by rumblings from the mountainsides, and managed to escape because they were nearer to the edges of the mudflow.

Raging rivers destroyed bridges and made roads impassable, so the hard-pressed authorities had to struggle to airlift in food, drinking water and emergency supplies.

Figure 2.28

The view across Lake Atitlan in Guatemala to the volcanic peaks on the far shore. Beside the lake, which is a caldera (page 25), are several long-established Mayan settlements and a few modern tourist resorts. One Mayan town was Panabaj

B Human mismanagement

The probability of slope failure in populated areas is often increased by thoughtless planning, or a total lack of it, or where human activity exerts too much pressure upon the land available. Three examples of how slope instability and the risk of slope failure may be increased by human activity are when land is used for:

(i) building dams to create reservoirs
(ii) the extraction of a natural resource or the dumping of waste material
(iii) rapid urbanisation.

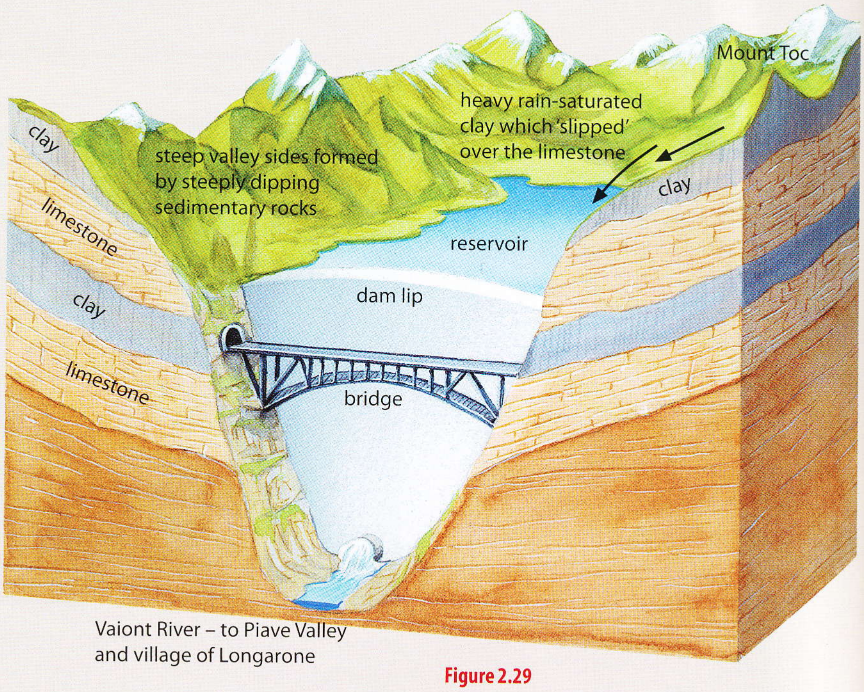


Figure 2.29
The Vaiont Dam

(i) Building dams to create reservoirs (Italy 1963)

The Vaiont Dam, built in the Italian Alps, was completed in 1960. The dam, the third highest in the world at that time, was built in a narrow valley with steep sides consisting of alternate layers of clays and limestone (Figure 2.29), and where landslides were not uncommon. Down the valley were several hamlets and the small town of Longarone.

Heavy rain in October 1963 saturated the clay. Just before midnight on 9 October, a landslide of rocks, clay, mud and vegetation slid over the harder beds of limestone and into the reservoir. The dam itself stood, but a wave of water spilled over the lip creating a towering wall of water which swept down the valley. Longarone was virtually destroyed. The final death toll was put at almost 1900, although several bodies were never recovered. Debris from the landslide filled in almost two-thirds of the lake. A court of enquiry concluded that the site was geologically unstable and that even during construction many smaller landslides had occurred. The dam was closed.

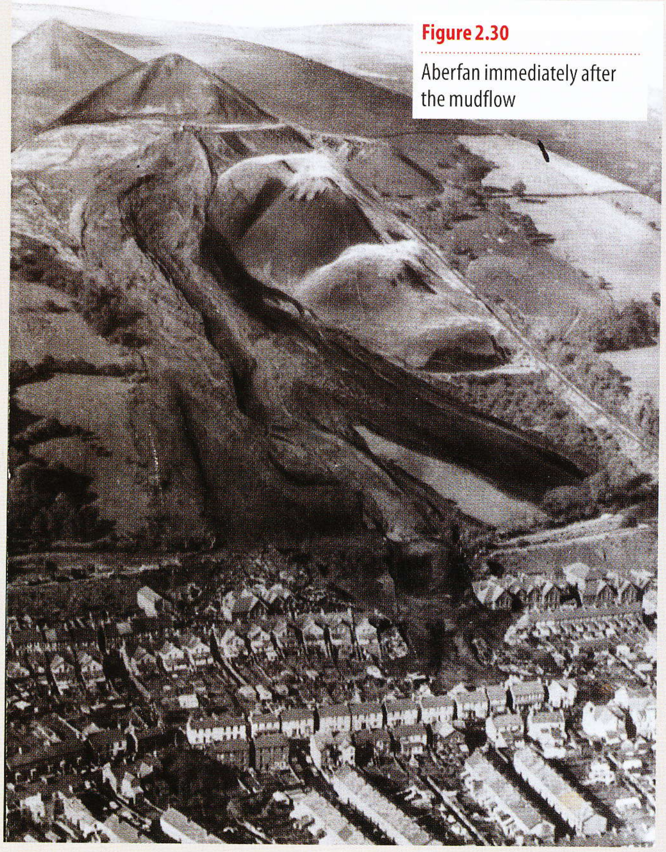


Figure 2.30
Aberfan immediately after the mudflow

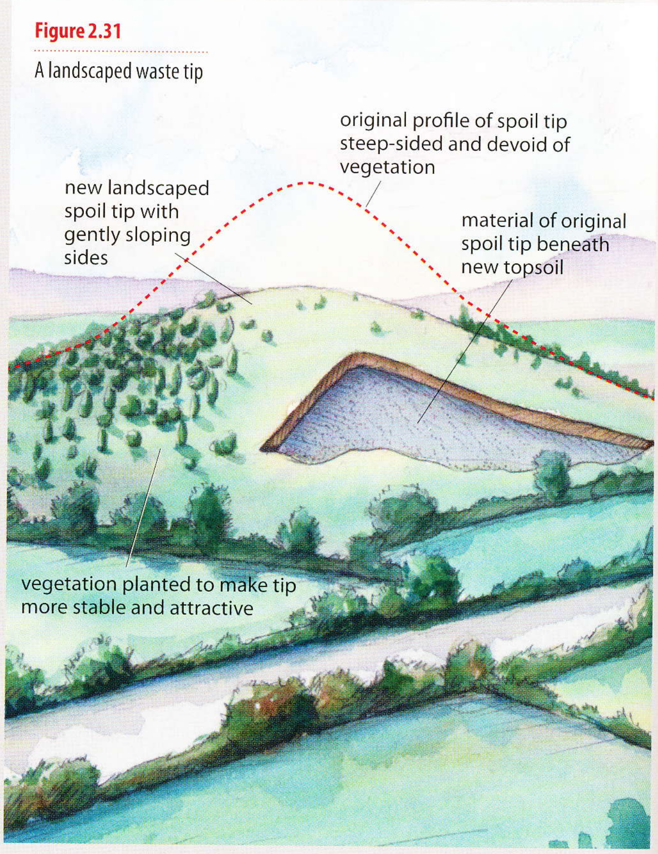


Figure 2.31
A landscaped waste tip

(ii) Dumping waste material (Aberfan 1966)

Aberfan, like many other settlements in the South Wales valleys, grew up around its colliery. However, the valley floors were rarely wide enough to store the coal waste and so it became common practice to tip it high above the towns on the steep valley sides. At Aberfan, the spoil tips were on slopes of 25°, over 200 m above the town and, unknowingly, on a line of springs. Water from these springs added weight to the waste heaps, which reduced their internal cohesion. Following a wet October in 1966 and a night of heavy rain, slope failure resulted in the waste material suddenly and rapidly moving downhill. The resultant mudflow, estimated to contain over 100 000 m^3 of material, engulfed part of the town which included the local junior school (Figure 2.30). The time was just after 0900 hours on 21 October, soon after lessons in the school had begun. Of the 147 deaths in Aberfan that morning, 116 were children and five their teachers.

Since then, the colliery has closed and, as elsewhere in the former coal-mining valleys, the potentially dangerous waste tips have been lowered, regraded and landscaped to try to prevent any occurrence of a similar event (Figure 2.31).

(iii) Urbanisation (Hong Kong 1957 to 2007)

Many parts of the world, especially in economically less developed countries, are experiencing rapid urbanisation (page 418). As most of the best sites for residential development have long since been used, it means that newcomers to a city are forced to live on land previously considered unusable (e.g. flood-prone valleys in Nairobi – Places 58, page 444), or unsafe (e.g. steep hillsides in Caracas 1999, and Rio de Janeiro – Places 57, page 443).

In Hong Kong, landslips have been responsible for 430 deaths since 1957 (Figure 2.32). Most landslips during this time have been attributed to two factors: the inadequacies of hillside construction works in the last 50 years, and deficiencies in maintaining slopes once they are utilised (Figure 2.33). In 1966, torrential rainstorms triggered massive landslides which killed 64 people, made 2500 homeless and caused 8000 to be evacuated. In 1976, a major landslide led to 22 deaths. The consequence of this was the setting up, in 1977, of the Geotechnical Engineering Office (GEO). GEO's main functions were:

- to investigate slopes for potential risk and to take preventive measures
- to control geotechnic aspects of new buildings and roads
- to promote slope maintenance by owners
- to undertake landslide warning and emergency services
- to advise on land-use plans to minimise public risk.

In 1997, most of Hong Kong experienced over 300 mm of rain in 24 hours. At the centre of the storm, 110 mm fell in one hour and 800 mm in the day. Resultant landslips caused the death of one person, injuries to eight people, the disruption of the Kowloon–Guangzhou railway (Places 106, page 640) and the closure of a six-lane highway for several hours. These losses and disruptions were, however, relatively minor, because the community had learned to cope better with the landslip hazard. Indeed the Hong Kong authorities now collaborate with their counterparts in other cities in Asia and South America with similar climatic and topographic characteristics, and where economic and social development is creating an unacceptable level of landslip risk.

The success of GEO can be seen by the decrease in the number of deaths (Figure 2.32).

Figure 2.32

Number of landslip fatalities in Hong Kong, 1957–2007

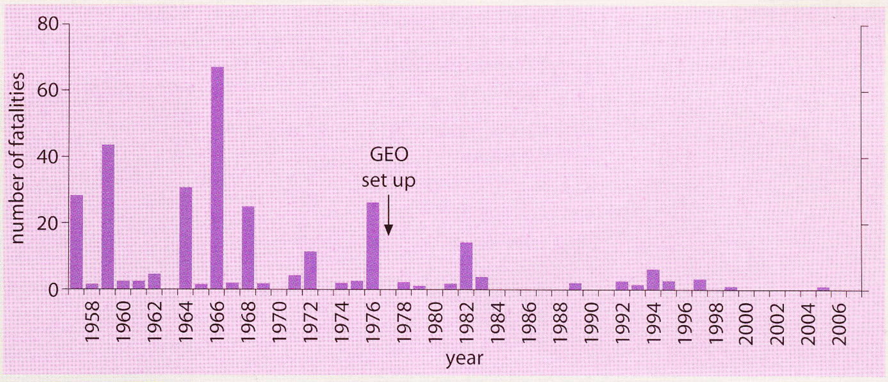
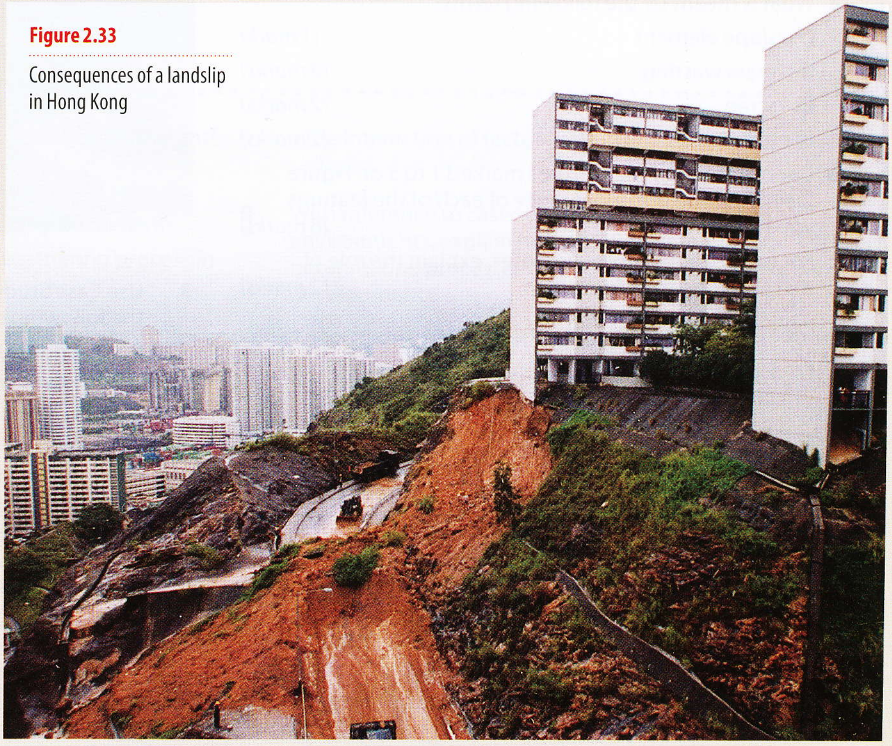


Figure 2.33

Consequences of a landslip in Hong Kong



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Carson, M.A. and Kirby, N.J. (1972) *Hillslope Form and Process*, Cambridge University Press.

Goudie, A.S. (2001) *The Nature of the Environment*, WileyBlackwell.

Guerra, T. *et al* (2007) 'Mass movement in Petropolis, Brazil' in *Geography Review* Vol 20 No 4 (March).

Trudgill, S.T. (1986) *Weathering and Erosion*, Heinemann.

Geoweb, landslides:
www.georesources.co.uk/edexunit6.htm

Glossary of related terminology:
www.scottishgeology.com/glossary/glossary.html

Slope weathering:
www.bgrg.org – search for 'slope weathering'
http://earthsci.org/Flooding/unit3/u3-02-03.html
www.georesources.co.uk/edexunit6.htm

Questions & Activities

Activities

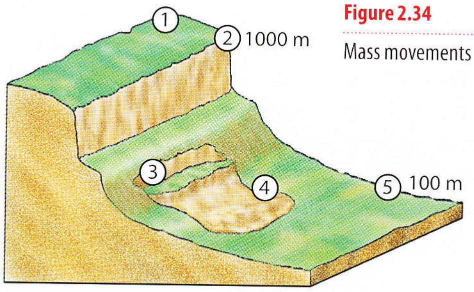


Figure 2.34

Mass movements

1 **a** What is meant by the following terms?

- **i** slope element *(1 mark)*
- **ii** mass wasting *(2 marks)*
- **iii** scree *(2 marks)*
- **iv** terracette *(2 marks)*

b Choose **three** of the features marked 1 to 5 on Figure 2.34. Describe the appearance of each of the features you have chosen. *(6 marks)*

c For each of your chosen features, explain the role of mass wasting in its formation. *(12 marks)*

2 Study Figure 2.35 and answer the following questions.

a **i** Explain the meaning of each of the following slope movement terms:

earth flow; mud flow; slide; rock fall. *(6 marks)*

ii Name **two** types of slope movement it is possible to see in the photograph. State where they can be found. *(4 marks)*

iii Identify **two** ways in which people have tried to protect slopes in this photograph. For each one suggest how it is intended to work. *(6 marks)*

b Had the slope movement finished when this photograph was taken? Suggest reasons for your answer. *(4 marks)*

c Should cliffs, such as the one in the photograph, be protected? Give reasons for your answer. *(5 marks)*

Figure 2.35

Holbeck Hall Hotel, Scarborough

3 Use Case Study 2B (iii) on Hong Kong (page 55) to answer the following questions.

a Describe the physical features of the hillside shown in the photograph. *(3 marks)*

b Why have people settled on this hillside? *(3 marks)*

c Why is a hillside, such as the one in the photograph, in danger of rapid mass movement even without human activities? *(7 marks)*

d Give **two** examples of human activities which increase the danger of rapid mass movement on such slopes. Explain how they increase the danger. *(6 marks)*

e The heavy rainfall in 1997 was an extreme climatic event but it created relatively little damage. Explain **one** way in which authorities such as those in Hong Kong are trying to manage the problems caused by the physical environment in which they operate. *(6 marks)*

Exam practice: basic structured questions

4 a Define the term 'weathering'. *(2 marks)*

b Choose one type of **mechanical weathering**.

i Making use of diagrams, explain the processes involved in the type of weathering. *(4 marks)*

ii Describe the landscape features which result from the weathering type you have chosen. *(4 marks)*

c Choose any **one** climatic region and identify the type of **chemical weathering** that will dominate the area.

Explain why this type of chemical weathering will be dominant. *(8 marks)*

d Human activity can influence the rate of weathering that occurs in an area. With the aid of specific examples, explain how human activity influences the rate of weathering. *(7 marks)*

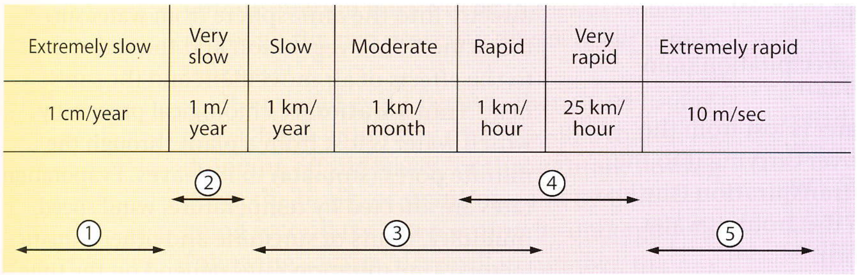
Exam practice: structured questions

5 a i Study Figure 2.36. Match each of the following types of slope movement with one of the labels on the graph numbered 1 to 5:

earth/mudflow; solifluction; rockfall; slide; soil creep. *(5 marks)*

ii For any **two** of the flow movements above, explain how the process occurs and describe the landform shape that results. *(10 marks)*

b Use examples of **two** types of rural land use you have studied to explain how people in rural areas try to manage slopes to reduce the downslope movement of soil. *(10 marks)*



6 a Study the photograph of Holbeck Hall Hotel (Figure 2.35).

i Draw an annotated diagram or sketch map **only** to illustrate the landscape features of the slopes. *(8 marks)*

ii Explain what has happened to these slopes and suggest why it has occurred. *(8 marks)*

b Making good use of examples, explain how human activities can increase the stability of some slopes and destabilise other slopes. *(9 marks)*

7 Choose a drainage basin that you have studied.

a Describe and suggest reasons for the variation in slope types that exist within the drainage basin. *(10 marks)*

b For any **one** slope, identify and explain changes that are likely to affect the slope in the future. *(8 marks)*

c Suggest how human activity can influence the rate of change and shape of slopes. *(7 marks)*

Figure 2.36

Speed of movement of mass movements

Exam practice: essays

8 'A range of processes, which differ in contrasting environments, affect slope shapes.' Discuss this statement with reference to slopes you have studied. In your answer you should refer to:

- the variation of slope elements in different environments
- the variation in importance of types of weathering process in different environments
- the interaction of factors within environments to create slopes. *(25 marks)*

9 With reference to case studies from a range of environments, explain how an understanding of natural slope processes can be used in planning urban developments. *(25 marks)*

Formulae for chemical weathering processes

Oxidation $4\,FeO + O_2 \rightarrow 2Fe_2O_3$
(ferrous oxide + oxygen → ferric oxide)

Hydrolosis Formula varies depending on rock type involved. For the hydrolosis of feldspar/granite to kaolin, this is a common example:
$K_2O, Al_2O_3, 6SiO_2 + H_2O \rightarrow Al_2O_3, 2SiO_2, 2H_2O$
(feldspar + water → kaolin)

Hydration $CaSO_4 + 2H_2O \rightarrow CaSO_42H_2O$
(anhydrite + water → gypsum)

Carbonation This process is in two stages:
$H_2O + CO_2 \rightarrow H_2CO_3$
(water + carbon dioxide → carbonic acid)
$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$
(calcium carbonate + carbonic acid → calcium bicarbonate)

Acid rain $2SO_2 + O_2 + 2H_2O \rightarrow 2H_2SO_4$
(sulphur dioxide + oxygen + water → weak sulphuric acid)