4

Glaciation

'Great God! this is an awful place.'
The South Pole, **Robert Falcon Scott**, *Journal*, 1912

Ice ages

It appears that roughly every 200–250 million years in the Earth's history there have been major periods of ice activity (Figure 4.1). Of these, the most recent and significant occurred during the Pleistocene epoch of the Quaternary period (Figure 1.1). In the 2 million years since the onset of the Quaternary, the time subject to most public interest and scientific research, there have been fluctuations in global temperature of up to 10°C which have led to cold phases (**glacials**) and warm phases (**interglacials**). Recent analyses of both ocean floor and Antarctic ice cores (Places 14) confirm that over the last 750 000 years the Earth has experienced eight **ice ages** (glacials) separated by eight interglacials (Figure 4.2).

Figure 4.1

A chronology of ice ages (in bold)

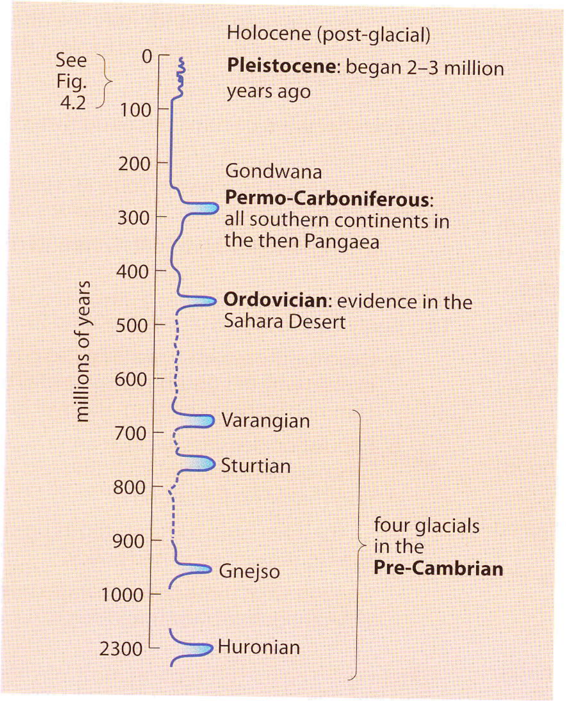
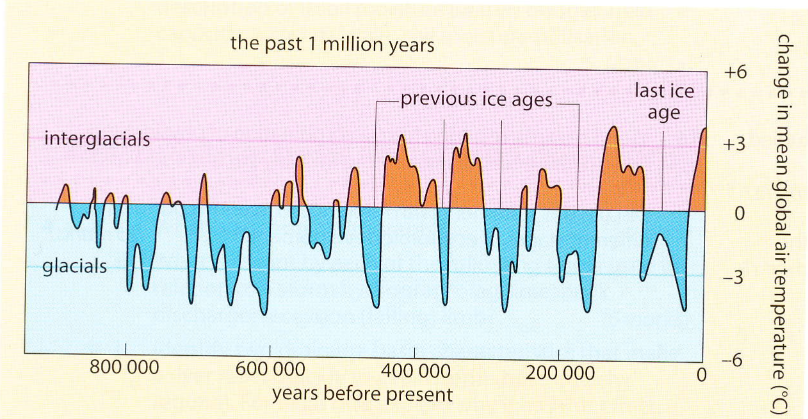


Figure 4.2

Generalised trends in mean global temperatures during the past 1 million years



When the ice reached its maximum extent, it is estimated that it covered 30 per cent of the Earth's land surface (compared with some 10 per cent today). However, its effect was not only felt in polar latitudes and mountainous areas, for each time the ice advanced there was a change in the global climatic belts (Figure 4.3). Only 18 000 years ago, at the time of the maximum advance within the last glacial, ice covered Britain as far south as the Bristol Channel, the Midlands and Norfolk. The southern part of Britain experienced **tundra conditions** (page 333), as did most of France.

Climatic change

Although it is accepted that climatic fluctuations occur on a variety of timescales, as yet there is no single explanation for the onset of major ice ages or for fluctuations within each ice age. The most feasible of theories to date is that of Milutin Milankovitch, mathematician/astronomer. Between 1912 and 1941, he performed exhaustive calculations which show that the Earth's position in space, its tilt and its orbit around the Sun all change. These changes, he claimed, affect incoming radiation from the Sun and produce three main cycles of 100 000, 40 000 and 21 000 thousand years (Figure 4.6). His theory, and the timescale of each cycle, has been given considerable support by evidence gained, since the mid-1970s, from ocean floor cores. As yet, although the relationship appears to have been established, it is not known precisely how these celestial cycles relate to climatic change.

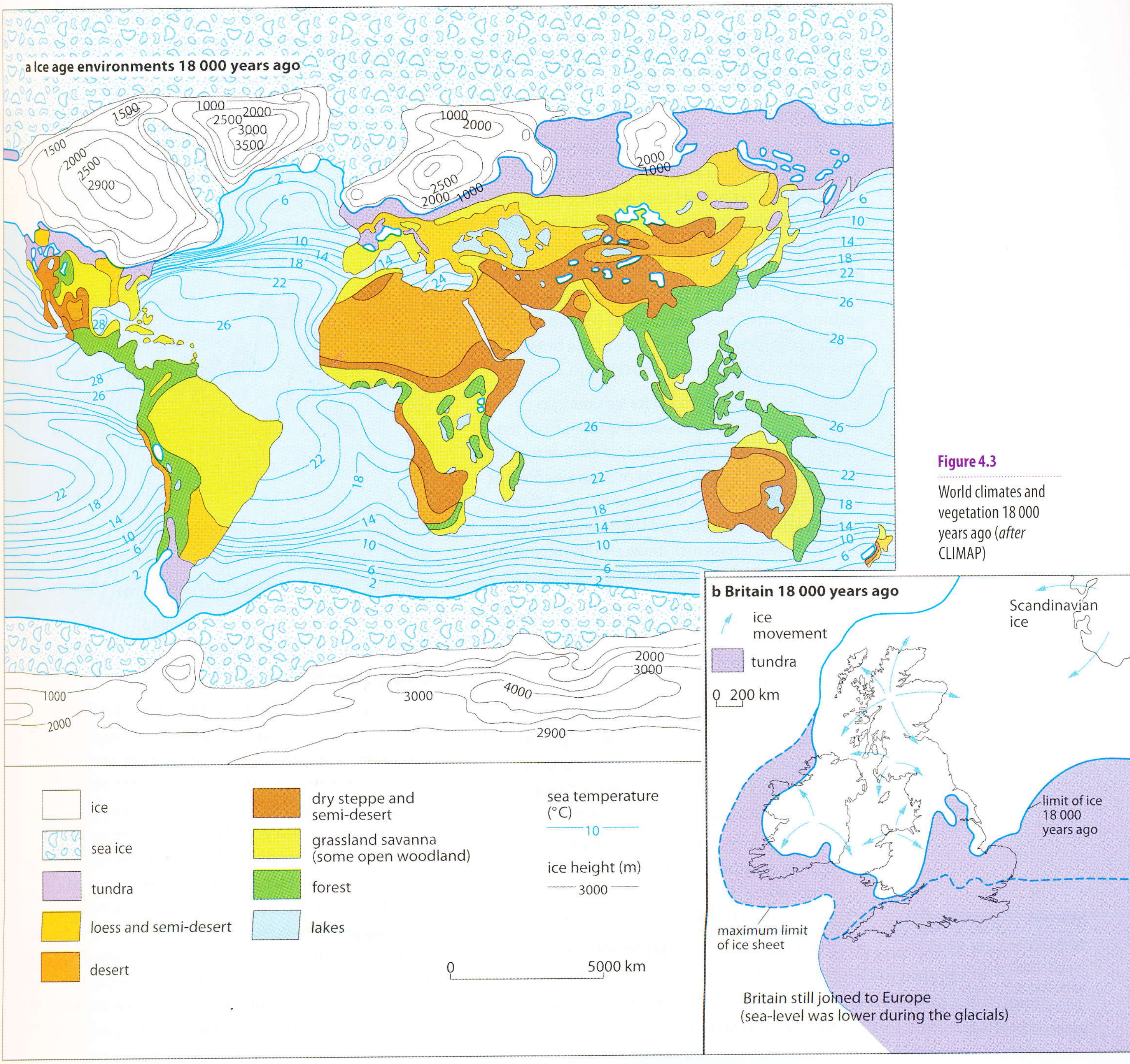


Figure 4.3

World climates and vegetation 18 000 years ago (*after* CLIMAP)

Other suggestions have been made as to the causes of ice ages. Some of these processes are likely to act in combination (Places 14) and may well amplify Milankovitch's variations.

- Variations in sunspot activity may increase or decrease the amount of radiation received by the Earth.
- Injections of volcanic dust into the atmosphere can reflect and absorb radiation from the Sun (page 207 and Figure 1.48).
- Changes in atmospheric carbon dioxide gas could accentuate the greenhouse effect (Case Study 9B). Initially extra CO_2 traps heat in the atmosphere, possibly raising world temperatures by an estimated 3°C. In time, some of this CO_2 will be absorbed by the seas, reducing the amount remaining in the atmosphere and causing a drop in world temperatures and the onset of another ice age (Figure 4.5).
- The movement of plates – either into colder latitudes or at constructive margins, where there is an increase in altitude – could lead to an overall drop in world land temperatures.
- Changes in ocean currents (page 211) or jet streams (page 227).

Places 14 Antarctica and Greenland: previous climatic change

Antarctica

In **1988**, the Russians announced the first results of a five-year drilling experiment in Antarctica in which they extracted ice cores descending downwards through the ice sheet for nearly 2 km. Each core is a cylinder of ice 10 cm in diameter and about 3 m in length. The cores show a succession of rings, each of which is equivalent to the accumulation of one year of snow (Figure 4.4). From this, it was estimated that the ice at the bottom of the core had been formed 160 000 ago.

In 2004, the European Project for Ice Coring in Antarctica (EPICA) went deeper. The team, from ten countries and including members of the former British Antarctic Survey, produced a 3 km deep ice core that contained, at it lowest point, snowfall from 740 000 years ago. The consortium are still drilling and hope, by 2010, to reach base rock under the ice sheet and to recover ice that fell as snow over 900 000 years ago.

Analysis of the core showed how temperature has changed in the past and how the concentration of gases, mainly CO_2 and methane, and particles in the atmosphere, have varied. Results confirmed that:

- there have been eight glacials in the last 750 000 years and our present warm period is part of an interglacial that could last for at least another 15 000 years (although this could, without evidence, be longer if global warming continues)
- there is a close link between temperature change and the content of CO_2 in the atmosphere (Figure 4.5) and the last glacial began when the CO_2 content was very low
- there have been several previous periods of considerable global volcanic activity
- there is a likelihood of the Earth wobbling on its axis causing Milankovitch's 21 million year cycle.

Figure 4.4

Dirt bands (englacial debris) in an Icelandic glacier: the amount of ice between each dirt band represents one year's accumulation of snow

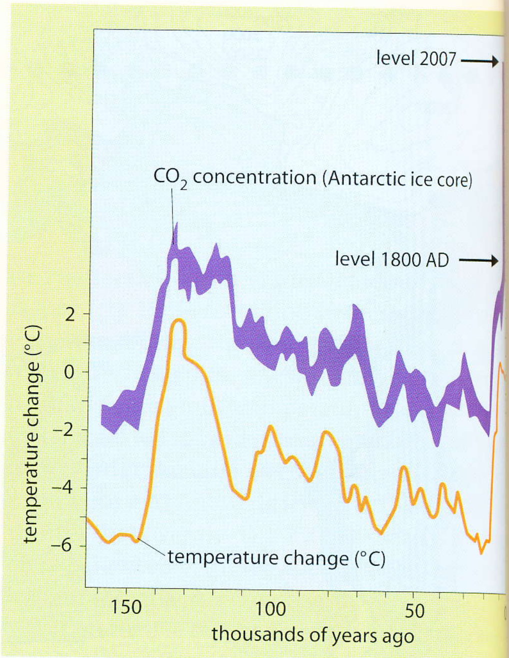
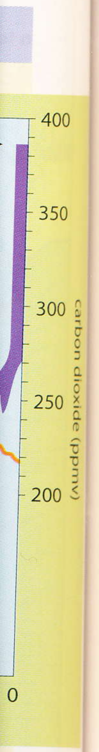


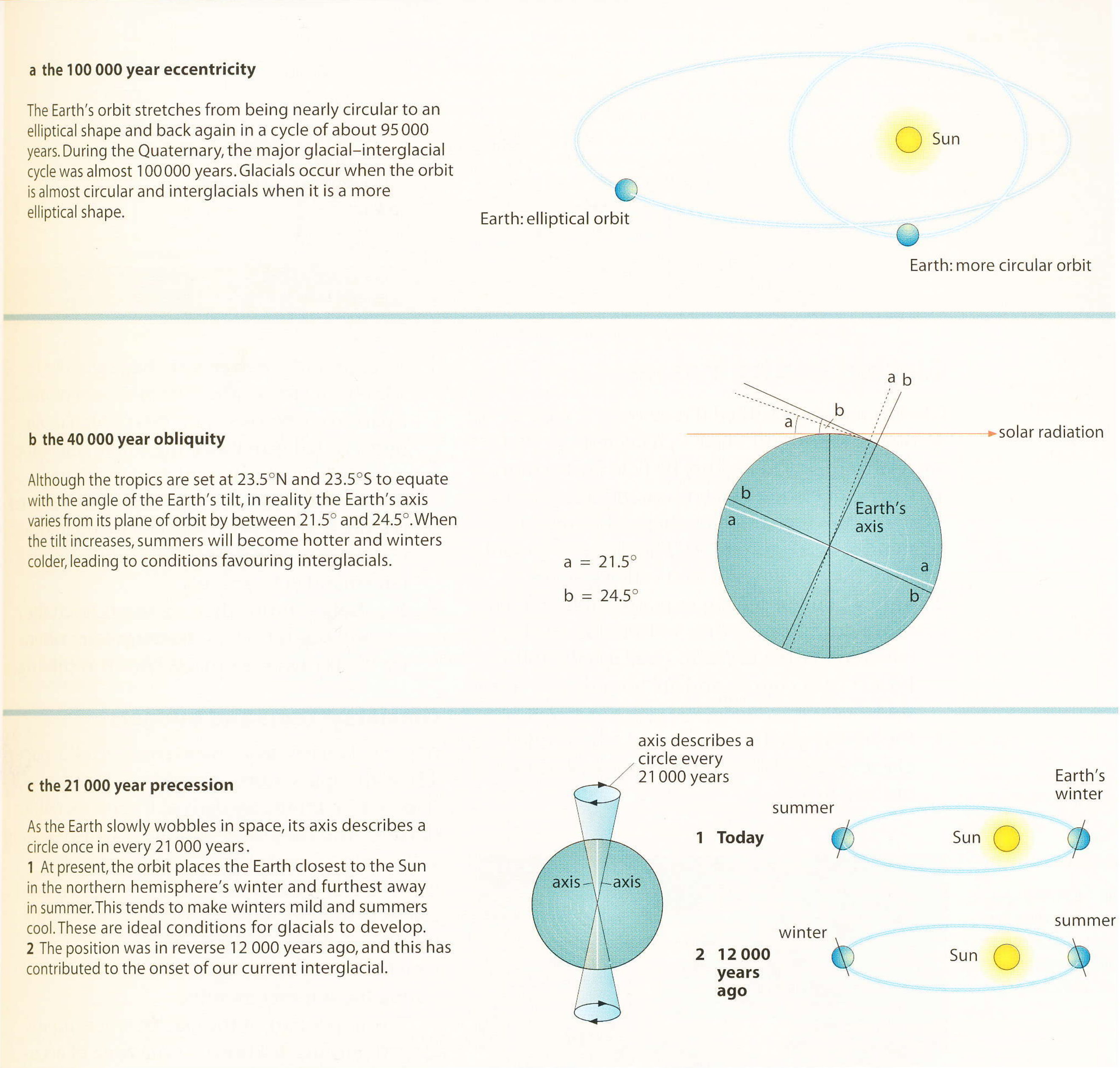
Figure 4.5

Atmospheric CO_2 concentration and temperature change

Greenland, 1998

Two projects conducted from 1989 to 1993 collected parallel cores of ice from two places 30 km apart in the central part of the Greenland ice sheet. Each core was over 2 km deep and has been shown to extend back 110 000 years. During that period snowfall averaged 15–20 cm a year. At the same time as the snow was being compressed into ice (page 105), volcanic dust, wind-blown dust, sea salt, gases and chemicals which were present in the atmosphere, were trapped within the ice. The gases included two types of oxygen isotope, O-16 and O-18 (page 248). The ratio between these two isotopes changes as the proportion of global water bound up in the ice changes (the amount of O-18 in the atmosphere increases as air temperature falls, and decreases as air temperature rises). The changing ratios from the Greenland cores showed short-term and long-term changes in temperature, and that rapid global change is more the norm for the Earth's climate than the stability and gradual adjustment that was previously assumed. The recent ice core from Antarctica directly correlates 'with an astounding regularity' with the abrupt climate changes in both polar areas. However, findings also suggest that as Antarctica warms up, Greenland cools and, likewise, when temperatures rise in Greenland, they fall in Antarctica. This link suggests that the two icy regions are connected by ocean currents in a bipolar seesaw (Case Study 4).




a the 100 000 year eccentricity

The Earth's orbit stretches from being nearly circular to an elliptical shape and back again in a cycle of about 95 000 years. During the Quaternary, the major glacial–interglacial cycle was almost 100 000 years. Glacials occur when the orbit is almost circular and interglacials when it is a more elliptical shape.

b the 40 000 year obliquity

Although the tropics are set at 23.5°N and 23.5°S to equate with the angle of the Earth's tilt, in reality the Earth's axis varies from its plane of orbit by between 21.5° and 24.5°. When the tilt increases, summers will become hotter and winters colder, leading to conditions favouring interglacials.

c the 21 000 year precession

As the Earth slowly wobbles in space, its axis describes a circle once in every 21 000 years.
1 At present, the orbit places the Earth closest to the Sun in the northern hemisphere's winter and furthest away in summer. This tends to make winters mild and summers cool. These are ideal conditions for glacials to develop.
2 The position was in reverse 12 000 years ago, and this has contributed to the onset of our current interglacial.

Figure 4.6

The orbital forcing mechanisms of Milankovitch's climatic change theory

Snow accumulation and ice formation

As the climate gets colder, more precipitation is likely to be in the form of snow in winter and there is less time for that snow to melt in the shorter summer. If the climate continues to deteriorate, snow will lie throughout the year forming a permanent **snow line** – the level above which snow will lie all year. In the northern hemisphere, the snow line is at a lower altitude on north-facing slopes, as these receive less insolation than south-facing slopes. The snow line is also lower nearer to the poles and higher nearer to the Equator: it is at sea-level in northern Greenland; at about 1500 m in southern Norway; at 3000 m in the Alps; and at 6000 m at the Equator. It is estimated that the Cairngorms in Scotland would be snow-covered all year had they been 200 m higher. In 2003 when Sir Edmund Hillary revisited the base camp for his 1953 ascent of Mount Everest, he found the snow-line had retreated uphill by 8 km in 50 years.

When snowflakes fall they have an open, feathery appearance, trap air and have a low density. Where snow collects in hollows, it becomes compressed by the weight of subsequent falls and gradually develops into a more compact, dense form called **firn** or **névé**. Firn is compacted snow which has experienced one winter's freezing and survived a summer's melting. It is composed of randomly oriented ice crystals separated by air passages. In temperate latitudes, such as in the Alps, summer meltwater percolates into the firn only to freeze either at night or during the following winter, thus forming an increasingly dense mass. Air is progressively squeezed out and after 20–40 years the firn will have turned into solid ice. This same process may take several hundred years in Antarctica and Greenland where there is no summer melting. Once ice has formed, it may begin to flow downhill, under the force of gravity, as a **glacier**.

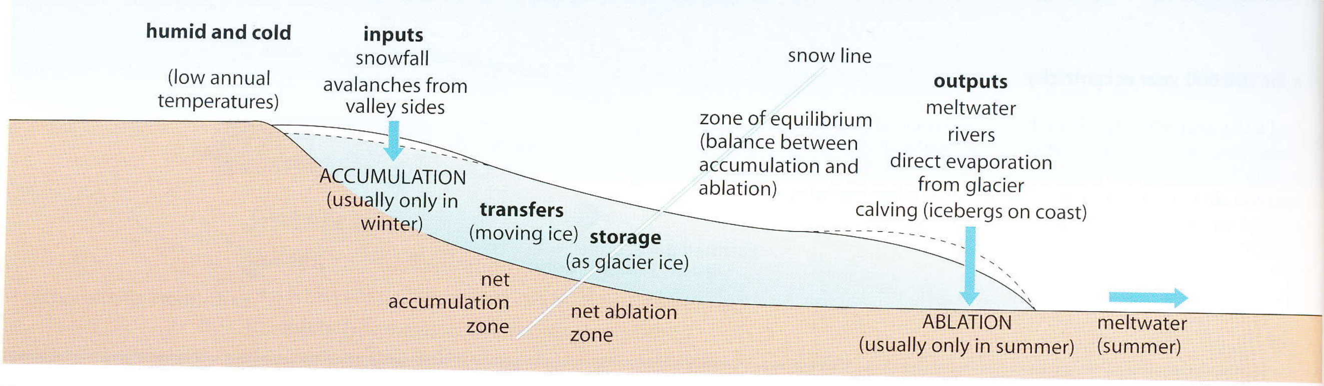


Figure 4.7

The glacial system showing inputs, stores, transfers and outputs

Glaciers and ice masses

Glaciers may be classified (Framework 7, page 167) according to size and shape – characteristics that are relatively easy to identify by field observation.

1 **Corrie** or **cirque glaciers** are small masses of ice occupying armchair-shaped hollows in mountains (Figure 4.14). They often overspill from their hollows to feed valley glaciers.
2 **Valley glaciers** are larger masses of ice which move down from either an icefield or a cirque basin source (Figure 4.8). They usually follow former river courses and are bounded by steep sides.
3 **Piedmont glaciers** are formed when valley glaciers extend onto lowland areas, spread out and merge.

Figure 4.8

The Gigjökull glacier, Iceland, showing the zones of accumulation, equilibrium (snow line) and ablation

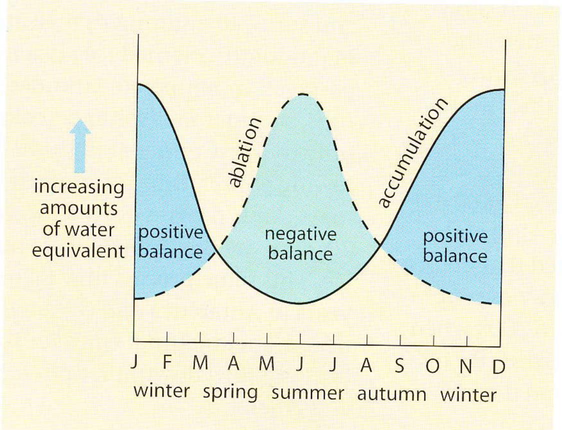


Figure 4.9

The glacial budget or net balance (northern hemisphere)

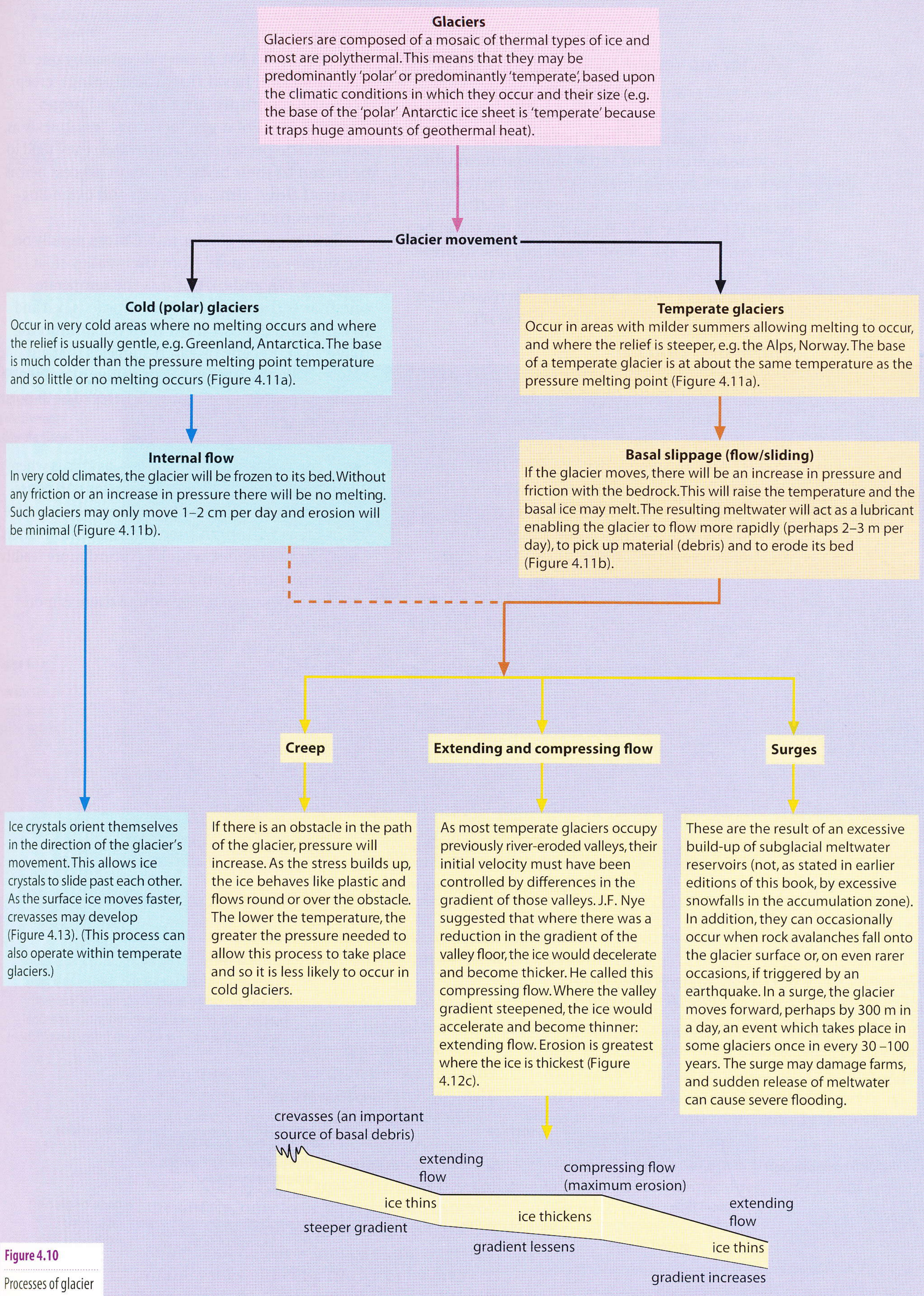
4 **Icecaps** and **ice sheets** are huge areas of ice which spread outwards from central domes. Apart from exposed summits of high mountains, called **nunataks**, the whole landscape is buried. Ice sheets, which once covered much of northern Europe and North America (Figure 4.3) are now confined to Antarctica (86 per cent of present-day world ice) and Greenland (11 per cent).
5 **Ice shelves** form when ice sheets reach the sea and begin to float. **Icebergs** form when ice breaks away, a process known as **calving**.

Glacial systems and budgets

A glacier behaves as a system (Framework 3, page 45), with inputs, stores, transfers and outputs (Figure 4.7). Inputs are derived from snow falling directly onto the glacier or from **avalanches** along valley sides (Case Study 4). The glacier itself is water in storage and transfer. Outputs from the glacier system include evaporation, calving (the formation of icebergs), and meltwater streams which flow either on top of or under the ice during the summer months.

The upper part of the glacier, where inputs exceed outputs, is known as the **zone of accumulation**; the lower part, where outputs exceed inputs, is called the **zone of ablation**. The **zone of equilibrium** is where the rates of accumulation and ablation are equal, and it corresponds with the snow line (Figures 4.7 and 4.8).

The **glacier budget**, or **net balance**, is the difference between the total accumulation and the total ablation for one year. In temperate glaciers (page 108), there is likely to be a negative balance in summer when ablation exceeds accumulation, and a positive balance in winter when the reverse occurs (Figure 4.9). If the summer and winter budgets cancel each other out, the glacier appears to be stationary. It appears stationary because the **snout** – i.e. the end of the glacier – is neither advancing nor retreating, although ice from the accumulation zone is still moving down-valley into the ablation zone. Because glaciers are acutely affected by changes to inputs and outputs, they are sensitive indicators of climatic change, both short term and long term.



Glaciers
Glaciers are composed of a mosaic of thermal types of ice and most are polythermal. This means that they may be predominantly 'polar' or predominantly 'temperate', based upon the climatic conditions in which they occur and their size (e.g. the base of the 'polar' Antarctic ice sheet is 'temperate' because it traps huge amounts of geothermal heat).

Glacier movement

Cold (polar) glaciers
Occur in very cold areas where no melting occurs and where the relief is usually gentle, e.g. Greenland, Antarctica. The base is much colder than the pressure melting point temperature and so little or no melting occurs (Figure 4.11a).

Internal flow
In very cold climates, the glacier will be frozen to its bed. Without any friction or an increase in pressure there will be no melting. Such glaciers may only move 1–2 cm per day and erosion will be minimal (Figure 4.11b).

Ice crystals orient themselves in the direction of the glacier's movement. This allows ice crystals to slide past each other. As the surface ice moves faster, crevasses may develop (Figure 4.13). (This process can also operate within temperate glaciers.)

Temperate glaciers
Occur in areas with milder summers allowing melting to occur, and where the relief is steeper, e.g. the Alps, Norway. The base of a temperate glacier is at about the same temperature as the pressure melting point (Figure 4.11a).

Basal slippage (flow/sliding)
If the glacier moves, there will be an increase in pressure and friction with the bedrock. This will raise the temperature and the basal ice may melt. The resulting meltwater will act as a lubricant enabling the glacier to flow more rapidly (perhaps 2–3 m per day), to pick up material (debris) and to erode its bed (Figure 4.11b).

Creep
If there is an obstacle in the path of the glacier, pressure will increase. As the stress builds up, the ice behaves like plastic and flows round or over the obstacle. The lower the temperature, the greater the pressure needed to allow this process to take place and so it is less likely to occur in cold glaciers.

Extending and compressing flow
As most temperate glaciers occupy previously river-eroded valleys, their initial velocity must have been controlled by differences in the gradient of those valleys. J.F. Nye suggested that where there was a reduction in the gradient of the valley floor, the ice would decelerate and become thicker. He called this compressing flow. Where the valley gradient steepened, the ice would accelerate and become thinner: extending flow. Erosion is greatest where the ice is thickest (Figure 4.12c).

Surges
These are the result of an excessive build-up of subglacial meltwater reservoirs (not, as stated in earlier editions of this book, by excessive snowfalls in the accumulation zone). In addition, they can occasionally occur when rock avalanches fall onto the glacier surface or, on even rarer occasions, if triggered by an earthquake. In a surge, the glacier moves forward, perhaps by 300 m in a day, an event which takes place in some glaciers once in every 30 –100 years. The surge may damage farms, and sudden release of meltwater can cause severe flooding.

Figure 4.10
Processes of glacier movement

Glacier movement and temperature

The character and movement of ice depend upon whether it is warm or cold, which in turn depends upon the **pressure melting point (PMP)**. The pressure melting point is the temperature at which ice is on the verge of melting. A small increase in pressure can therefore cause melting. PMP is normally 0°C on the surface of a glacier, but it can be lower within a glacier (due to an increase in pressure caused by either the weight or the movement of ice). In other words, as pressure increases, then the freezing point for water falls below 0°C.

Warm and cold ice

Warm ice has a temperature of around 0°C (PMP) throughout its depth (Figure 4.11a) and consequently is able, especially in summer, to release large amounts of meltwater. Temperatures in cold ice are permanently below 0°C (PMP) and so there is virtually no meltwater (Figure 4.11a). It is the presence of meltwater that facilitates the movement of a glacier. Temperature is therefore an alternative criterion to size or shape for use when categorising glaciers – they may be either **temperate** (mainly warm ice) or **polar** (mainly cold ice) – Figure 4.10. Movement is much faster in temperate glaciers where the presence of meltwater acts as a lubricant and reduces friction (Figure 4.11b). It can take place by one of four processes: **basal flow** (or **slipping**); **creep**; **extending–compressing flow**; and **surges** (Figure 4.10). Polar glaciers move less quickly as, without the presence of meltwater, they tend to be frozen to their beds. The main process here is **internal flow**, although creep and extending–compressing flow may also occur.

Both types of glacier move more rapidly on the surface and away from their valley sides (Figure 4.12a and b), but it is the temperate one that is the more likely to erode its bed and to carry and deposit most material as **moraine** (page 117). Recent research suggests that any single glacier may exhibit, at different points along its profile, the characteristics of both polar and temperate glaciers.

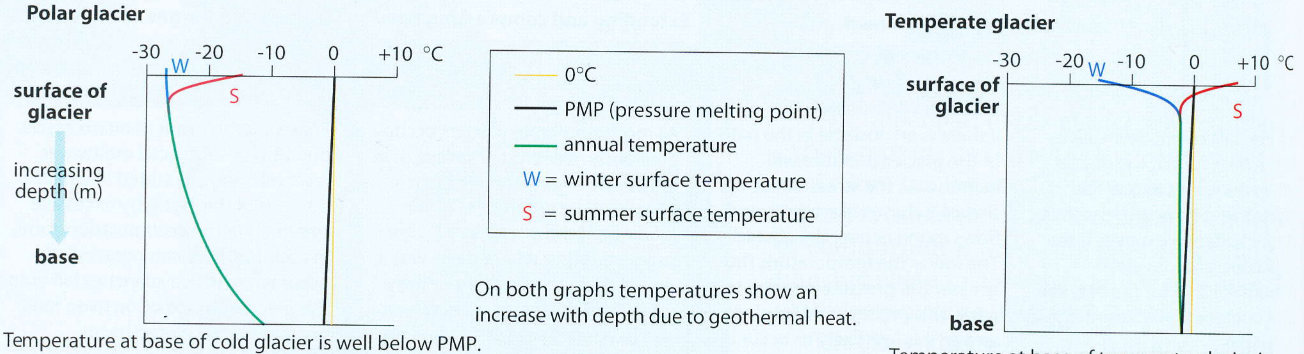
Movement is greatest:

- at the point of equilibrium – as this is where the greatest volume of ice passes and consequently where there is most energy available
- in areas with high precipitation and ablation
- in small glaciers, which respond more readily to short-term climatic fluctuations
- in temperate glaciers, where there is more meltwater available, and
- in areas with steep gradients.

Figure 4.11

Comparison of temperature and velocity profiles in polar and temperate glaciers

a Temperature profiles

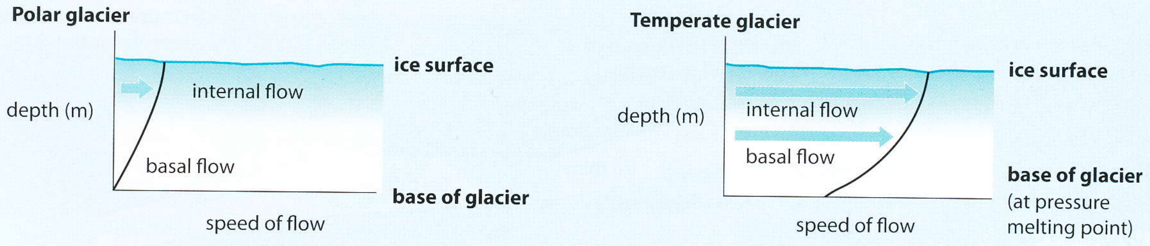


Temperature at base of cold glacier is well below PMP. Little or no meltwater beneath glacier prevents it from moving freely. Only under thickest parts of glaciers in Antarctica does temperature exceed PMP to allow melting and movement to occur.

On both graphs temperatures show an increase with depth due to geothermal heat.

Temperature at base of temperate glacier is about the same as PMP. Meltwater beneath glacier can either be permanent or seasonal allowing the glacier to move freely (less friction).

b Velocity profiles



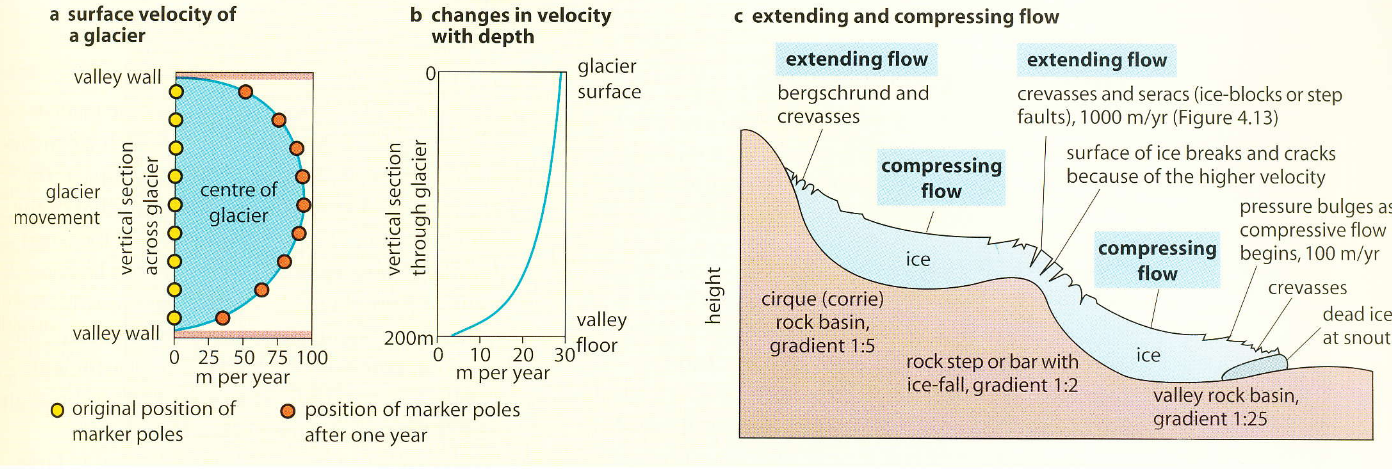


Figure 4.12

Plan view to show **a** and **b** velocity **c** flow of a glacier

Figure 4.13

Crevasses on an icefall, Skafta glacier, Iceland

Transportation by ice

Glaciers are capable of moving large quantities of debris. This rock debris may be transported in one of three ways:

1 **Supraglacial debris** is carried on the surface of the glacier as lateral and medial moraine (page 117). It consists of material that has fallen onto the glacier from the surrounding valley sides. In summer, the relatively small load carried by surface meltwater streams often disappears down crevasses.

2 **Englacial debris** is material carried within the body of the glacier. It may once have been on the surface, only to be buried by later snowfalls or to fall into crevasses (Figure 4.4).

3 **Subglacial debris** is moved along the floor of the valley either by the ice or by meltwater streams formed by pressure melting (page 108).

Glacial erosion

Ice that is stationary or contains little debris has limited erosive power, whereas moving ice carrying with it much debris can drastically alter the landscape. Although ice lacks the turbulence and velocity of water in a river, it has the 'advantage' of being able to melt and refreeze in order to overcome obstacles in its path (Figure 4.10) and consequently has the ability to lower (i.e. erode) the landscape more quickly than can running water. Virtually all the glacial processes of erosion are physical, as the climate tends to be too cold for chemical reactions to operate (Figure 2.10).

Processes of glacial erosion

The processes associated with glacial erosion are: frost shattering, abrasion, plucking, rotational movement, and extending and compressing flow.

Frost shattering

This process (page 40) produces much loose material which may fall from the valley sides onto the edges of the glacier to form **lateral moraine**, be covered by later snowfall, or plunge down crevasses to be transported as **englacial debris**. Some of this material may be added to rock loosened by frost action as the climate deteriorated (but before glaciers formed) to form **basal debris** (page 117).

Abrasion

This is the sandpapering effect of angular material embedded in the glacier as it rubs against the valley sides and floor. It usually produces smoothened, gently sloping landforms.

Plucking

At its simplest, this process involves the glacier freezing onto rock outcrops, after which ice movement pulls away masses of rock. In reality, as the strength of the bedrock is greater than that of the ice, it would seem that only previously loosened material can be removed. Material may be continually loosened by one of three processes:

1 The relationship between local pressure and temperature (the PMP) produces sufficient meltwater for freeze–thaw activity to break up the ice-contact rock.
2 Water flowing down a **bergschrund** (a large, crevasse-like feature found near the head of some glaciers – Figure 4.14b) or smaller crevasses will later freeze onto rock surfaces.
3 Removal of layers of bedrock by the glacier causes a release in pressure and an enlarging of joints in the underlying rocks (pressure release, page 41).

Plucking generally creates a jagged-featured landscape.

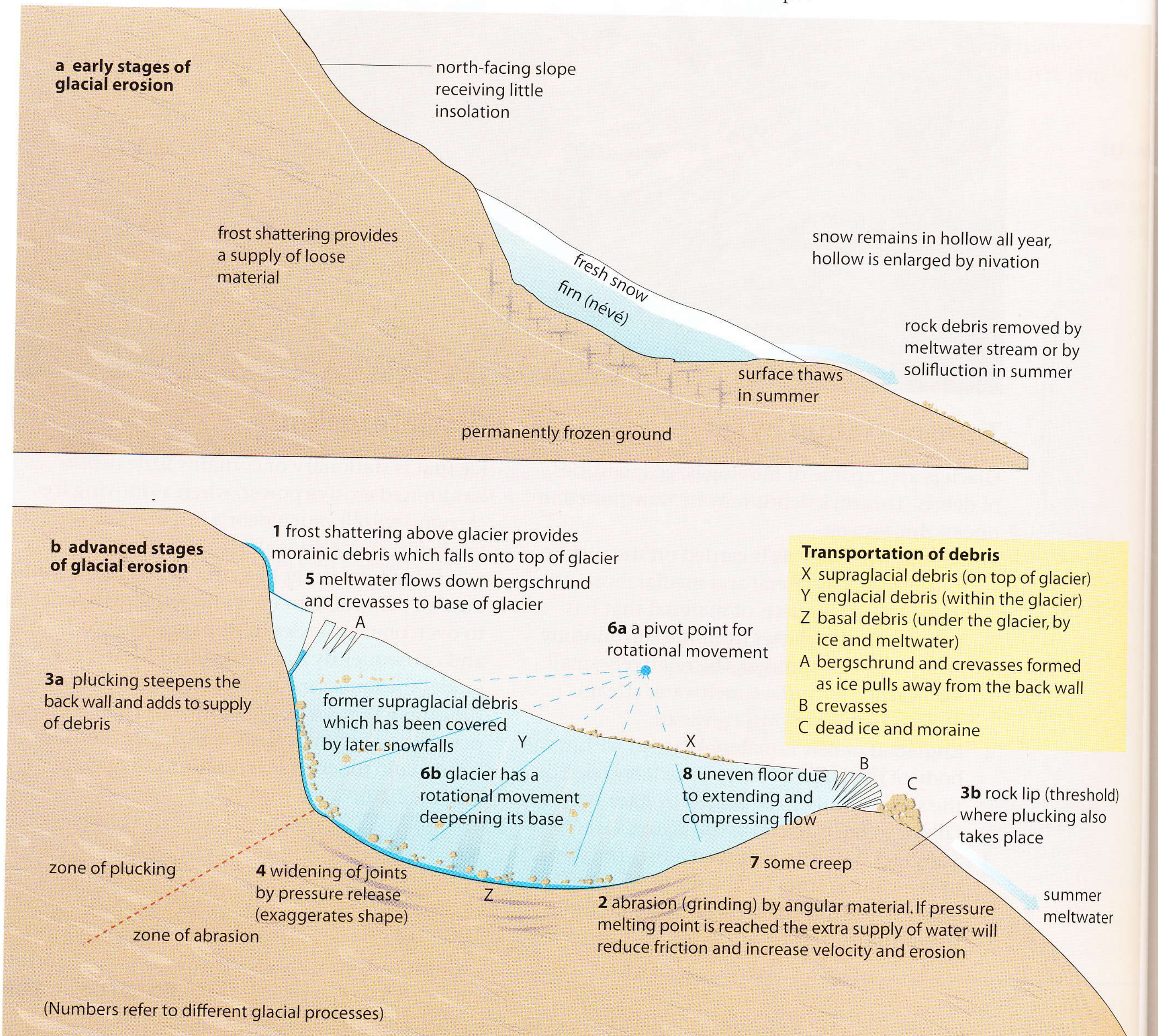


Figure 4.14

Processes in the formation of a cirque

Figure 4.15

A cirque in West Wales (Cader Idris). The steep wall maintains its shape as freeze–thaw still operates. Broken-off material forms scree which is beginning to infill the lake, which itself has been dammed behind a natural rock lip

Rotational movement

This is a downhill movement of ice which, like a landslide (Figure 2.17), pivots about a point. The increase in pressure is responsible for the over-deepening of a cirque floor (Figure 4.14b).

Extending and compressing flow

Figures 4.10 and 4.12c show how this process causes differences in the rate of erosion at the base of a glacier.

Maximum erosion occurs:

- where temperatures fluctuate around 0°C, allowing frequent freeze–thaw to operate
- in areas of jointed rocks which can be more easily frost shattered
- where two tributary glaciers join, or the valley narrows, giving an increased depth of ice, and
- in steep mountainous regions in temperate latitudes, where the velocity of the glacier is greatest.

Landforms produced by glacial erosion

Cirques

These are amphitheatre or armchair-shaped hollows with a steep back wall and a rock basin (Figure 4.15). They are also known as **corries** (Scotland) and **cwms** (Wales – Figures 4.25 and 4.26).

During periglacial times (Chapter 5), before the last glacial, snow collected in hollows, especially on north-facing slopes. A series of processes, collectively known as **nivation** and which included freeze–thaw, solifluction and possibly chemical weathering, operated under and around the snow patch (Figure 4.14a). These processes caused the underlying rocks to disintegrate. The resultant debris was then removed by summer meltwater streams to leave, in the enlarged hollow, an embryo cirque. It has been suggested that the overdeepening process might need several periglacials or interglacials and glacials in which to form. As the snow patch grew, its layers became increasingly compressed to form firn and, eventually, ice (page 105).

It is accepted that several processes interact to form a fully developed cirque (Figure 4.14b). Plucking is one process responsible for steepening the back wall, but this partly relies upon a supply of water for freeze–thaw and partly upon pressure release in well-jointed rocks. A rotational movement, aided by water from pressure point melting and angular subglacial debris from frost shattering, enables abrasion to over-deepen the floor of the cirque. A **rock lip** develops where erosion decreases. This may be increased in height by the deposition of morainic debris at the glacier's snout. When the climate begins to get warmer, the ice remaining in the hollow melts to leave a deep, rounded lake or tarn (Figures 4.15 and 4.26).

In Britain, as elsewhere in the northern hemisphere, cirques are nearly always oriented between the north-west (315°), through the north-east (where the frequency peaks) to the south-east (135°). This is because in the UK:

- northern slopes receive least **insolation** and so glaciers remained there much longer than those facing in more southerly directions (less melting on north-facing slopes)
- western slopes face the sea and, although still cold, the relatively warmer winds which blew from that direction were more likely to melt the snow and ice (more snow accumulated on east-facing slopes)
- the prevailing westerly winds cause snow to drift into east-facing hollows.

Lip orientation is the direction of an imaginary line from the centre of the back wall of the cirque to its lip. Of 56 cirques identified in the Snowdon area, 51 have a lip orientation of between 310° and 120°, and of 15 on Arran, 14 have an orientation between 5° and 115°.

Framework 5 Mean, median and mode

Mean, median and mode are all types of average (measures of dispersion, Framework 8, page 246).

1 The **mean** (or arithmetic average) is obtained by totalling the values in a set of data and dividing by the number of values in that set. It is expressed by the formula:

$$\bar{x} = \frac{\Sigma x}{n}$$

where:

$\bar{x}$ = mean, Σ = the sum of, x = the value of the variable, n = the number of values in the set

The mean is reliable when the number of values in the sample is high and their range, i.e. the difference between the highest and lowest values, is low, but it becomes less reliable as the number in the sample decreases, as it is then influenced by extreme values.

2 The **median** is the mid-point value of a set of data. For example, you have to find the median height of students in your class. To do this you will have to rank each person in descending order of height. If there were 15 students then the mid-point would be the eighth student as there will be seven taller and seven shorter. Had there been an even number in the sample, such as 16, then the median would have been the mean of the two middle values. The median is a less accurate measure of dispersion than the mean because widely differing sets of data can return the same median, but it is less distorted by extreme values.

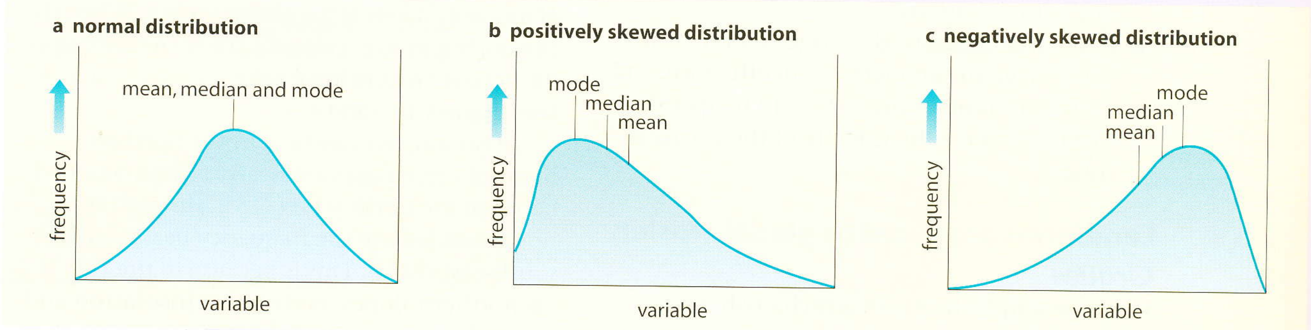
3 The **mode** is the value or class that occurs most frequently in the data. In the set of values 4, 6, 4, 2, 4 the mode would be 4. Although it is the easiest of the three 'averages' to obtain, it has limited value. Some data may not have two values in the same class (e.g. 1, 2, 3, 4, 5), while others may have more than one modal value (e.g. 1, 1, 2, 4, 4).

Relationships between mean, median and mode

When data is plotted on a graph we can often make useful observations about the shape of the curve. For example, we would expect A-level results nationally to show a few top grades, a smaller number of 'unclassifieds' and a large number of average passes. Graphically this would show a normal distribution, with all three averages at the peak. If the distribution is skewed, then by definition only the mode will lie at the peak (Figure 4.16).

Figure 4.16

Normal and skewed distributions



Arêtes and pyramidal peaks

When two adjacent cirques erode backwards or sideways towards each other, the previously rounded landscape is transformed into a narrow, rocky, steep-sided ridge called an **arête**, as at Striding Edge in the Lake District (Figure 4.17) and Crib Goch on Snowdon (Figure 4.25). If three or more cirques develop on all sides of a mountain, a **pyramidal peak**, or horn, may be formed. This feature has steep sides and several arêtes radiating from the central peak (Figures 4.18 and 4.19), e.g. the Matterhorn.

Figure 4.17

An arête: Striding Edge on Helvellyn in the Lake District


Figure 4.18

Arêtes in the Karakoram Mountains, northern Pakistan

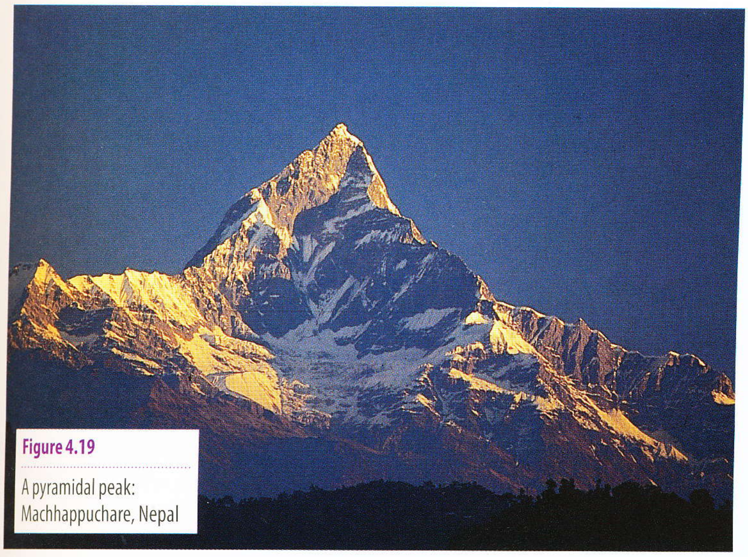


Figure 4.19

A pyramidal peak: Machhappuchare, Nepal

Glacial troughs, rock steps, truncated spurs and hanging valleys

These features are interrelated in their formation. Valley glaciers straighten, widen and deepen preglacial valleys, turning the original V-shaped, river-formed feature into the characteristic U shape typical of glacial erosion, e.g. Wast Water in the Lake District (Figure 4.20). These steep-sided, flat-floored valleys are known as **glacial troughs**. The overdeepening of the valleys is credited to the movement of ice which, aided by large volumes of meltwater and subglacial debris, has a greater erosive power than that of rivers. Extending and compressing flow may overdeepen parts of the trough floor, which later may be occupied by long, narrow **ribbon lakes**, such as Wast Water, or may leave less eroded, more resistant **rock steps**.

Theories to explain pronounced overdeepening of valley floors are debated amongst glaciologists and geomorphologists. Suggested causes include: extra erosion following the confluence of two glaciers; the presence of weaker rocks; an area of rock deeply weathered in preglacial times; or a zone of well-jointed rock. Should the deepening of the trough continue below the former sea-level, then during deglaciation and subsequent rises in sea-level the valley may become submerged to form a **fiord** (Figures 4.21 and 6.48).

Abrasion by englacial and subglacial debris and plucking along the valley sides remove the tips of preglacial interlocking spurs leaving cliff-like **truncated spurs** (Figure 4.20, and to the left of Figure 4.27).


Figure 4.20

Glacial trough with ribbon lake: Wast Water in the Lake District

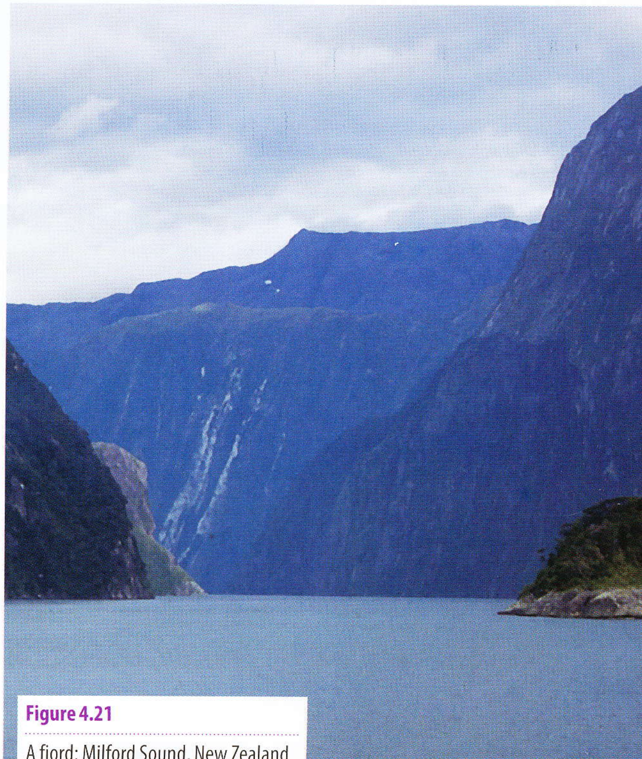


Figure 4.21

A fiord: Milford Sound, New Zealand

Figure 4.22

Hanging valley: Lake Bigden, Norway

Hanging valleys result from differential erosion between a main glacier and its tributary glaciers. The floor of any tributary glacier is deepened at a slower rate so that when the glaciers melt it is left hanging high above the main valley and its river has to descend by a single waterfall or a series of waterfalls, e.g. Lake Bigden, Norway (Figure 4.22) and Cwm Dyli, Snowdonia (Figure 4.25).

Striations, roches moutonnées, rock drumlins and crag and tail

These are all smaller erosion features which help to indicate the direction of ice movement. As a glacier moves across areas of exposed rock, larger fragments of angular debris embedded in the ice tend to leave a series of parallel scratches and grooves called **striations** (e.g. Central Park in New York).

A **roche moutonnée** is a mass of more resistant rock. It has a smooth, rounded upvalley or stoss slope facing the direction of ice flow, formed by abrasion, and a steep, jagged, down-valley or lee slope resulting from plucking (Figures 4.23 and 4.24).

Rock drumlins are more streamlined bedrock which lack the quarried lee face of the roche moutonnée. They are sometimes referred to as **whalebacks** as they resemble the backs of whales breaking the ocean surface.

A **crag and tail** consists of a larger mass of resistant rock or crag (e.g. the basaltic crag upon which Edinburgh Castle has been built) which protected the lee-side rocks from erosion, thus forming a gently sloping tail of deposited material (e.g. the tail down which the Royal Mile extends).

It should be remembered that while many of these erosional landforms may be found together in most glaciated uplands, their arrangement, frequency and presence is likely to change from one area to another. Places 15 describes some of these glacial features as found in one part of Snowdonia.

Figure 4.23

A roche moutonnée: Yosemite National Park, California

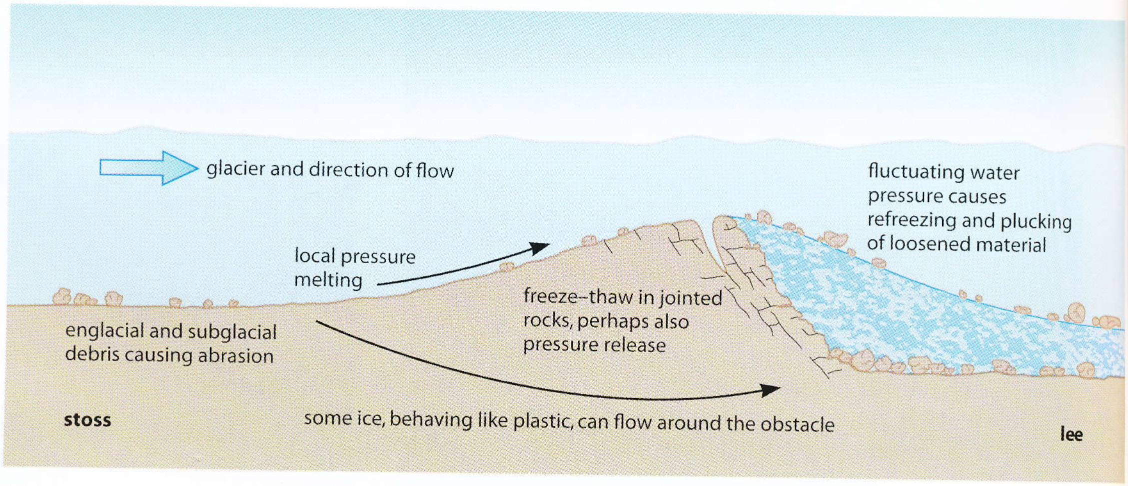


Figure 4.24

The formation of a roche moutonnée

Places 15 Snowdonia: glacial landforms

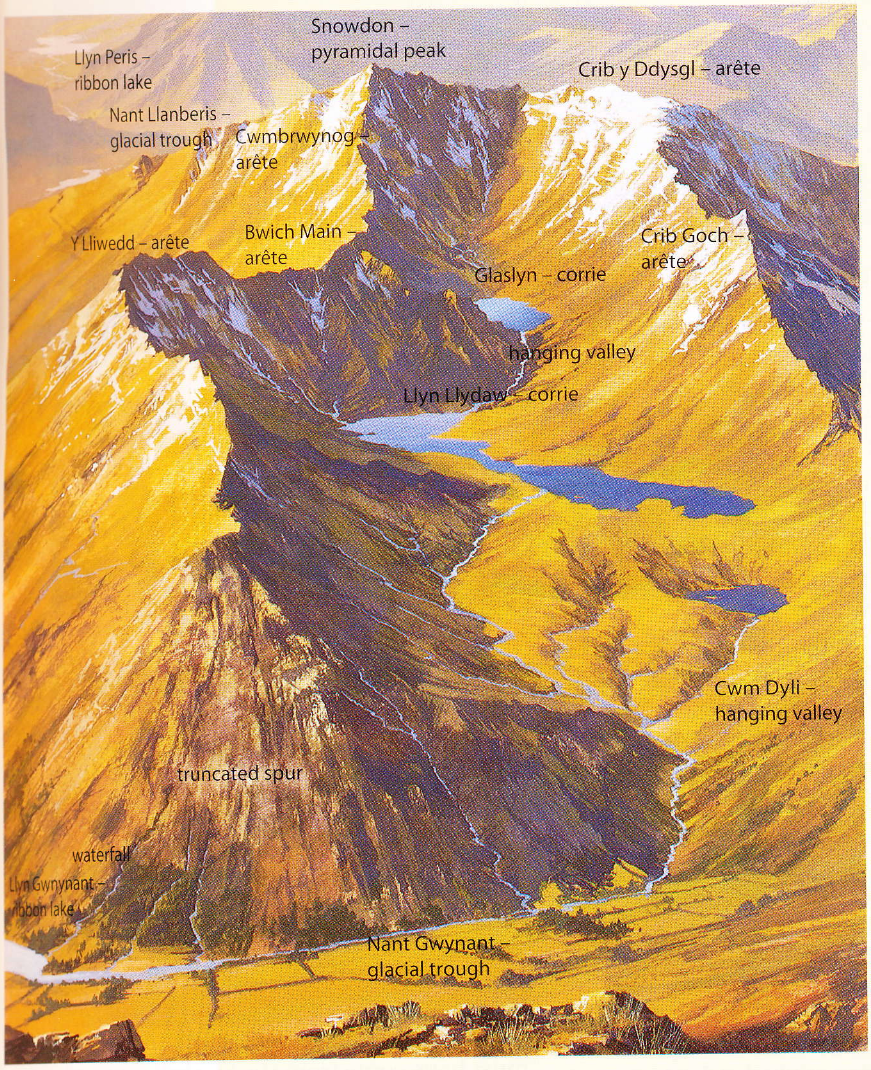


Figure 4.25

Landsketch of glacial features in Snowdonia (looking west)

Snowdonia is an example of a glaciated upland area. Although Snowdon itself has the characteristics of a pyramidal peak, the ice age was too short (by several thousand years) for the completed development of the classic pyramidal shape which makes the appearance of the Matterhorn so spectacular (compare Figure 4.19). What *are* well developed are the arêtes, such as Crib Goch and Bwlch Main, which radiate from the central peak. Between these arêtes are up to half a dozen cirques (cwms, as this is Wales), including the eastward-facing Glaslyn and the north-eastward-oriented (page 111) Llyn (lake) Llydaw. Glaslyn, which is trapped by a rock lip, is 170 m higher than Llyn Llydaw (Figure 4.26). Striations and roches moutonnées can be found in several places where the rocks are exposed on the surface. To the north and south-east of Snowdon are the glacial troughs of Nant (valley) Llanberis, Nant Ffrancon and Nant Gwynant. These valleys have the characteristic U shape, with steep valley sides, truncated spurs and a flat valley floor (Figure 4.27). Located on the valley floors are ribbon lakes, including Llyn Peris and Llyn Gwynant (Figure 3.24). Numerous small rivers, with their sources in hanging valleys, descend by waterfalls, as at Cwm Dyli, into the two main valleys. Although the ice has long since gone, the actions of frost and snow, together with that of rain and more recently people, continue to modify the landscape – remember that rarely does a landscape exhibit stereotyped 'textbook' features (see Figure 4.25)!

Figure 4.26

Llyn Glaslyn: a cirque lake formed behind a rock lip, and a hanging valley into Llyn Llydaw

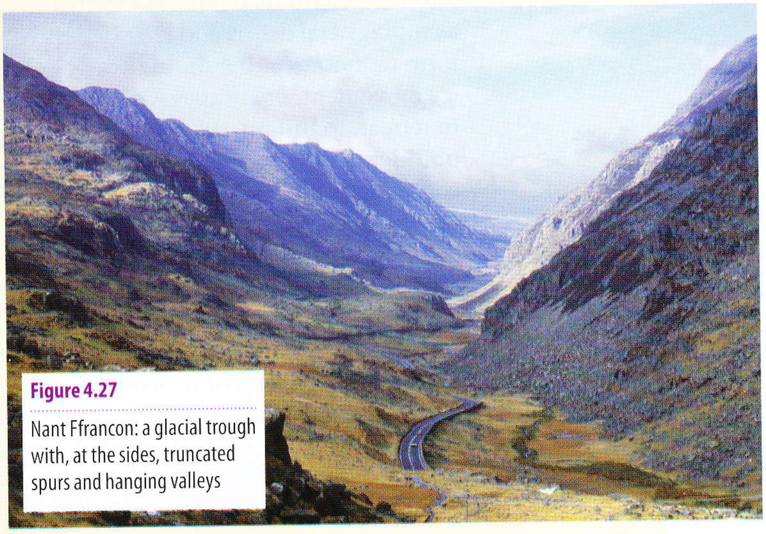


Figure 4.27

Nant Ffrancon: a glacial trough with, at the sides, truncated spurs and hanging valleys

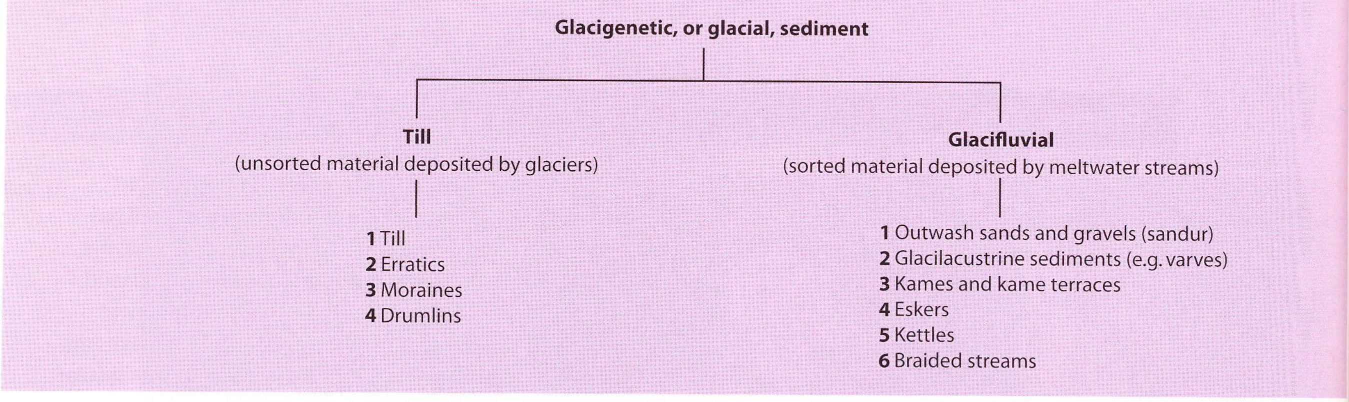


Figure 4.28

Landforms resulting from glacial deposition

Glacial deposition

Glacigenetic sediment (or **glacial sediments**) has replaced 'drift' as the term which was used historically by British geologists and glaciologists when referring collectively to all glacial deposits (Figure 4.28). These deposits, which include boulders, gravels, sands and clays, may be subdivided into **till**, which includes all material deposited directly by the ice, and **glacifluvial material**, which is the debris deposited by meltwater streams. Glacifluvial material includes deposits which may have been deposited initially by the ice and which were later picked up and redeposited by meltwater – either during or after the ice age. Till consists of largely unsorted material, whereas glacifluvial deposits have been sorted. Deposition occurs in upland valleys and across lowland areas. A study of glacigenetic deposits helps to explain the:

- nature and extent of an ice advance
- frequency of ice advances
- sources and directions of ice movement, and
- postglacial chronology (including climatic changes, page 294).

Till deposits

Although the term **till** is often applied today to all materials deposited by ice, it is more accurately used to mean an unsorted mixture of rocks, clays and sands. This material was largely transported as supraglacial debris and later deposited to form moraine – either during periods of active ice movement, or at times when the glacier was in retreat. In Britain, till was commonly called **boulder clay** but – since some deposits may contain neither boulders nor clay – this term is now obsolete. Individual stones are sub-angular – that is, they are not rounded like river or beach material but neither do they possess the sharp edges of rocks that have recently been broken up by frost shattering. The composition of till reflects the character of the rocks over which it has passed; East Anglia, for example, is covered by chalky till because the ice passed over a chalk escarpment, i.e. the East Anglian Heights.

Till fabric analysis is a fieldwork technique used to determine the direction and source of glacial deposits. Stones and pebbles carried by a glacier tend to become aligned with their long axes parallel to the direction of ice flow, as this offers least resistance to the ice. For example, a small sample of 50 stones was taken from a moraine in Glen Rosa, Arran. As each stone was removed, its geology was examined and its orientation was carefully measured using a compass. The results allowed two conclusions to be reached:

1 The pebbles were grouped into classes of 20° and plotted onto a rose diagram (Figure 4.29). The classes were plotted as respective radii from the midpoint of the diagram and then the ends of the radii were joined up to form a star-like polygonal graph. As each stone has two orientations which must be opposites (e.g. 10° and 190°), the graph will be symmetrical. The results show that the ice must have come from the north-north-west or the south-south-east.

2 Although most of the pebbles taken in the sample were composed of local rock, some were of material not found on the island (erratics). This suggests that some of the ice must have come from the Scottish mainland.

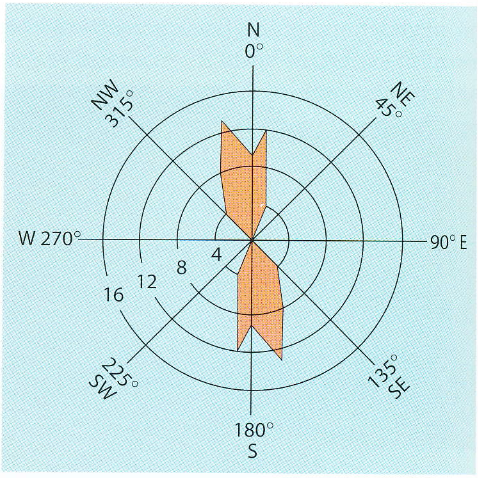


Figure 4.29

Till fabric analysis: orientation of a sample of stones taken from a moraine in Glen Rosa, Arran

Landforms characteristic of glacial deposition

Erratics

These are boulders picked up and carried by ice, often for many kilometres, to be deposited in areas of completely different lithology (Figure 4.30). **Lithology** is the study of the nature and composition of rocks. By determining where the boulders originally came from, it is possible to track ice movements. For example, volcanic material from Ailsa Craig in the Firth of Clyde has been found 250 km to the south on the Lancashire plain, while some deposits on the north Norfolk coast originated in southern Norway.

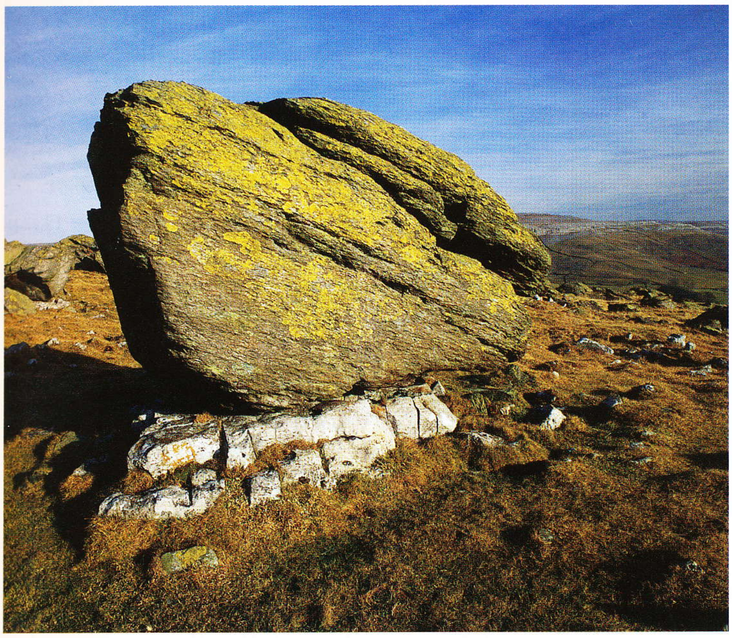


Figure 4.30

An erratic near Ingleborough in the Yorkshire Dales: Silurian rock lying on top of Carboniferous limestone (Figure 1.1)

Moraine

Moraine is a type of landform that develops when the debris carried by a glacier is deposited. It is *not*, therefore, the actual material that is being transported by the glacier – with the exception of the medial moraine, which is a term that refers to a landform both on the glacier and in the valley after glacial recession. It is possible to recognise at least five types of moraine (Figure 4.31):

- **Lateral moraine** is formed from debris derived from frost shattering of valley sides and carried along the edges of the glacier (Figure 4.32). When the glacier melts, it leaves an embankment of material along the valley side.
- **Medial moraine** is found in the centre of a valley and results from the merging of two lateral moraines where two glaciers joined (Figure 4.32).
- **Terminal** or **end moraine** is often a high mound (or series of mounds) of material extending across a valley, or lowland area, at right-angles to and marking the maximum advance of the glacier or ice sheet.
- **Recessional moraines** mark interruptions in the retreat of the ice when the glacier or ice sheet remained stationary long enough for a mound to build up. Recessional moraines are usually parallel to the terminal moraine.
- **Push moraines** may develop if the climate deteriorates sufficiently for the ice temporarily to advance again. Previously deposited moraine may be shunted up into a mound. It can be recognised by individual stones which have been pushed upwards from their original horizontal positions, or even large blocks of sediment that have been bulldozed whole, while frozen.

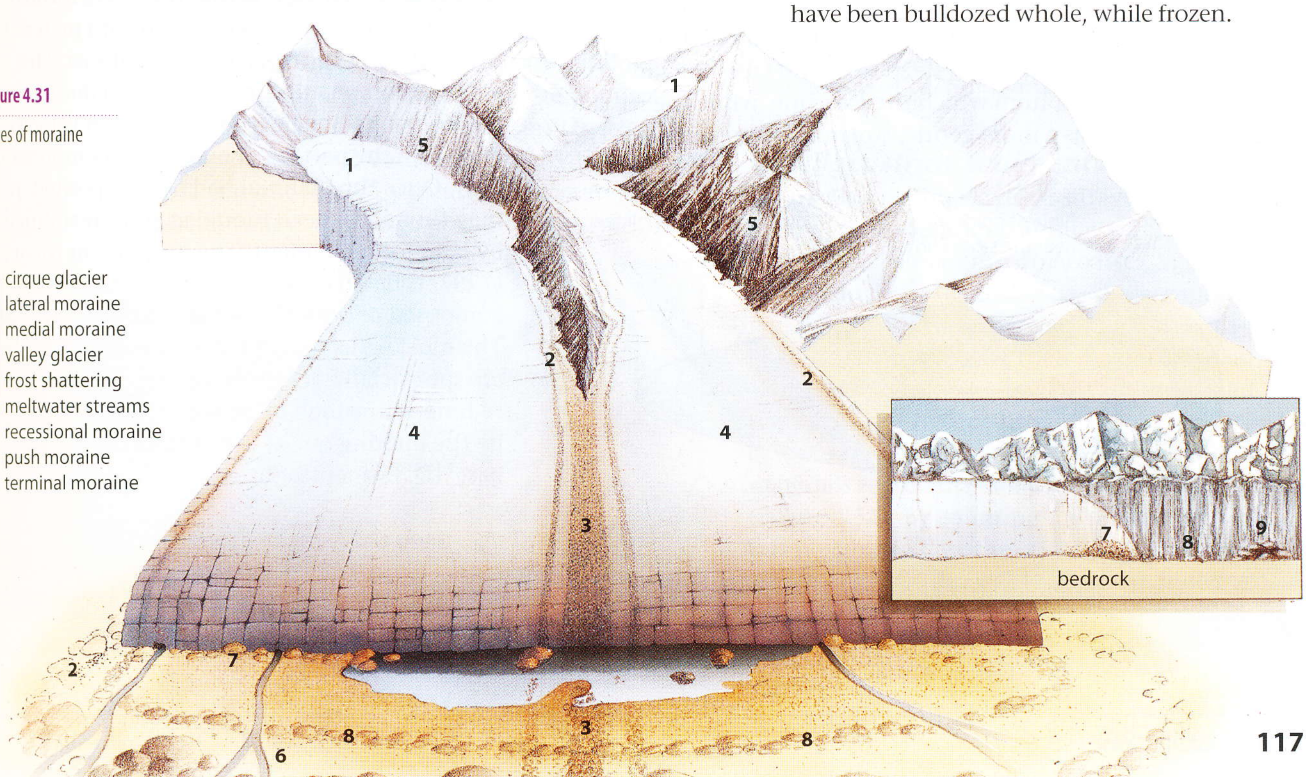


Figure 4.31

Types of moraine

1 cirque glacier
2 lateral moraine
3 medial moraine
4 valley glacier
5 frost shattering
6 meltwater streams
7 recessional moraine
8 push moraine
9 terminal moraine

Figure 4.32

Medial and lateral moraines, Meade Glacier, Alaska

Figure 4.33

Morainic mounds above Haweswater, Cumbria

Drumlins

These are smooth, elongated mounds of till with their long axis parallel to the direction of ice movement. Drumlins may be over 50 m in height, over 1 km in length and nearly 0.5 km in width. The steep stoss end faces the direction from which the ice came, while the lee side has a more gentle, streamlined appearance. The highest point of the feature is near to the stoss end (Figure 4.34). The shape of drumlins can be described by using the **elongation ratio**:

$$E = \frac{I}{W}$$

where I is the maximum bedform length, and W is the maximum bedform width. Drumlins are always longer than they are wide, and they are usually found in **swarms** or *en echelon*.

There is much disagreement as to how drumlins are formed. Theories suggest they may be an erosion feature, or formed by deposition around a central rock. However, neither of these accounts for the fact that the majority of drumlins are composed of till which, lacking a central core of rock and consisting of unsorted material, would be totally eroded by moving ice. The most widely accepted view is that they were formed when the ice became overloaded with material, thus reducing the capacity of the glacier. The reduced competence may have been due to the melting of the glacier or to changes in velocity related to the pattern of extending–compressing flow. Once the material had been deposited, it may then have been moulded and streamlined by later ice movement. The most recent theory (1987) is based on evidence that drumlins can be composed of both till and glacifluvial sediments. The most widely accepted view now is that 'they are subglacially deformed masses of pre-existing sediment to which more sediment may be added by the melting out of debris from the glacier base' (D. Evans, 1999).

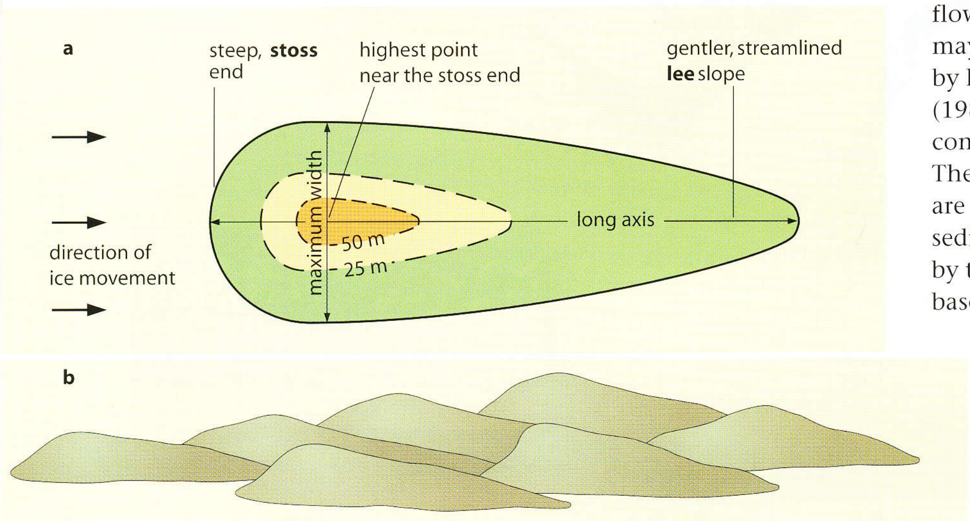


Figure 4.34

Drumlins

a plan showing typical dimensions

b swarm – *en echelon*

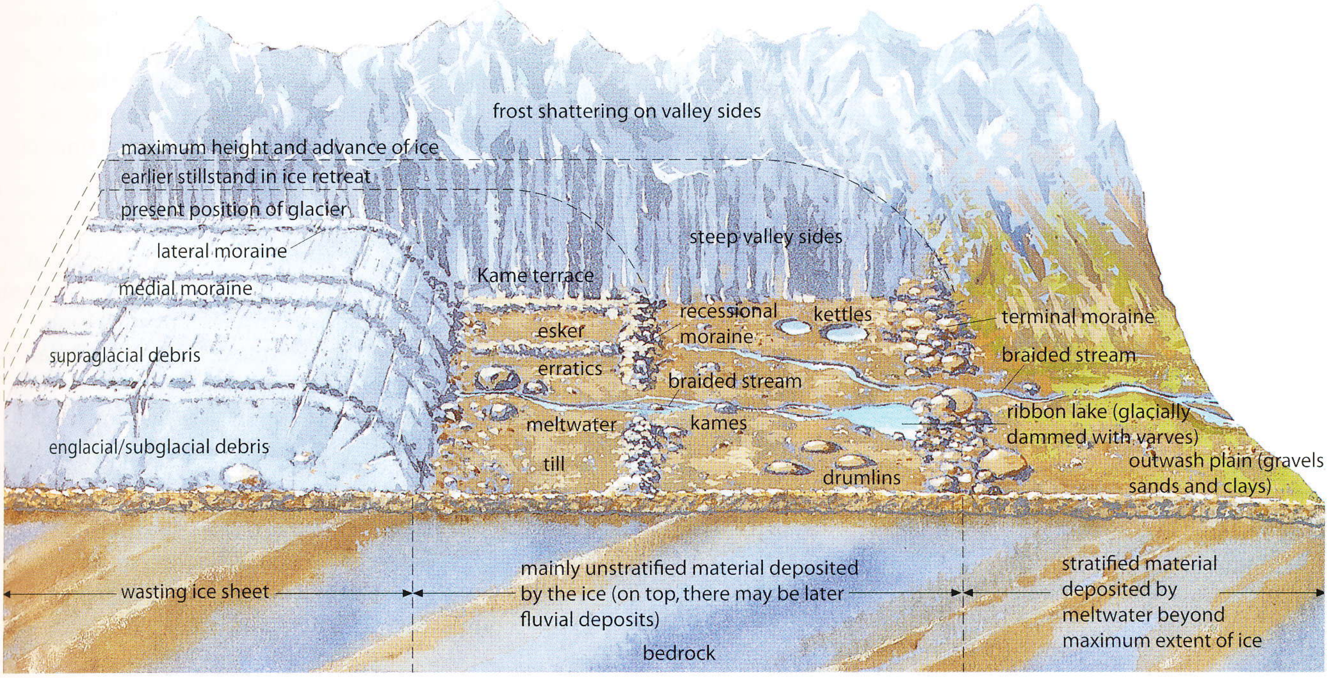


Figure 4.35

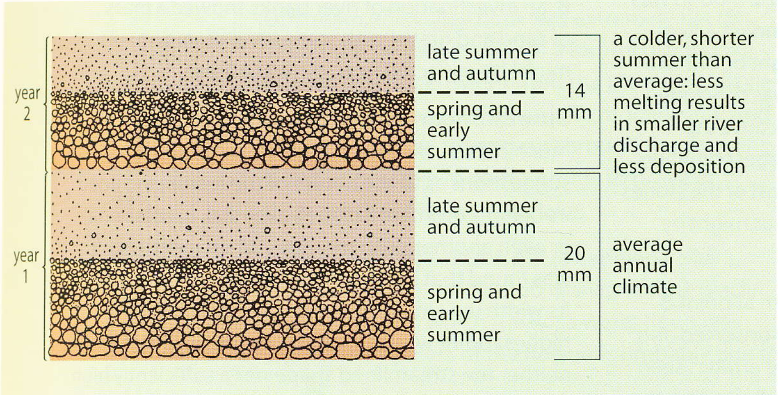
Features of lowland glaciation

Glacifluvial landforms

Glacifluvial landforms are those moulded by glacial meltwater and have, in the past, been considered to be mainly depositional. More recently it has been realised that meltwater plays a far more important role in the glacial system than was previously thought, especially in temperate glaciers and in creating erosion features as well as depositional landforms. Most meltwater is derived from ablation. The discharge of glacial streams, both supraglacial and subglacial, is high during the warmer, if not warm, summer months. As the water often flows under considerable pressure, it has a high velocity and is very turbulent. It is therefore able to pick up and transport a larger amount of material than a normal river of similar size. This material can erode vertically, mainly through abrasion but partly by solution, to create subglacial valleys and large potholes, some of the latter being up to 20 m in depth. Deposition occurs whenever there is a decrease in discharge, and it is responsible for a group of landforms (Figures 4.35 and 4.37).

Figure 4.36

The formation of varves in a postglacial lake



Outwash plains (sandur)

These are composed of gravels, sands and, uppermost and furthest from the snout, clays. They are deposited by meltwater streams issuing from the ice either during summer or when the glacier melts. The material may originally have been deposited by the glacier and later picked up, sorted and dropped by running water beyond the maximum extent of the ice sheets. In parts of the North German Plain, deposits are up to 75 m deep. Outwash material may also be deposited on top of till following the retreat of the ice (Figure 4.35).

Glacilacustrine sediments (varves)

A varve is a distinct layer of silt lying on top of a layer of sand, deposited annually in lakes found near to glacial margins. The coarser, lighter-coloured sand is deposited during late spring when meltwater streams have their peak discharge and are carrying their maximum load. As discharge decreases towards autumn when temperatures begin to drop, the finer, darker-coloured silt settles. Each band of light and dark materials represents one year's accumulation (Figure 4.36). By counting the number of varves, it is possible to date the origin of the lake; variations in the thickness of each varve indicate warmer and colder periods (e.g. greater melting causing increased deposition).

Kames and kame terraces

Kames are undulating mounds of sand and gravel deposited unevenly by meltwater, similar to a series of deltas, along the front of a stationary or slowly melting ice sheet (Figure 4.35). As the ice retreats, the unsupported kame often collapses. Kame terraces, also of sand and gravel, are flat areas found along the sides of valleys. They are deposited by meltwater streams flowing in the trough between the glacier and the valley wall. Troughs occur here because, in summer, the valley side heats up faster than the glacier ice and so the ice in contact with it melts. Kame terraces are distinguishable from lateral moraines by their sorted deposits.

Eskers

These are very long, narrow, sinuous ridges composed of sorted coarse sands and gravel. It is thought that eskers are the fossilised courses of subglacial meltwater streams. As the channel is restricted by ice walls, the hydrostatic pressure and the transported load are both considerable. As the bed of the channel builds up (there is no floodplain), material is left above the surrounding land following the retreat of the ice. Like kames, eskers usually form during times of deglaciation (Figure 4.35).

Kettles

These form from detached blocks of ice, left by the glacier as it retreats, and then partially buried by the glacifluvial deposits left by meltwater streams. When the ice blocks melt, they leave enclosed depressions which often fill with water to form kettle-hole lakes and 'kame and kettle' topography (Figure 4.35).

Braided streams

Channels of meltwater rivers often become choked with coarse material as a result of the marked seasonal variations in discharge (compare Figures 3.32 and 5.16).

Places 16 Arran: glacial landforms

Using fieldwork to answer an Advanced GCE question: 'Describe the landforms found near the snout of a former glacier.'

Figure 4.28 lists the types of feature formed by glacial deposition, subdividing them into those composed of unsorted material, left by the glacier, and sorted material deposited by glacifluvial activity. If the snout of a glacier had remained stationary for some time, indicating a balance between accumulation and ablation, and had then slowly retreated, several of these landforms might be visible following deglaciation. One such site studied by a sixth form was the lower Glen Rosa valley on the Isle of Arran (Figure 4.37).

The dominant feature was a mound **A**, 14 m high, into which the Rosa Water had cut, giving a fine exposed section of the deposited material. As the mound was a long, narrow, ridge-like feature extending across the valley, it was suggested that it might be either a terminal or a recessional moraine. It was concluded that the feature was ice-deposited because the material was unsorted: many of the largest boulders were high up in the exposure; also, most of the stones were sub-angular (not more rounded as might be expected in glacifluvial deposits).

However, an observation downstream at point **B** revealed that material there was also unsorted and this, together with some large granite erratics seen earlier nearer the coast, seemed to indicate that the mound could not be a terminal moraine as it did not mark the maximum advance of the ice. When a till fabric analysis was carried out, it was noted that the average dip of the stones was about 25°, suggesting that the feature might instead have been a push moraine resulting from a minor re-advance during deglaciation. The orientation of 50 sample stones (Figure 4.29) showed that the ice must have come either from the north-north-west (probable, as this was the highland) or the south-south-east (unlikely, as the lower ground would not be the source of a glacier). An examination of the geology of the stones showed that 80 per cent were granite, and therefore were erratics carried from the upper Rosa valley; 15 per cent were schists (the local rock); and 5 per cent were other igneous rocks not found on the island. It was inferred from the presence of these other rocks that some of the ice must have originated on the Scottish mainland. Also at point **B**, an investigation of river banks showed a mass of sand and gravel with some level of sorting – as might be expected in an outwash area.

Upstream from **A** was a second mound, **C**, filling much of the valley floor (Figure 4.38). Student suggestions as to the nature of the feature included its being a drumlin, a lateral, a medial, a recessional or even another push moraine. When measured, it was found that its length was slightly greater than its width (an elongation ratio of 1.25:1) and the highest point was nearest the up-valley end; it had neither the streamlined shape nor a sufficiently high

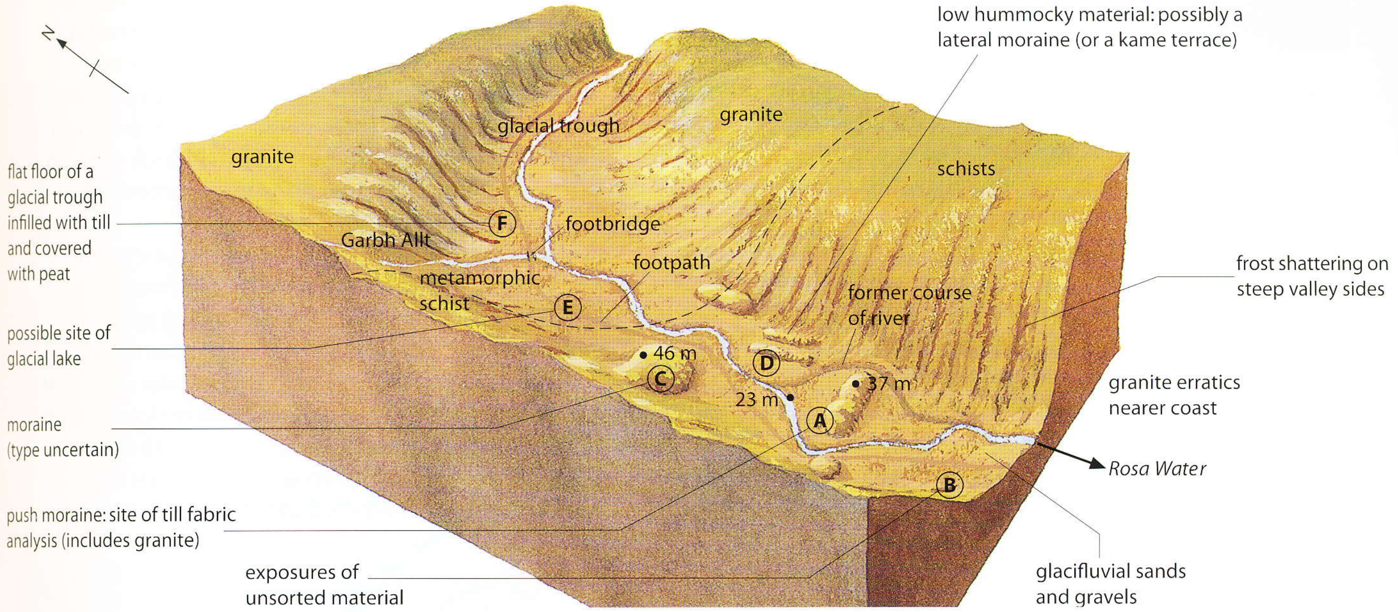


Figure 4.37

Sketch to show features of glacial deposition in the lower Glen Rosa valley, Arran

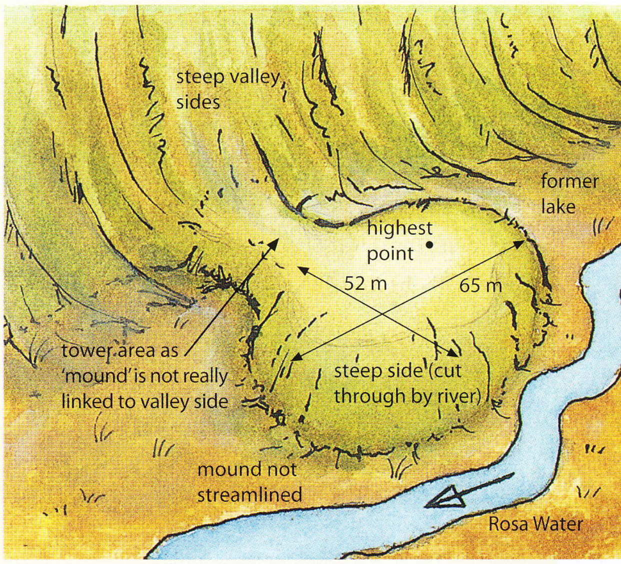


Figure 4.38

Fieldsketch of landform at **C** in Figure 4.37

elongation ratio to be a drumlin (and there were no signs of a swarm!). It appeared to be too far from the valley side to be a lateral moraine; and as two glaciers could not have met here, neither could it have been a medial moraine. It was concluded that it *was* another moraine – perhaps formed during an intermediate stillstand in the glacier's retreat, or if the glacier lost momentum after having negotiated a bend in the glacial trough.

Across the river (**D**), was an area of low hummocky material winding along the foot of the valley side to as far as **A**. It was speculated that the feature may have been formed in one of three ways: meltwater depositing sands and gravel between the valley side and the former glacier as a kame terrace; a lateral moraine from frost shattering on the valley sides; or solifluction deposits (page 47) formed as the climate grew milder and the glacier retreated (the feature was not flat enough for a river terrace to be seriously considered).

Upstream, the valley floor was extremely flat (**E**). This could be the remains of a former glacial lake, formed when meltwater from the retreating glacier had become trapped behind the moraine at **C** and before it had had time to cut through the deposits. It was impossible to gain a profile to prove or disprove the existence of a lake.

After crossing the Garbh Allt (a hanging valley), the steep-sided, flat-floored U-shape of the glacial trough through which the Rosa Water flows was visible. The flatness of the floor was probably due to the deposition of subglacial debris – although the till has since been covered by peat, a symptom of the cold, wet conditions.

Although not every feature of glacial deposition was present – there was no evidence of eskers or kettles – this small area did contain several of the landforms and deposits that might be expected at, or near to, the snout of a former glacier.

Other effects of glaciation

Drainage diversion and proglacial lakes

Where ice sheets expand, they may divert the courses of rivers. For example, the preglacial River Thames flowed in a north-easterly direction. It was progressively diverted southwards by advancing ice (Figure 4.40).

Where ice sheets expand and dam rivers, proglacial lakes are created (Figure 4.39), e.g. Lakes Lapworth and Harrison (Figure 4.40). Before the ice age, the River Severn flowed northwards into the River Dee, but this route became blocked during the Pleistocene by Irish Sea ice. A large lake, Lapworth, was impounded against the edge of the ice until the waters rose high enough to breach the lowest point in the southern watershed. As the water overflowed through an **overspill channel**, there was rapid vertical erosion which formed what is now the Ironbridge Gorge. When the ice had completely melted, the level of this new route was lower than the original course (which was also blocked by drift), forcing the present-day River Severn to flow southwards.

Other rivers, e.g. the Warwickshire Avon (Figure 4.40) and the Yorkshire Derwent (Places 17), have also been diverted as a consequence of glacial activity. Sometimes the glacial overspill channels have been abandoned, e.g. at Fenny Compton, where the Warwickshire Avon temporarily flowed south-east into the Thames (O^1 in Figure 4.40). Proglacial lakes are also found behind eskers and recessional moraines.

Figure 4.40

Glacial diversion of drainage and proglacial lakes in England and Wales

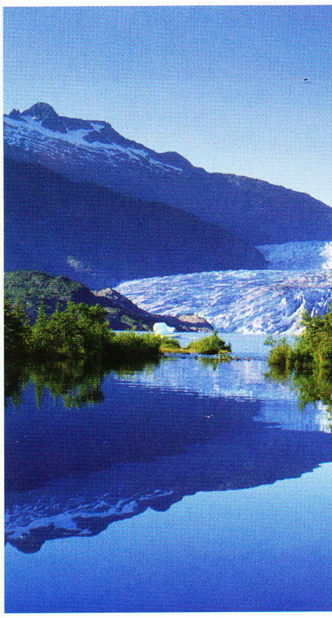
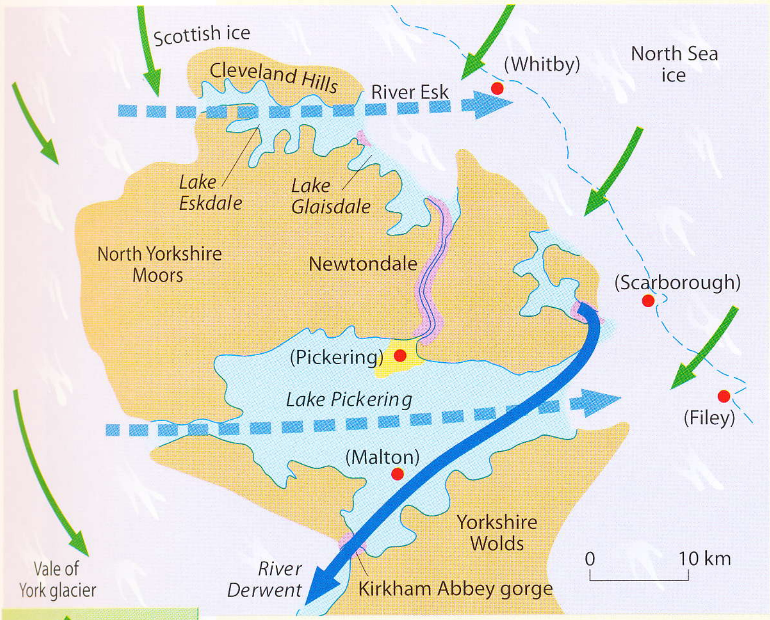


Figure 4.39

Ice-dammed lake: Mendenhall Glacier, Alaska

Places 17 The Vale of Pickering, North Yorkshire: a glacial lake



Lake Eskdale, a proglacial lake, formed when the North Sea ice sheet blocked the mouth of the River Esk. The level of the lake rose until its water found a new route over a low point in its southern watershed on the North Yorkshire Moors. The overflow river flowed through Lake Glaisdale before cutting the deep, narrow, steep-sided, flat-floored Newtondale valley. At the end of this valley, the river formed a delta where it flowed into another proglacial lake – Lake Pickering. Lake Pickering, also dammed by North Sea ice, found an outlet to the south-west where it formed an overflow channel – the present-day Kirkham Gorge. After the ice melted, the Esk reverted to its original course, entering the sea near Whitby; Newtondale became virtually a dry valley; and the River Derwent, its eastward exit from Lake Pickering blocked by glacial deposits, continued to follow its new south-westerly course. Today, the site of Lake Pickering forms the fertile, flat-floored Vale of Pickering.

Figure 4.41

Proglacial lakes and overflow channels in North Yorkshire

Changes in sea-level

The expansion and contraction of ice sheets affected sea-level in two different ways. **Eustatic** (also now called **glacio-eustatic**) refers to a world-wide fall (or rise) in sea-level due to changes in the hydrological cycle caused by water being held in storage on land in ice sheets (or released following the melting of ice sheets). **Isostatic** (or **glacio-isostatic**) adjustment is a more local change in sea-level resulting from the depression (or uplift) of the Earth's crust by the increased (or decreased) weight imposed upon it by a growing (or a declining) ice sheet. Evans (1991) claims that 'Because of their great weight, ice sheets depress the Earth's crust below them by approximately 0.3 times their thickness. So, at the centre of an ice sheet 700 m thick, there will be a maximum of 210 m of depression.' The history of sea-level depends on the location. For example, an equatorial site will experience the rise and fall of the sea solely associated with eustatic changes. In contrast, a site close to, or under, a glacier will have a history dominated by the isostatic rebound of the crust after glacial retreat. The sequence of events resulting from eustatic and isostatic changes during and after the last glacial can be summarised as follows:

1. At the beginning of the glacial, water in the hydrological cycle was stored as ice on the land instead of returning to the sea. There was a universal (eustatic) fall in sea-level, giving a negative change in base level (page 81).
2. As the glacial continued towards its peak, the weight of ice increased and depressed the Earth's crust beneath it. This led to a local (isostatic) rise in sea-level relative to the land and a positive change in base level.
3. As the ice sheets began to melt, large quantities of water, previously held in storage, were returned to the sea causing a worldwide (eustatic) rise in sea-level (a positive change in base level). This formed fiords, rias and drowned estuaries (page 163 and Places 22, page 164).
4. Finally, and still continuing in several places today, there was a local (isostatic) uplift of the land as the weight of the ice sheets decreased (a negative change in base level). This change created raised beaches (Places 23, page 166) and caused rejuvenation of rivers (page 82).

Looking into the future:

- If the ice sheets continue to melt at their present rate, caused by global warming (Case Study 9B) or a milder climate, sea-levels could rise by 60 cm by the end of the century, with 1 m probably a reasonable high-end (and pessimistic?) estimate.
- If isostatic uplift continues in Britain, it will increase the tilt that has already resulted in north-west Scotland rising by an estimated 10 m in the last 9000 years, and south-east England sinking. Tides in London are now more than 4 m higher than they were in Roman times – hence the need for the Thames Barrier (and its proposed replacement) – due to a combination of south-east England sinking and modern sea-level rise.

4a Case Study

Avalanches

Figure 4.42

An avalanche

An avalanche is a sudden downhill movement of snow, ice and/or rock (Case Study 2A). It occurs, like a landslide, when the weight (mass) of material is sufficient to overcome friction (Figure 4.42). This allows the debris to descend at a considerable speed under the force of gravity (mass movement). The average speed of descent is 40–60 km/hr, but video-recordings have shown extreme speeds in excess of 200 km/hr.

There are several different types of avalanche, which makes a simple classification difficult. Figure 4.43 gives a mainly descriptive classification put forward in the 19th century, while Figure 4.44 gives a modern classification based more on genetic and morphological characteristics.

Figure 4.43

A late 19th-century classification of avalanches

a Staublawinen (airborne powder snow)	Pure (completely airborne)
	Common (some contact with the ground)
b Grundlawinen (ground-hugging)	Rolling
	Sliding

a Avalanche break-away point	single point – loose snow avalanche	easier (not easy) to predict and manage; originates from a single point, usually soon after the snow falls
	large area, or 'slab'	often localised, hardest to predict, greatest threat to off-piste skiers; originates from a wider area and after the snow has had time to develop cohesion
b Depth	total snow depth	total mass of snow moves
	top layers of snow move over lower layers	alpine inhabitants regard this as the most dangerous
c Channel (track) width	unconfined – no channel	wide area, hard to manage
	gulley – confined to narrow track	dangerous, as it can reach higher speeds, but easier to manage
d Nature of snow (water content)	dry snow – mainly rolling	above ground-level so friction is reduced; can reach speeds of 200 km/hr – very destructive
	wet snow – mainly sliding	follows ground topography, occurs under föhn conditions (page 241), limited protection, much damage

Figure 4.44

A more recent classificati
of avalanches (1979)

Causes

- Heavy snowfall compressing and adding weight to earlier falls, especially on windward slopes.
- Steep slopes of over 25° where stability is reduced and friction is more easily overcome.
- A sudden increase in temperature, especially on south-facing slopes and, in the Alps, under föhn wind conditions (page 241).
- Heavy rain falling upon snow (more likely in Scotland than the Alps).
- Deforestation, partly for new ski-runs, which reduces slope stability.
- Vibrations triggered by off-piste skiers, any nearby traffic and, more dangerously, earth movements (Case Study 2A).
- Very long, cold, dry winters followed by heavy snowfalls in spring. Under these conditions, earlier falls of snow will turn into ice over which later falls will slide (some local people perceive this to pose the greatest avalanche risk).

Consequences

Avalanches can block roads and railways, cut off power supplies and telecommunications and, under extreme conditions, destroy buildings and cause loss of life. Between 1980 and 1991 there were, in Alpine Europe alone, 1210 recorded avalanche deaths, of whom nearly half were skiers – virtually all in off-piste areas. This death rate is increasing as the popularity of skiing grows and alpine weather becomes less predictable (a record total of 145 deaths in 1998–99).

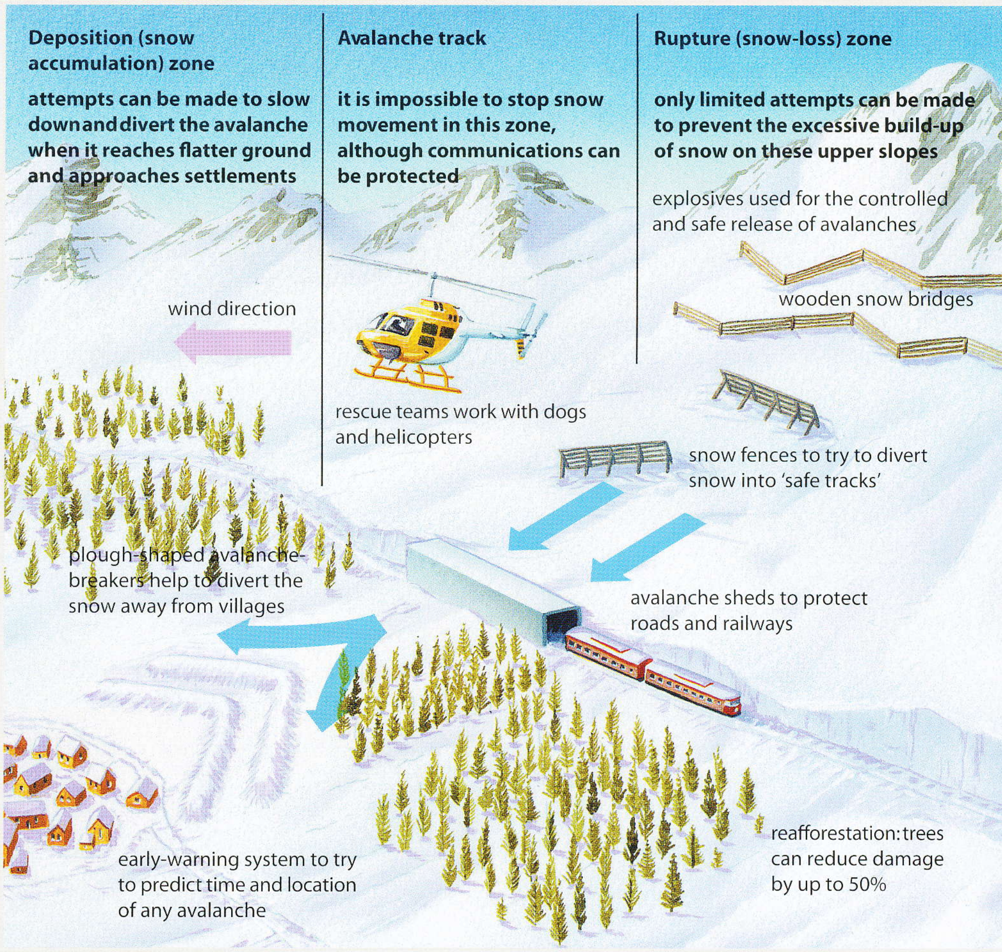


Figure 4.45

Avalanche management schemes

Management

There is a close link between avalanches and:

- time of year – almost 80 per cent of avalanches in the French Alps occur between January and March, the 'avalanche season'
- altitude – over 90 per cent occur between 1500 and 3000 m.

Although it is possible to predict *when* and in which regions avalanches are most likely to occur, it is less easy to predict exactly *where* an event is likely to happen. It is this unpredictability that makes avalanches a major environmental hazard in alpine areas. However, despite this uncertainty, many avalanches do tend to follow certain 'tracks'. Consequently, as well as setting up early-warning systems and training rescue teams (Figure 4.46), it is possible to take some measures to try to protect life and property (Figure 4.45).

Figure 4.46

Avalanche protection and rescue schemes

4b Case Study

The effects of melting ice

Changed rates of melting ice and subsequent potential rises in sea-level are the main reasons why most scientists are working on glaciers at the present time, and why it should interest so many other people.

Ice helps to stabilise the world's climate by insulating large areas of ocean in summer and preventing heat loss in winter. Ice and snow also have a higher reflectivity, or **albedo** (page 207), than any other surface, reflecting 80 per cent of incoming solar radiation back into the atmosphere. As ice melts then the albedo will be reduced, less solar radiation will be reflected back and the Earth's temperature will rise.

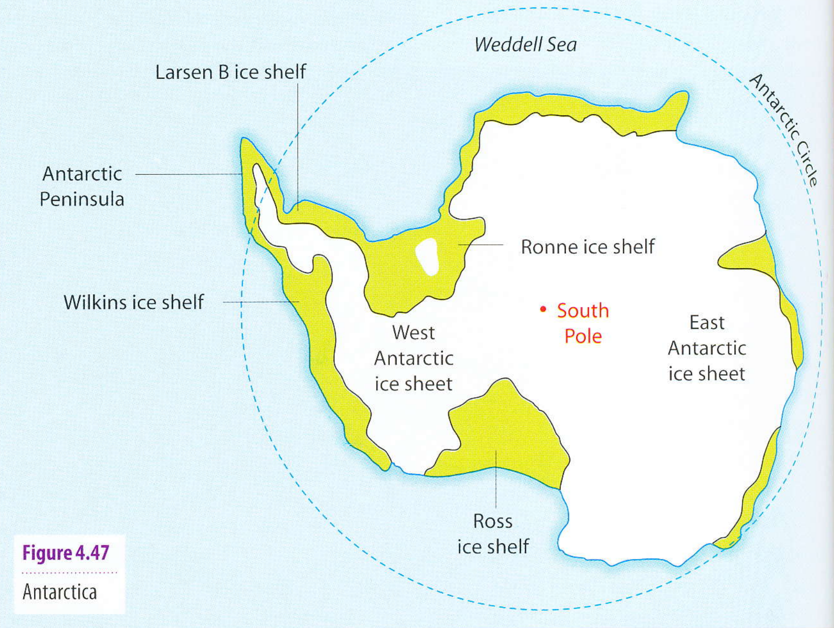


Figure 4.47

Antarctica

(i) Ice shelves: Antarctica

Antarctica is covered by two huge ice sheets: the larger East Antarctic Ice Sheet (EAIS), which is bigger than the USA and holds most of the world's fresh water in storage; and the smaller West Antarctic Ice Sheet (WAIS). Scientists predict that even if only the EAIS melted, the world's sea-level would rise by 61 m. On the edges of the two ice sheets, and extending from them, are several ice shelves, the two largest being the Ross and Ronne (Figure 4.47). As global temperatures rise, especially around the Antarctic peninsula which extends beyond the Antarctic Circle, these ice shelves are becoming less stable and parts are collapsing.

The collapse of the Larsen B ice shelf in 2002 was the latest and most spectacular (it was the size of East Anglia) of ten collapses that have occurred off the coast of the Antarctic Peninsula since the mid-1980s (Figure 4.48). In 2008, part of the nearby Wilkins ice shelf was said to be 'hanging on by a thread'. The ice, following its collapse, drifts away from the polar region, often as huge icebergs, into warmer water where it melts. Being fresh water in a frozen state, its melting adds to the volume of the ocean, causing a global rise in sea-level. As ice shelves collapse, glaciers moving behind them on the ice sheet are accelerating by 1 per cent a year, the fastest now travelling at 3.5 km/yr.

The collapses are credited to global warming, the average annual temperature in the Antarctic having risen by 2.5°C in the last 50 years compared with 0.5°C globally. According to Bentley in a series of articles in *Geography Review*, 'the key to the collapse is the formation of pools of meltwater on the surface of the ice shelf during the Antarctic summer. In some places, the meltwater begins to fill crevasses in the ice shelf. Normally, crevasses are only tens of metres deep, but as the meltwater progressively fills them the weight of water forces the lowermost tip of the crevasse to crack even more deeply into the ice. Eventually the crevasses may penetrate through the full thickness of the ice shelf and a chunk of ice will break off.'

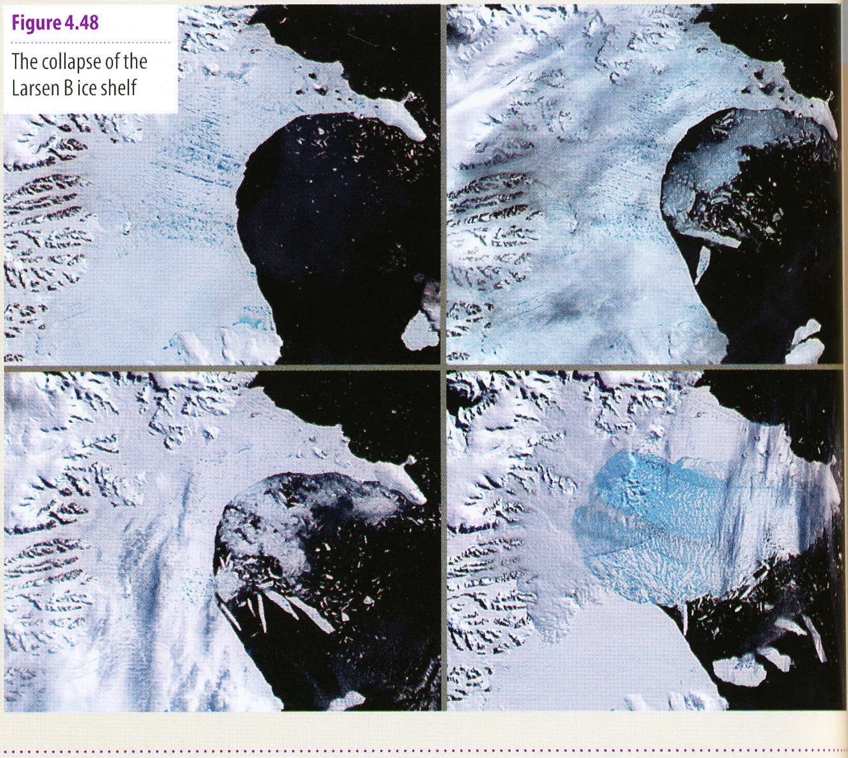


Figure 4.48

The collapse of the Larsen B ice shelf

(ii) Ice sheets: Greenland

The average thickness of the Greenland ice sheet has been calculated to be 1800 m. However, while this thickness was believed to have decreased by an average of 1 m/yr throughout the last century, satellite imagery suggests that the rate of decrease had accelerated to 5 m/yr in 2000 and 10 m/yr by 2007. The increase in surface melting is creating more meltwater which sinks down crevasses to the bedrock where it acts as a lubricant accelerating basal flow (pages 107–108). This in turn causes glaciers leading from the ice sheet to flow faster. One of these, the Jokobshavn, reaches a speed of 1 m/hr as it nears the coast, making it the fastest-flowing glacier in the world.

As in Antarctica, Greenland's ice is fresh water in frozen storage. It is believed that should the whole ice sheet totally melt then the global sea-level would rise by 6.7 m.

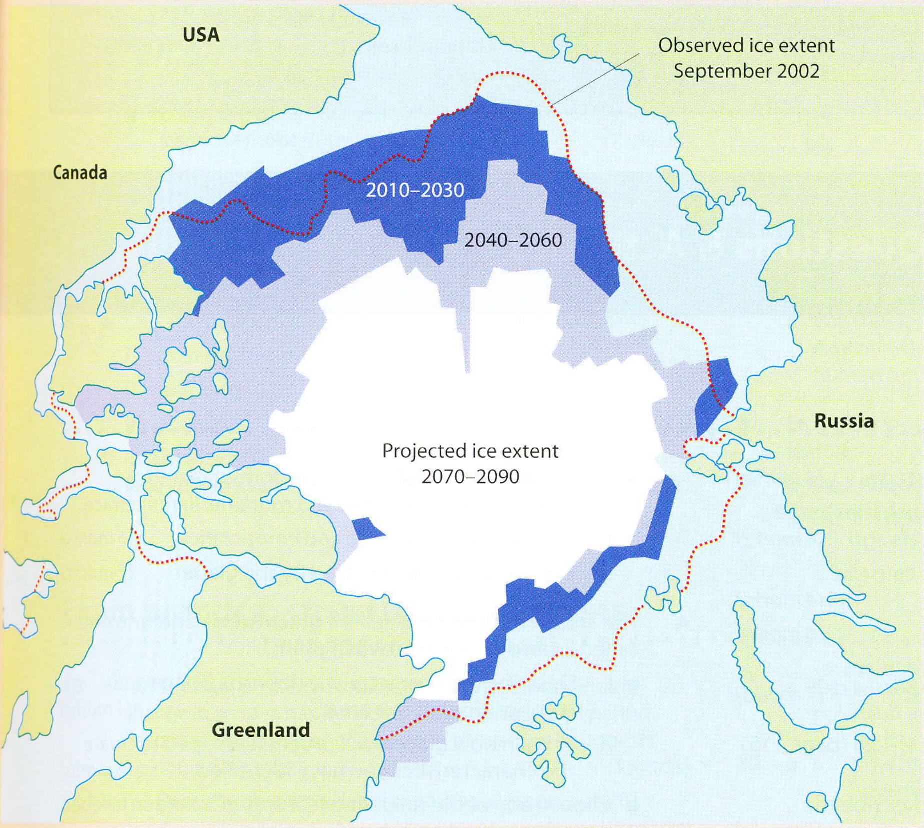


Figure 4.49

Present and predicted coverage of sea ice in the Arctic

(iii) Sea ice: the Arctic

Sea ice is frozen salt water and forms when temperatures remain for some time below −1.5°C. Recent satellite images have shown that the area covered by sea ice is now decreasing by 8 per cent annually. More significantly, nuclear submarines, operating under the ice for over half a century, have indicated that the thickness of the ice has decreased in that time from 4 m to 1.3 m. As the ice thins, the remaining ice will melt more quickly, speeding up the process. In the 19th century, explorers tried unsuccessfully to find a sea route around the north of Canada – the so-called North West Passage – and in the early 20th century the first explorers claiming to have reached the North Pole only did so after several weeks' travelling over sea ice. Some scientists are now predicting that, due to global warming, all the polar sea ice will have disappeared within 30 years (Figure 4.49).

As it is frozen seawater that is melting, then the effect on global sea-level will be minimal. Figure 4.50 shows some of the advantages and disadvantages that will result from an ice-free Arctic.

Figure 4.50

Advantages and disadvantages of an ice-free Arctic

Advantages	Disadvantages
Easier to exploit resources such as oil and natural gas found under the seabed.	Less ice will mean a reduced albedo and an increase in global warming.
Improved navigation will reduce distances and travel time, e.g. i Tokyo to New York – distance reduced from 18 000 km to 14 000 km via the North West Passage (Canada) which in 2007 was open apart from 100 km of scattered ice floes ii Tokyo to London – distance reduced from 21 000 km to 13 000 km via the North East Passage (Russia) which in 2007 was open for six weeks.	An increase in the number of icebergs from surrounding ice shelves could make navigation more dangerous. An increased threat to wildlife – polar bears and other species threatened with extinction.

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Glacier Project:
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Questions & Activities

Activities

1 **a** Define the terms 'interglacial' and 'interstadial'. *(4 marks)*

b Describe the extent of ice across the British Isles at the height of the last ice advance 18 000 years ago. *(4 marks)*

c Suggest and explain **one** theory for the cause of ice ages. *(4 marks)*

d How is glacier ice formed? *(6 marks)*

e Explain the **difference** in movement processes between **temperate** and **polar glaciers.** *(7 marks)*

2 Choose **one** of the features named in Figure 4.25 (page 115) and give its name.

a **i** With the aid of a labelled diagram, describe the feature. *(5 marks)*

ii Explain how a glacier created the feature you have chosen. *(5 marks)*

iii Describe and explain **one** change in the feature, probably since the last ice age. *(4 marks)*

b Many hollows in a glaciated upland are filled with water. Where does the water come from? *(2 marks)*

c Suggest **two** pieces of evidence you would look for to suggest the direction of movement of a glacier if you were to carry out a study of a glaciated valley. *(4 marks)*

d Describe and explain **one** difference between a glaciated upland area and an unglaciated one. *(5 marks)*

3 A glacier erodes, transports and deposits material using a range of methods.

a **i** Name **two** types of glacial erosion. *(2 marks)*

ii For **one** of the types of erosion in **a i**, explain how the glacier erodes. *(4 marks)*

b Some loose material is carried on top of the glacier. Making good use of diagrams, show where, on the surface, this material is carried. *(4 marks)*

c Where else is material carried by a glacier? *(2 marks)*

d Choose **one** of the following landforms created by glacial deposition: drumlin; end moraine; kame terrace.

i Describe its shape, size and composition. *(6 marks)*

ii Explain how it was created by the glacier. *(7 marks)*

4 The area in front of a glacier is a **glacifluvial** landform often called a **sandur** or an **outwash plain**.

a **i** Describe the characteristic deposits (shape and composition) of this area. *(4 marks)*

ii Explain how glacifluvial processes helped to create the characteristics you have identified. *(4 marks)*

b Choose one of the following features of a sandur: lakebed deposits; esker; kame; braided stream. Describe the shape and characteristics of the feature. *(4 marks)*

c **i** What is a **kettle lake**? *(2 marks)*

ii How is a kettle lake formed? *(5 marks)*

iii Suggest how a kettle lake may disappear after the glacial period. *(6 marks)*

5 **a** What is a valley glacier? *(2 marks)*

b Describe and explain the origins of **two** surface features of a moving glacier. *(6 marks)*

c Explain how you could measure the movement of a valley glacier. *(4 marks)*

d Why does the snout of a glacier sometimes retreat even though the ice always moves forward? *(6 marks)*

e What feature may mark where the snout of a retreating glacier was in the past? Describe the shape and composition of the feature. *(7 marks)*

6 Ice movement during the last ice age had **indirect** as well as **direct** effects on the landscape. Indirect effects occur where the ice itself was not involved in the effect.

a **i** Explain what is meant by the term 'drainage diversion'. *(2 marks)* ii Choose one example of drainage diversion. Draw a sketch map to show the diversion and explain the role of glacier ice in the cause of the diversion. *(6 marks)*

b Why did the land experience an isostatic change of sea-level during the ice age? *(4 marks)*

c Why are 'raised beaches' found in coastal areas where glacial ice caused an isostatic change in sea-level? *(6 marks)*

d Choose **one** landform (other than a raised beach) which has been affected by sea-level change associated with glaciation. Describe the feature and explain how it was formed. *(7 marks)*

7 In a field survey (till fabric analysis) the orientation of clasts (stones) showed the data given in the table on the right. Orientation shows **two** possible directions (e.g. NW/SE).

a i Draw a graph to illustrate the data. *(6 marks)*

ii Using the data, suggest an interpretation of the ice movement in this area. *(7 marks)*

b Why do glacial deposits have a particular orientation? *(7 marks)*

c Suggest **two** other sources of data to indicate the direction of ice movement in an area. For one of these sources, explain how it shows the direction of ice movement. *(5 marks)*

Degrees	No. of clasts	Degrees	No. of clasts	Degrees	No. of clasts
0	0	**120**	2	**240**	8
15	0	**135**	3	**255**	3
30	10	**150**	1	**270**	1
45	12	**165**	1	**285**	1
60	8	**180**	0	**300**	2
75	3	**195**	0	**315**	3
90	1	**210**	10	**330**	1
105	1	**225**	12	**345**	1

Exam practice: basic structured questions

8 a Describe how ice can erode the rocks of upland areas by:

i frost shattering

ii plucking

iii abrasion. *(9 marks)*

b Explain how these processes combine to produce cirques (also known as corries or cwms). *(6 marks)*

c With reference to one or more areas that you have studied, explain why upland glaciated areas are often difficult for human settlement. *(10 marks)*

9 Study Figure 4.25 on page 115. Select and name any **two** features of glacial erosion shown on the diagram.

a Describe **each** of your chosen features. *(5 + 5 marks)*

b Explain how **each** of these features was formed. *(15 marks)*

Exam practice: structured questions

10 a Identify **two** pieces of evidence to suggest that climatic change in an area has included at least **one** glacial period. For one of these pieces of evidence, show how it suggests a past glacial period. *(5 marks)*

b i Describe how a glacier operates as an 'open system'. *(8 marks)*

ii How and why does a glacier budget vary between winter and summer seasons? *(12 marks)*

11 a Geographers often classify glaciers into different types. Describe **one** system of classification. *(5 marks)*

b Why does movement of glacier ice vary across and within the glacier? *(12 marks)*

c Explain the difference in movement between glaciers in polar and temperate latitudes. *(8 marks)*

12 a i How has glacial ice affected sea-level in the past, and how might it affect sea-level in the next century or so? *(9 marks)*

ii How is glacial ice involved in sea-level change? *(9 marks)*

b i Describe the shape and scale of a fiord.

ii Explain the roles of glacial processes and sea level change in the formation of a fiord. *(12 marks)*

Exam practice: essays

13 Describe and evaluate the evidence **(including geomorphological evidence)** that there has been a series of ice ages in the northern hemisphere during the last million years. *(25 marks)*

14 For any one drainage diversion system you have studied, discuss the role of glacial ice and other factors in its formation. *(25 marks)*

15 Describe the features of glacial and glacifluvial deposition that might be found on a lowland plain from which an ice sheet had recently melted, and explain how you would recognise the difference between selected features of glacial origin and selected features of glacifluvial origin. *(25 marks)*

16 Scientists have suggested that there is evidence from the Arctic and Antarctic ice sheets that global warming is happening. Describe and evaluate this evidence, and suggest how melting of the ice might affect the Earth's future geography. *(25 marks)*