6 Coasts

'A recent estimate of the coastline of England and Wales is 2750 miles and it is very rare to find the same kind of coastal scenery for more than 10 to 15 miles together.'

J.A. Steers, *The Coastline of England and Wales*, 1960

'I do not know what I may appear to the world; but to myself I seem to have been only a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me.'

Isaac Newton, *Philosophiae Naturalis Principia Mathematica*, 1687

The coast is a narrow zone where the land and the sea overlap and directly interact. Its development is affected by terrestrial, atmospheric, marine and human processes (Figure 6.1) and their interrelationships. The coast is the most varied and rapidly changing of all landforms and ecosystems.

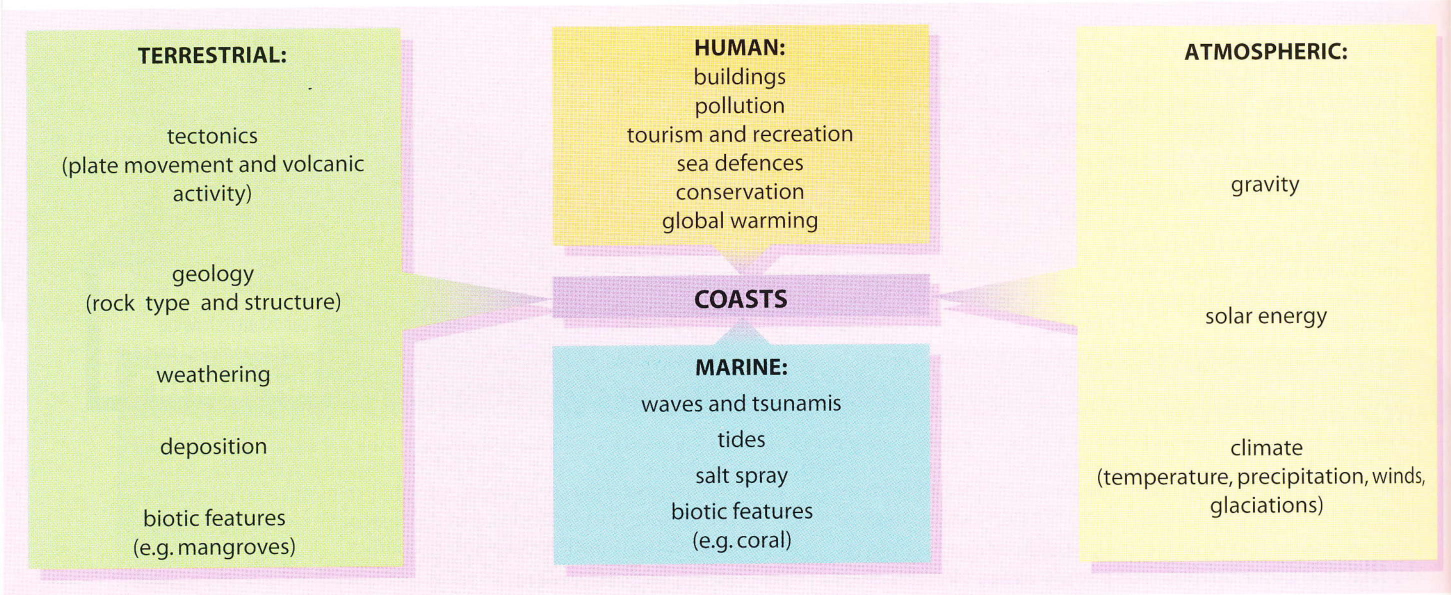
Waves

Waves are created by the transfer of energy from the wind blowing over the surface of the sea. (An exception to this definition is those waves – **tsunamis** – that result from submarine shock waves generated by earthquake or volcanic activity.) As the strength of the wind increases, so too does **frictional drag** and the size of the waves. Waves that result from local winds and travel only short distances are known as **sea**, whereas those waves formed by distant storms and travelling large distances are referred to as **swell**.

The energy acquired by waves depends upon three factors: the wind velocity, the period of time during which the wind has blown, and the length of the fetch. The **fetch** is the maximum distance of open water over which the wind can blow, and so places with the greatest fetch potentially receive the highest-energy waves. Parts of south-west England are exposed to the Atlantic Ocean and when the south-westerly winds blow it is possible that some waves may have originated several thousand kilometres away. The Thames estuary, by comparison, has less open water between it and the Continent and consequently receives lower-energy waves.

Figure 6.1

Factors affecting coasts



Wave terminology

The **crest** and the **trough** are respectively the highest and lowest points of a wave (Figure 6.2).

Wave height (H) is the distance between the crest and the trough. The height has to be estimated when in deep water. Wave height rarely exceeds 6 m although freak waves of 15 m have been reported by offshore oil-rigs, and 25 m by a wave-tracking satellite. Such waves can be a serious hazard to shipping.

Wave period (T) is the time taken for a wave to travel through one wave length. This can be timed either by counting the number of crests per minute or by timing 11 waves and dividing by 10 – i.e. the number of intervals.

Wave length (L) is the distance between two successive crests. It can be determined by the formula:

$$L = 1.56\,T^2$$

Wave velocity (C) is the speed of movement of a crest in a given period of time.

Wave steepness ($H \div L$) is the ratio of the wave height to the wave length. This ratio cannot exceed 1:7 (0.14) because at that point the wave will break. Steepness determines whether waves will build up or degrade beaches. Most waves have a steepness of between 0.005 and 0.05.

The **energy** (E) of a wave in deep water is expressed by the formula:

$$E \propto \text{(is proportional to) } LH^2$$

This means that even a slight increase in wave height can generate large increases in energy. It is estimated that the average pressure of a wave in winter is 11 tonnes per m^2, but this may be three times greater during a storm – it is little wonder that under such conditions sea defences may be destroyed and that wave power is a potential source of renewable energy (page 541).

Swell is characterised by waves of low height, gentle steepness, long wave length and a long period. **Sea**, with opposite characteristics, usually has higher-energy waves.

Waves in deep water

Deep water is when the depth of water is greater than one-quarter of the wave length:

$$(D = > \tfrac{L}{4})$$

The drag of the wind over the sea surface causes water and floating objects to move in an **orbital motion** (Figure 6.3). Waves are surface features (submerged submarines are unaffected by storms) and therefore the sizes of the orbits decrease rapidly with depth. Any floating object in the sea has a small net horizontal movement but a much larger vertical motion.

Waves in shallow water

As waves approach shallow water, i.e. when their depth is less than one-quarter of the wave length,

$$(D = < \tfrac{L}{4})$$

friction with the seabed increases. As the base of the wave begins to slow down, the circular oscillation becomes more elliptical (Figure 6.4). As the water depth continues to decrease, so does the wave length.

Meanwhile the height and steepness of the wave increase until the upper part spills or plunges over. The point at which the wave breaks is known as the **plunge line**. The body of foaming water which then rushes up the beach is called the **swash**, while any water returning down to the sea is the **backwash**.

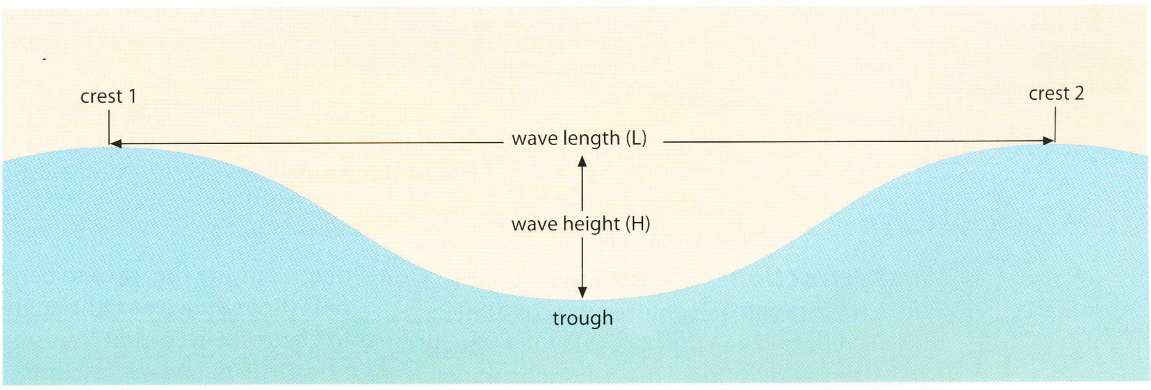


Figure 6.2
Wave terminology

Figure 6.3

Movement of an object in deep water: the diagrams show the circular movement of a ball or piece of driftwood through five stages in the passage of one wave length (crest 1 to crest 2); although the ball moves vertically up and down and the wave moves forward horizontally, there is very little horizontal movement of the ball until the wave breaks; the movement is orbital and the size of the orbit decreases with depth

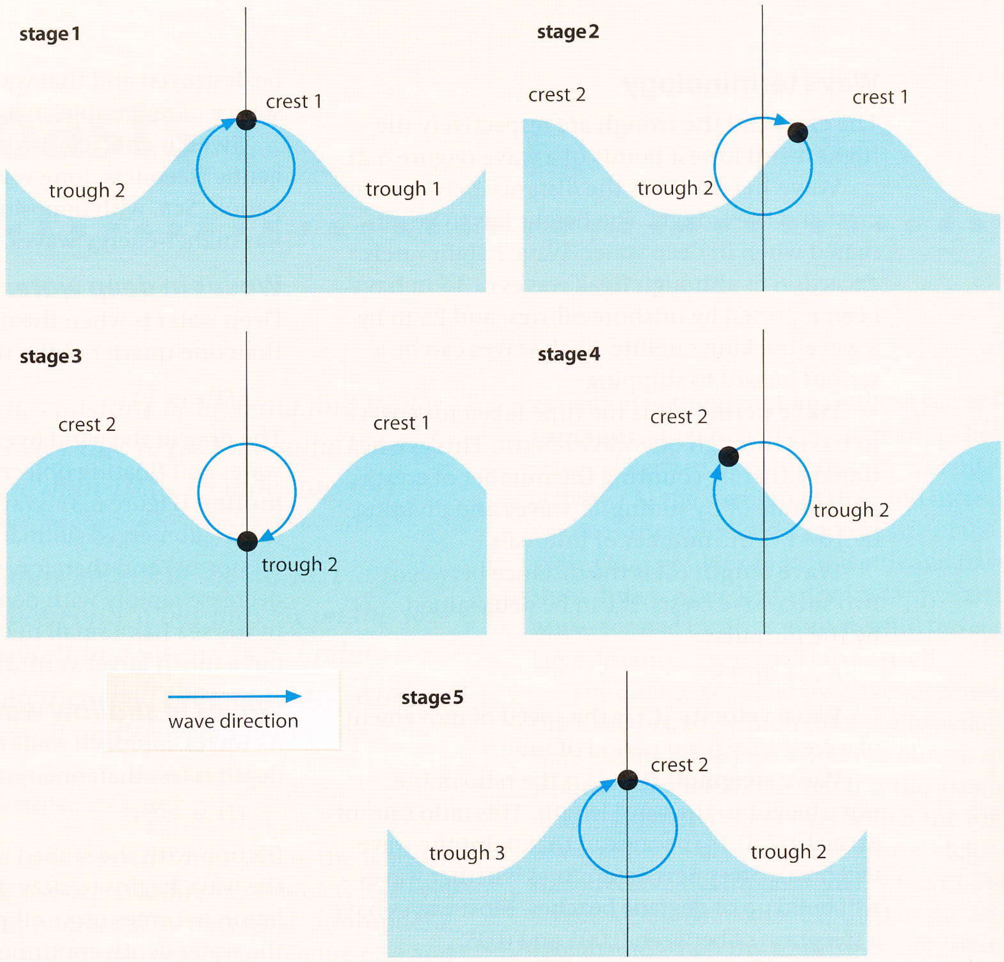
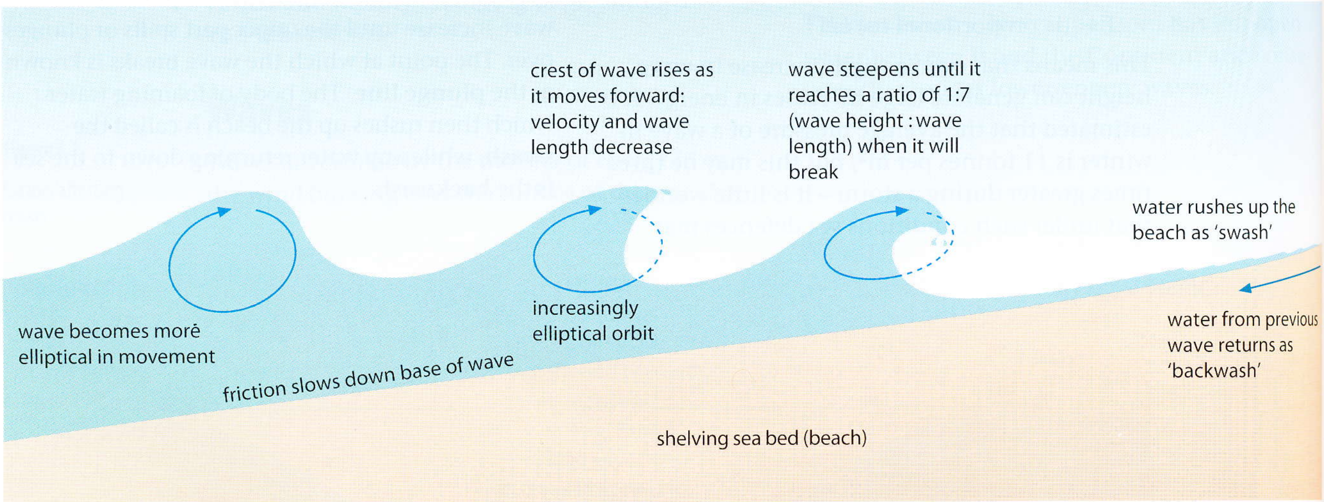


Figure 6.4

Why a wave breaks

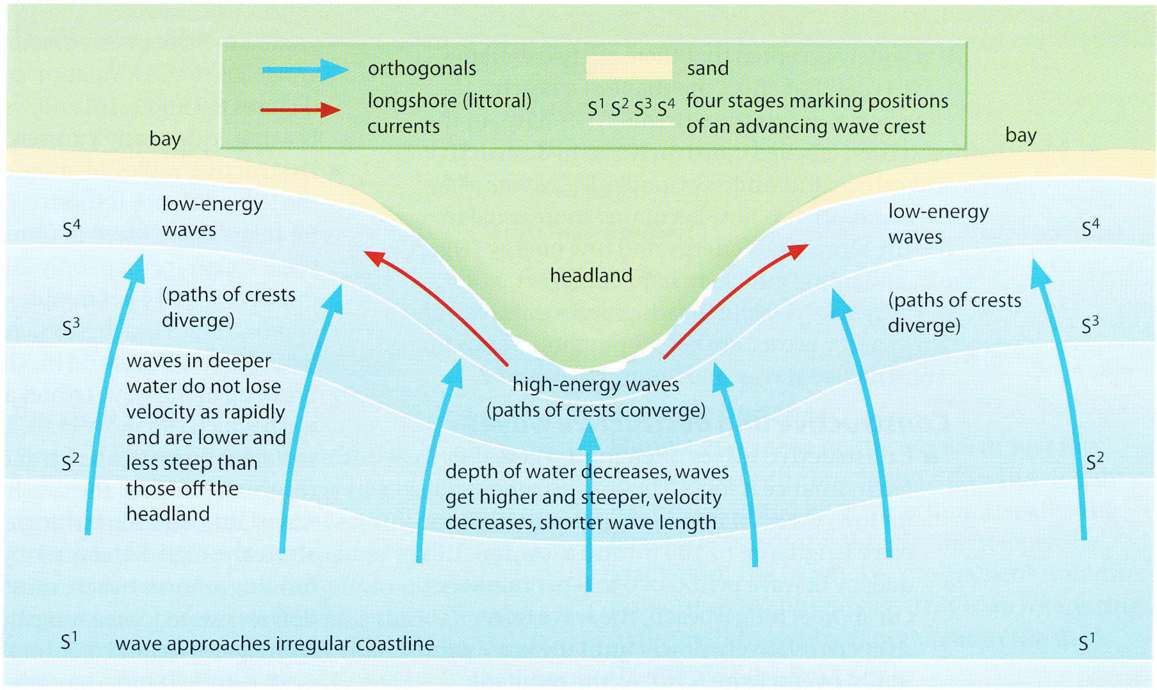


Wave refraction

Where waves approach an irregular coastline, they are refracted, i.e. they become increasingly parallel to the coastline. This is best illustrated where a headland separates two bays (Figure 6.5). As each wave crest nears the coast, it tends to drag in the shallow water near to a headland, or indeed any shallow water, so that the portion of the crest in deeper water moves forward while that in shallow water is retarded (by frictional drag), causing the wave to bend. The **orthogonals** (lines drawn at right-angles to wave crests) in Figure 6.5 represent four stages in the advance of a particular wave crest. It is apparent from the convergence of lines S^1, S^2, S^3 and S^4 that wave energy becomes concentrated upon, and so accentuates erosion at, the headland. The diagram also shows the formation of **longshore** (littoral) **currents**, which carry sediment away from the headland.

Figure 6.5

Wave refraction at a headland



Beaches

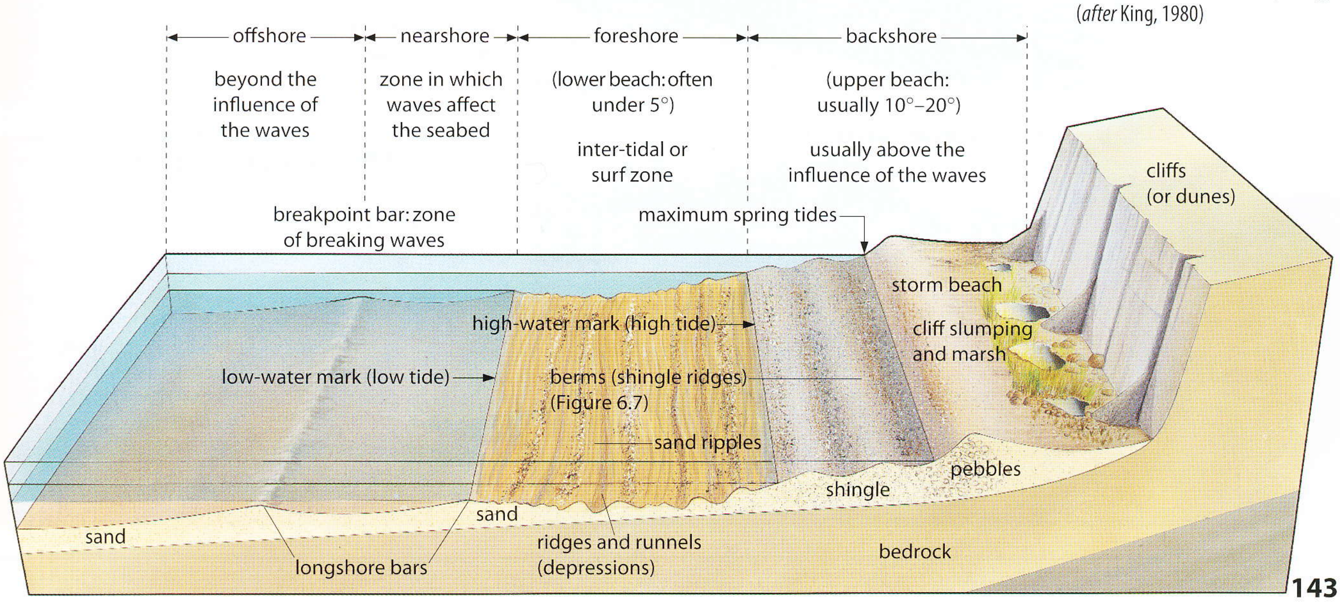
Beaches may be divided into three sections – **backshore** (upper), **foreshore** (lower) and **nearshore** – based on the influence of waves (Figure 6.6). A beach forms a buffer zone between the waves and the coast. If the beach proves to be an effective buffer, it will dissipate wave energy without experiencing any net change itself. Because it is composed of loose material, a beach can rapidly adapt its shape to changes in wave energy. It is, therefore, in dynamic equilibrium with its environment (Framework 3, page 45).

Beach profiles fall between two extremes: those that are wide and relatively flat; and those that are narrow and steep. The gradient of natural beaches is dependent upon the interrelationship between two main variables:

- **Wave energy** Field studies have shown a close relationship between the profile of a beach and the action of two types of wave: constructive and destructive (page 144). However, the effect of wave steepness on beach profiles is complicated by the second variable.
- **Particle size** There is also, due to differences in the relative dissipation of wave energy, a distinct relationship between beach slope and particle size. This relationship is partly due to grain size and partly to percolation rates, both of which are greater on shingle beaches than on sand (pages 145–146). Consequently, shingle beaches are steeper than sand beaches (Figure 6.6).

Figure 6.6

Wave zones and beach morphology (*after* King, 1980)



Types of wave

It is widely accepted that there are two extreme wave types that affect the shape of a beach. However, whereas the extreme types have, in the past, been labelled **constructive** and **destructive** (Figure 6.7, and Andrew Goudie *The Nature of the Environment*), it is now becoming more usual to use the terms **high energy** and **low energy** (Figure 6.8, and John Pethick *An Introduction to Coastal Geomorphology*). Note that 'high-energy waves' and 'low-energy waves' are *not* synonymous terms for 'constructive waves' and 'destructive waves'.

Constructive and destructive waves

- **Constructive waves** often form where the fetch distance is long. They are usually small (or low) waves, flat in form and with a long wave length (up to 100 m) and a low frequency (a wave period of 6 to 8 per minute). On approaching a beach, the wave front steepens relatively slowly until the wave gently 'spills' over (Figure 6.7a). As the resultant swash moves up the beach, it rapidly loses volume and energy due to water percolating through the beach material. The result is that the backwash, despite the addition of gravity, is weak and has insufficient energy either to transport sediment back down the beach or to impede the swash from the following wave. Consequently sand and shingle is slowly, but constantly, moved up the beach. This will gradually increase the gradient of the beach and leads to the formation of **berms** at its crest (Figures 6.9 and 6.10) and, especially on sandy beaches, **ridges** and **runnels** (Figure 6.6).
- **Destructive waves** are more common where the fetch distance is shorter. They are often large (or high) waves, steep in form and with a short wave length (perhaps only 20 m) and a high frequency (10 to 14 per minute). These waves, on approaching a beach, steepen rapidly until they 'plunge' over (Figure 6.7b). The near-vertical breaking of the wave creates a powerful backwash which can move considerable amounts of sediment down the beach and, at the same time, reduce the effect of the swash from the following wave. Although some shingle may be thrown up above the high-water mark by very large waves, forming a **storm beach**, most material is moved downwards to form a **longshore (breakpoint) bar** (Figures 6.6 and 6.7b).

High-energy waves and low-energy waves

Recent opinion appears to support the view that beach shape is more dependent on, and linked to, wave energy. The correlation between the two types of wave energy and beach profile is given in Figure 6.8.

Figure 6.7

Constructive and destructive waves

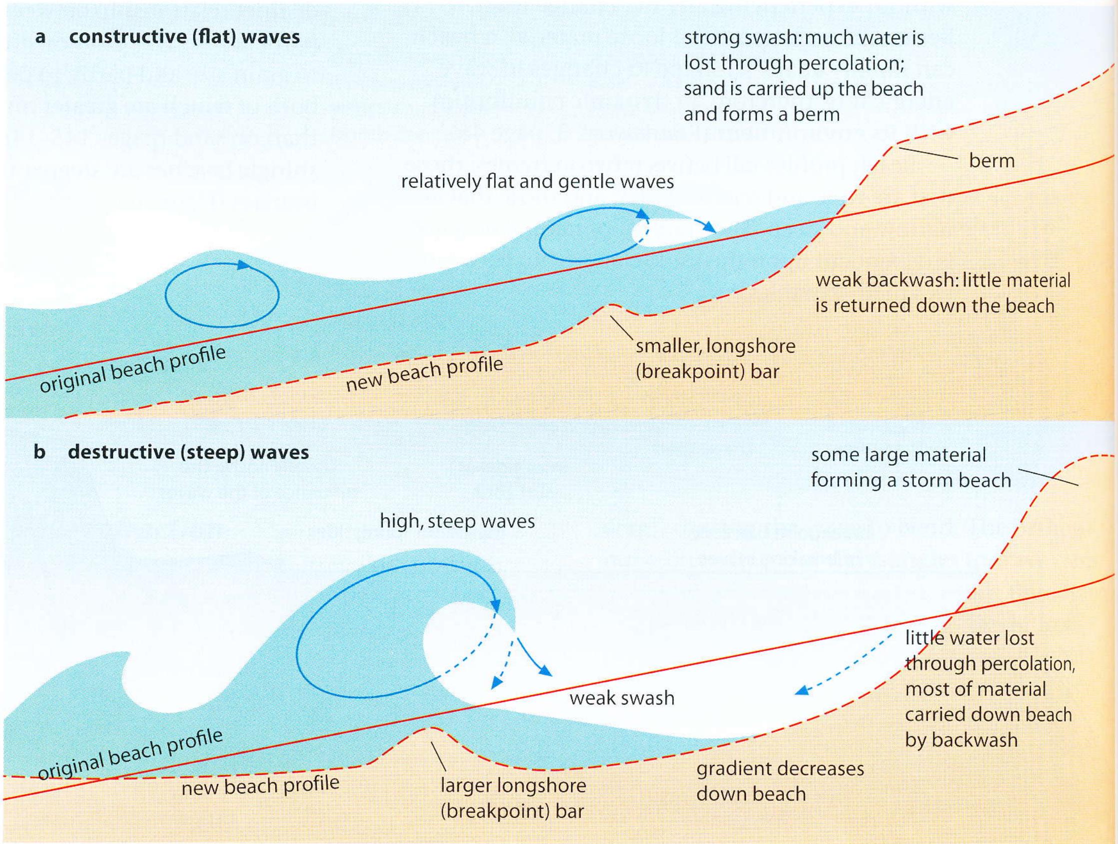


Figure 6.8

High-energy and low-energy waves (*after* J. Pethick)

High-energy waves		Low-energy waves
Produced by distant storms	**Source**	Formed more locally
Large	**Fetch distance**	Short
Long (up to 100 m)	**Wave length**	Short (perhaps only 20 m)
High and short	**Wave height**	Low and flat
Move quickly and so lose little energy	**Speed of wave movement**	Move less quickly and so lose more energy
Spilling	**Type of breaker**	Surging
Long	**Dissipation distance**	Shorter
Flat and wide	**Beach shape**	Steeper and narrower

Particle size

This factor complicates the influence of wave steepness on the morphology of a beach. The fact that shingle beaches have a steeper gradient than sandy beaches is due mainly to differences in percolation rates resulting from differences in particle size – i.e. water will pass through coarse-grained shingle more rapidly than through fine-grained sand (Figure 8.2).

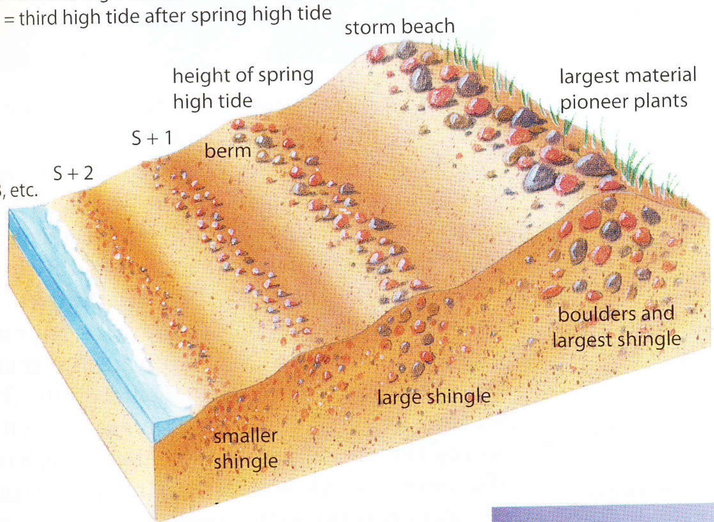


Figure 6.9

Storm beaches and berms: berms mark the limits of successively lower high tides

Shingle beaches

Shingle may make up the whole, or just the upper part, of the beach and, like sand, it will have been sorted by wave action. Usually, the larger the size of the shingle, the steeper the gradient of the beach, i.e. the gradient is in direct proportion to shingle size. This is an interesting hypothesis to test by experiment in the field (Framework 10, page 299).

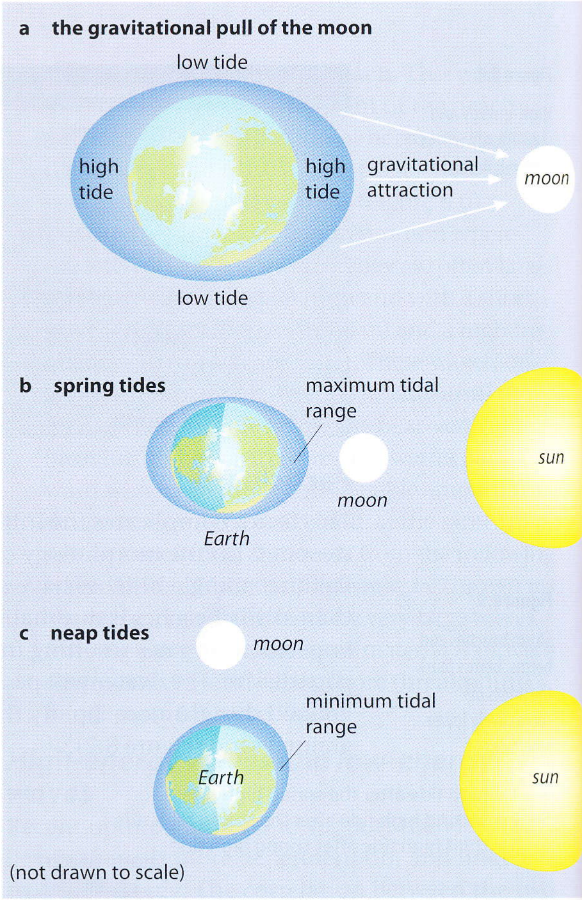
Regardless of whether waves on shingle beaches are constructive or destructive, most of the swash rapidly percolates downwards leaving limited surface backwash. This, together with the loss of energy resulting from friction caused by the uneven surface of the shingle (compare this with the effects of bed roughness of a stream, page 70), means that under normal conditions, very little shingle is moved back down the beach. Indeed, the strong swash will probably transport material up the beach forming a berm at the spring high-tide level. Above the berm there is often a storm beach, composed of even bigger boulders thrown there by the largest of waves, while below may be several smaller ridges, each marking the height of the successively lower high tides which follow the maximum spring tide (Figures 6.9 and 6.10).

Figure 6.10

Berms and storm beaches in north-east Anglesey, Wales

Figure 6.11

Causes of tides



Sand beaches

Sand usually produces beaches with a gentle gradient. This is because the small particle size allows the sand to become compact when wet, severely restricting the rate of percolation. Percolation is also hindered by the storage of water in pore spaces in sand which enables most of the swash from both constructive and destructive waves to return as backwash. Relatively little energy is lost by friction (sand presents a smoother surface than shingle) so material will be carried down the beach. The material will build up to form a longshore bar at the low-tide mark (Figure 6.6). This will cause waves to break further from the shore, giving them a wider beach over which to dissipate their energy. The lower parts of sand beaches are sometimes crossed by shore-parallel ridges and runnels (Figure 6.6). The ridges may be broken by channels which drain the runnels at low tide.

The interrelationship between wave energy, beach material and beach profiles may be summarised by the following generalisations which refer to net movements:

- Destructive waves carry material down the beach.
- Constructive waves carry material up the beach.
- Material is carried upwards on shingle beaches.
- Material is carried downwards on sandy beaches.

Tides

The position at which waves break over the beach, and their range, are determined by the state of the tide. It has already been seen that the levels of high tides vary (berms are formed at progressively lower levels following spring high tides; Figure 6.9). Tides are controlled by gravitational effects, mainly of the moon but partly of the sun, together with the rotation of the Earth and, more locally, the geomorphology of sea basins.

The moon has the greatest influence. Although its mass is much smaller than that of the sun, this is more than compensated for by its closer proximity to the Earth. The moon attracts, or pulls, water to the side of the Earth nearest to it. This creates a bulge or **high tide** (Figure 6.11a), with a complementary bulge on the opposite side of the Earth. This bulge is compensated for by the intervening areas where water is repelled and which experience a **low tide**. As the moon orbits the Earth, the high tides follow it.

A lunar month (the time it takes the moon to orbit the Earth) is 29 days and the tidal cycle (the time between two successive high tides) is 12 hours and 25 minutes, giving two high tides, near enough, per day. The sun, with its smaller gravitational attraction, is the cause of the difference in tidal range rather than of the tides themselves. Once every 14/15 days (i.e. twice in a lunar month), the moon and sun are in alignment on the same side of the Earth (Figure 6.11b). The increase in gravitational attraction generates the **spring tide** which produces the highest high tide, the lowest low tide and the maximum tidal range.

Midway between the spring tides are the **neap tides**, which occur when the sun, Earth and moon form a right-angle, with the Earth at the apex (Figure 6.11c). As the sun's attraction partly counterbalances that of the moon, the tidal range is at a minimum with the lowest of high tides and the highest of low tides (Figure 6.12). Spring and neap tides vary by approximately 20 per cent above and below the mean high-tide and low-tide levels.

So far, we have seen how tides might change on a uniform or totally sea-covered Earth. In practice, the tides may differ considerably from the above scenario due to such factors as: the Earth's rotation (and the effect of the Coriolis force, page 224); the distribution of land masses; and the size, depth and configuration of ocean and sea basins.

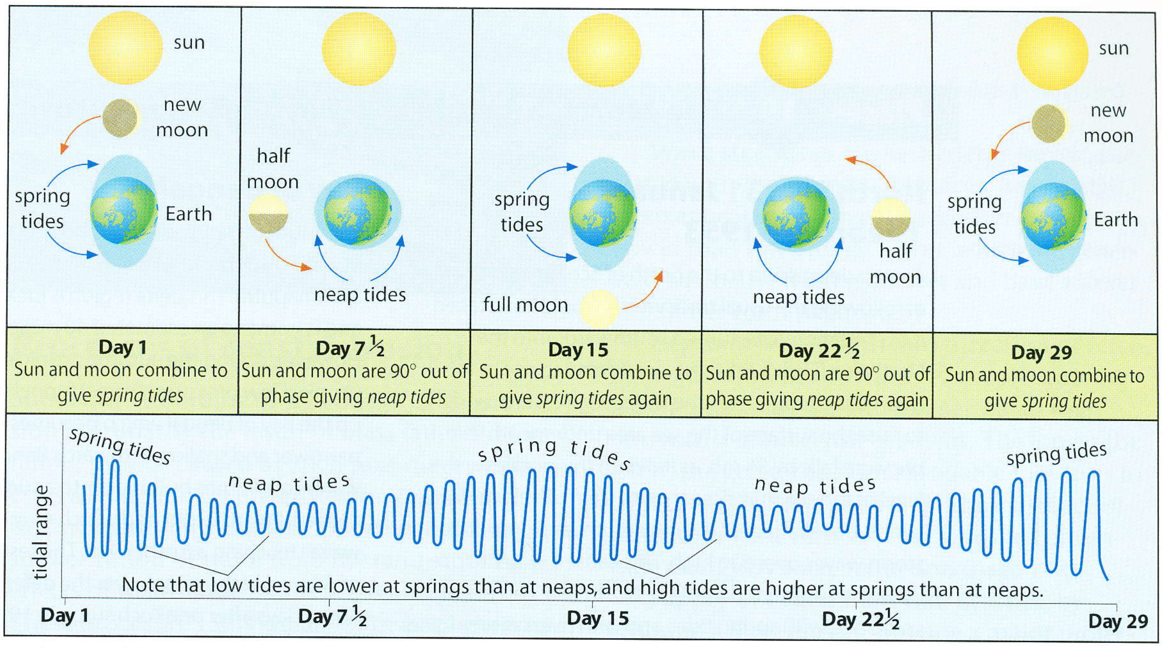


Figure 6.12

Tidal cycles during the lunar month

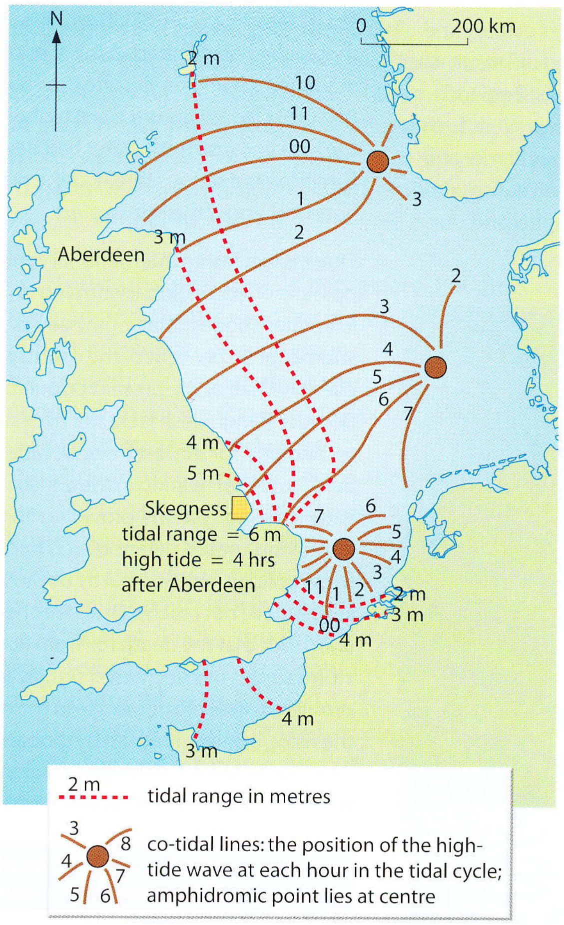


Figure 6.13

Tidal range and difference in times of high tide in the North Sea

The morphology of the seabed and coastline affects tidal range. In the example of the North Sea, as the tidal wave travels south it moves into an area where both the width and the depth of the sea decrease. This results in a rapid accumulation, or funnelling, of water to give an increasingly higher tidal range – the range at Dover is several metres greater than in northern Scotland (Figure 6.13). Estuaries where incoming tides are forced into rapidly narrowing valleys also have considerable tidal ranges, e.g. the Severn estuary with 13 m, the Rance (Brittany) with 11.6 m and the Bay of Fundy (Canada) with 15 m. It is due to these extreme tidal ranges that the Rance has the world's first tidal power station, while the Bay of Fundy and the Severn have, respectively, experimental and proposed schemes for electricity generation (page 542). Extreme narrowing of estuaries can concentrate the tidal rise so rapidly that an advancing wall of water, or **tidal bore**, may travel upriver, e.g. the Rivers Severn and Amazon. In contrast, small enclosed seas have only minimal tidal ranges, e.g. the Mediterranean with 0.01 m.

Storm surges

Storm surges are rapid rises in sea-level caused by intense areas of low pressure, i.e. depressions (page 230) and tropical cyclones (page 235). For every drop in air pressure of 10 mb (page 224), sea-level can rise 10 cm. In tropical cyclones, pressure can fall by 100 mb causing the sea-level to rise by 1 m. Areas at greatest risk are those where sea basins become narrower and more shallow (e.g. southern North Sea and the Bay of Bengal) and where tropical cyclones move from the sea and cross low-lying areas (e.g. Bangladesh and Florida). When these storms coincide with hurricane-force winds and high tides, the surge can be topped by waves reaching 8 m in height. Where such events occur in densely populated areas, they pose a major natural hazard as they can cause considerable loss of life and damage to property (Places 19 and 31, page 238).

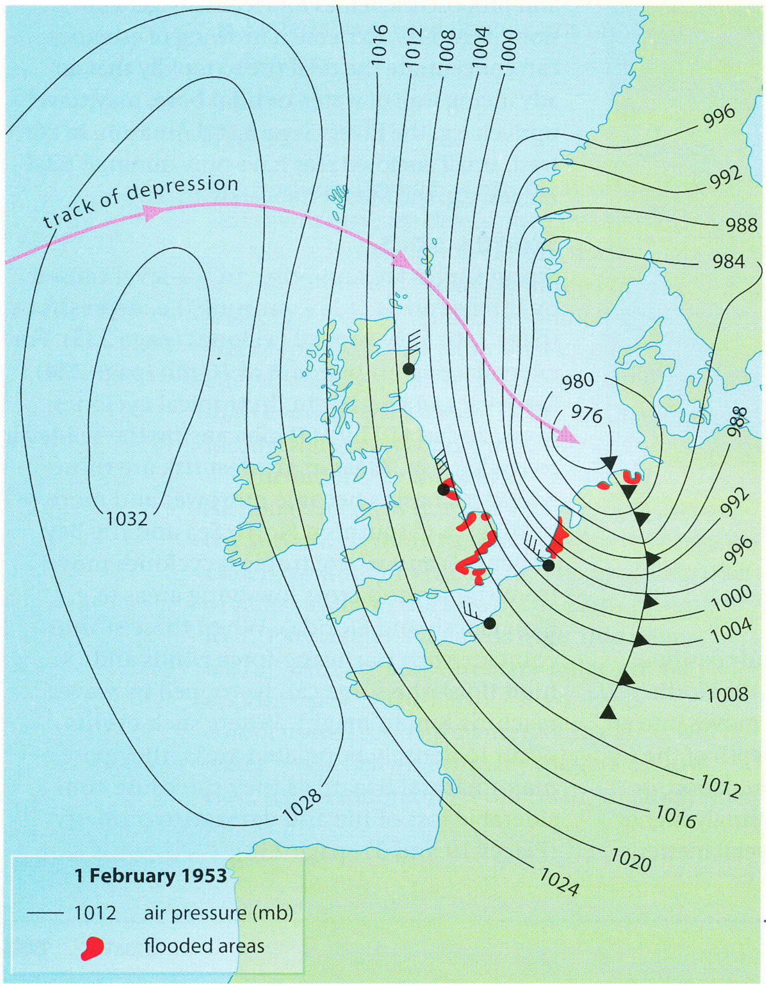
Places 19 The North Sea and the Bay of Bengal: storm surges

North Sea, 31 January – 1 February 1953

A deep depression to the north of Scotland, instead of following the usual track which would have taken it over Scandinavia, turned southwards into the North Sea (Figure 6.14). As air is forced to rise in a depression (page 230), the reduced pressure tends to raise the surface of the sea area underneath it. If pressure falls by 56 mb, as it did on this occasion, the level of the sea may rise by up to 0.5 m. The gale-force winds, travelling over the maximum fetch, produced storm waves over 6 m high. This caused water to pile up in the southern part of the North Sea. This event coincided with spring tides and with rivers discharging into the sea at flood levels. The result was a high tide, excluding the extra height of the waves, of over 2 m in Lincolnshire, over 2.5 m in the Thames estuary and over 3 m in the Netherlands. The immediate result was the drowning of 264 people in south-east England and 1835 people in the Netherlands. To prevent such devastation by future surges, the Thames Barrier and the Dutch Delta Scheme have since been constructed. Both schemes needed considerable capital and technology to implement.

Figure 6.14

The North Sea storm surge of 1 February 1953



Bay of Bengal

The south of Bangladesh includes many flat islands formed by deposition from the Rivers Ganges and Brahmaputra. This delta region is ideal for rice growing and is home to an estimated 40 million people. However, during the autumn, tropical cyclones (tropical low pressure storms) funnel water northwards up the Bay of Bengal which becomes increasingly narrower and shallower towards Bangladesh. The water sometimes builds up into a surge which may exceed 4 m in height and which may be capped by waves reaching a further 4 m. The result can be a wall of water which sweeps over the defenceless islands. Three days after one such surge in 1994, the Red Cross suggested that over 40 000 people had probably been drowned, many having been washed out to sea (Places 31, page 238). The only survivors were those who had climbed to the tops of palm trees and managed to cling on despite the 180 km/hr winds. The Red Cross feared outbreaks of typhoid and cholera in the area because fresh water had been contaminated. Famine was a serious threat as the rice harvest had been lost under the salty waters.

There is increasing international concern about the possible effect of global warming on Bangladesh. Estimates suggest that a 1 m rise in sea-level could submerge 25 per cent of the country, affecting over one-half of the present population (page 169). Because Bangladesh lacks the necessary capital and technology, for the last three decades the World Bank has been helping in the construction of cyclone early warning systems, providing flood shelters and improving coastal defences. It is partly because of these precautions, and partly because recent storm surges have not reached the peak heights of 1990 and 1991, that the death toll from flooding caused by storm surges has decreased significantly. However, the problem is likely to get worse in the near future due to the rising sea-level caused by global warming, and the lowering in height of the delta region resulting from the extraction of groundwater for agriculture.

Year	Height of storm surge	Death toll (estimated)
1966	6.1	80 000
1985	5.7	40 000
1988	4.8	25 000
1990	6.3	140 000
1991	6.1	150 000
1994	5.8	40 000
2007	5.1	2 300

Figure 6.15

Waves breaking on Filey Brigg, Yorkshire: wave energy is absorbed by a band of residual rock and so the cliff behind is protected

Processes of coastal erosion

Subaerial According to J. Pethick, 'Cliff recession is primarily the result of mass failure.' Mass failure may be caused by such non-marine processes as: rain falling directly onto the cliff face; by throughflow or, under extreme conditions, surface runoff of water from the land; and the effects of weathering by the wind and frost. These processes, individually or in combination, can cause mass movement either as soil creep on gentle slopes or as slumping and landslides on steeper cliffs (Figures 2.17 and 2.18).

Wave pounding Steep waves have considerable energy. When they break as they hit the foot of cliffs or sea walls, they may generate shock-waves of up to 30 tonnes per m^2. Some sea walls in parts of eastern England need replacing within 25 years of being built, due to wave pounding (Case Study 6).

Hydraulic pressure When a parcel of air is trapped and compressed, either in a joint in a cliff or between a breaking wave and a cliff, then the resultant increase in pressure may, over a period of time, weaken and break off pieces of rock or damage sea defences.

Abrasion/corrasion This is the wearing away of the cliffs by sand, shingle and boulders hurled against them by the waves. It is the most effective method of erosion and is most rapid on coasts exposed to storm waves.

Attrition Rocks and boulders already eroded from the cliffs are broken down into smaller and more rounded particles.

Corrosion/solution This includes the dissolving of limestones by carbonic acid in sea water (compare Figure 2.8), and the evaporation of salts to produce crystals which expand as they form and cause the rock to disintegrate (Figure 2.2). Salt from sea water or spray is capable of corroding several rock types.

Factors affecting the rate of erosion

Breaking point of the wave A wave that breaks as it hits the foot of a cliff releases most energy and causes maximum erosion. If the wave hits the cliff before it breaks, then much less energy is transmitted, whereas a wave breaking further offshore will have had its energy dissipated as it travelled across the beach (Figure 6.15).

Wave steepness Highest-energy waves, associated with longer fetch distances, have a high, steep appearance. They have greater erosive power than low-energy waves, which are generated where the fetch is shorter and have a lower and flatter form (Figure 6.8).

Depth of sea, length and direction of fetch, configuration of coastline A steeply shelving beach creates higher and steeper waves than one with a more gentle gradient. The longer the fetch, the greater the time available for waves to collect energy from the wind. The existence of headlands with vertical cliffs tends to concentrate energy by wave refraction (page 142).

Supply of beach material Beaches, by absorbing wave energy, provide a major protection against coastal erosion.

Beach morphology Beaches, by dissipating wave energy, act as a buffer between waves and the land. As they receive high-energy inputs at a rapid rate from steep waves, and low-energy inputs at a slower rate from flat waves, they must adopt a morphology (shape) to counteract the different energy inputs. High, rapid energy inputs are best dissipated by wide, flat beaches which spread out the oncoming wave energy. In contrast, the lower-energy inputs of flatter waves can easily be dissipated by narrow, steep beaches which act rather like a wall against which the waves flounder. An exception is when steep waves break onto a shingle beach. As energy is rapidly dissipated through friction and percolation, then a wide, flat beach profile is unnecessary (page 145).

Rock resistance, structure and dip The strength of coastal rocks influences the rate of erosion (Figure 6.16). In Britain, it is coastal areas where glacial till was deposited that are being worn back most rapidly (Places 20). When Surtsey first arose out of the sea off the south-west coast of Iceland in 1963 (Places 3, page 16), it consisted of unconsolidated volcanic ash. It was only when the ash was covered and protected by a lava flow the following year that the island's survival was seemingly guaranteed.

Rocks that are well-jointed (Figure 8.1) or have been subject to faulting have an increased vulnerability to erosion. The steepest cliffs are usually where the rock's structure is horizontal or vertical and the gentlest where the rock dips upwards away from the sea. In the latter case, blocks may break off and slide downwards (Figure 2.17). Erosion is also rapid where rocks of different resistance overlie one another, e.g. chalk and Gault clay in Kent.

Figure 6.16

Rock type and average rates of cliff recession

Rock type	Location	Rate of erosion (m/yr)
Volcanic ash	Krakatoa	40
Glacial till	Holderness	2
Glacial till	Norfolk	1
Chalk	South-east England	0.3
Shale	North Yorkshire	0.09
Granite	South-west England	0.001

Human activity The increase in pressure resulting from building on cliff tops and the removal of beach material which may otherwise have protected the base of the cliff both contribute to more rapid coastal erosion.

Although rates of erosion may be reduced locally by the construction of sea defences, such defences often lead to increased rates of erosion in adjacent areas. Human activity therefore has the effect of disturbing the equilibrium of the coast system (Case Study 6).

Places 20 Holderness: coastal processes

The coastline at Holderness is retreating by an average of 1.8 m a year. Since Roman times, the sea has encroached by nearly 3 km, and some 50 villages mentioned in the Domesday Book of 1086 have disappeared.

The following extract was taken from a management report, 'Humber Estuary & Coast' (1994) prepared by Professor J.S. Pethick (then of the University of Hull and now at the University of Newcastle) for Humberside County Council.

'The soft glacial till cliffs of Holderness are eroding at a rapid rate. The reasons for such erosion are, however, less to do with the soft sediment of the cliff than with the lack of beach material and the poorly developed nearshore zone [Figure 6.6]. Retreat of the cliff line here is matched by progressive lowering of the seabed to give a wide shallow platform stretching several kilometres seaward. Eventually this platform will be so extensive that most of the incident wave energy will be expended here rather than at the cliff so that erosion rates will decrease or even halt. Since this may take several thousand years, it cannot form part of any management plan for this coast – yet it is important to recognise that the natural erosional processes here are neither random nor pernicious.

The process of cliff retreat along the Holderness coast is more complex than appears at first sight. Mass failures of the cliff are triggered by wave action at the cliff toe. Such failures may be 50 to 100 m wide and up to 30 m deep giving a scalloped edge to the cliff. The retreat rate varies temporarily; a large failure may produce a 10 m retreat in one year but no further retreat will then occur for 3 or 4 years – giving a periodicity of 4 or 5 years in total. This means that attempts to measure erosion rates over periods of less than 10 years, that is over 2 cycles, can be extremely misleading, resulting in massive over- or under-estimates of the long-term retreat rate which is remarkably constant at 1.8 m per year [Figure 6.17]. Three issues may be highlighted here.

- The beaches of Holderness are thin veneers covering the underlying glacial tills. The beaches do not increase in volume since, south of Hornsea, a balance exists between the input of sand by erosion and the removal of the sand by wave action, principally from the north-east, which drives sands south.
- The sediment balance on the Holderness coast is maintained by the action of storm waves from the north-east. These waves approach the coast obliquely, the angle between wave crest and shore being critical for the sediment transport rate. A clockwise movement would increase the transport and erosion rate while an anti-clockwise swing would decrease both of these. Random changes in the orientation of the shore are quickly eradicated by changes in the sediment balance, but any permanent change in the orientation of the coastline, such as that caused by the introduction of hard sea defences as at Hornsea, Mappleton and Withernsea, means that the sediment balance is disturbed.

Figure 6.17

Houses collapsing into the sea, Holderness

- Hard defences [Case Study 6A] can have two long-term effects: first, although erosion is halted at the defence itself, several kilometres to the north erosion continues as before. This causes an anti-clockwise re-orientation of the coast, sand transport is reduced and sand accumulates immediately north of the defences – as can be seen north of Hornsea. Second, the accumulation of sand north of the defences starves the beaches to the south causing an increase in erosion there. The fine-grained sediments from the Holderness cliff and seabed erosion are not transported along the beaches as are the sands and shingle but are moved in suspension. Research is presently under way which is intended to chart the precise movement of this material but it is clear that its dominant movement is south towards the Humber. A large proportion may enter the estuary and become deposited there. The remainder is moved south and east into the North Sea where the transport pathway is towards the Dutch and German coast.'

Figure 6.18

Wave-cut notch at Coromandel Peninsula, New Zealand

Figure 6.19

Abrasion or wave-cut platform at Flamborough Head, Yorkshire

Erosion landforms

Headlands and bays

These are most likely to be found in areas of alternating resistant and less resistant rock. Initially, the less resistant rock experiences most erosion and develops into **bays**, leaving the more resistant outcrops as **headlands**. Later, the headlands receive the highest-energy waves and so become more vulnerable to erosion than the sheltered bays (Figure 6.5). The latter now experience low-energy breakers which allow sand to accumulate and so help to protect that part of the coastline.

Abrasion or wave-cut platforms

Wave energy is at its maximum when a high, steep wave breaks at the foot of a cliff. This results in undercutting of the cliff to form a **wave-cut notch** (Figure 6.18). The continual undercutting causes increased stress and tension in the cliff until eventually it collapses. As these processes are repeated, the cliff retreats leaving, at its base, a gently sloping **abrasion** or **wave-cut platform** which has a slope angle of less than 4° (Figure 6.19). The platform, which appears relatively even when viewed from a distance, cuts across rocks regardless of their type and structure. A closer inspection of this inter-tidal feature usually reveals that it is deeply dissected by abrasion, resulting from material carried across it by tidal movements, and corrosion. As the cliff continues to retreat, the widening of the platform means that incoming waves break further out to sea and have to travel over a wider area of beach. This dissipates their energy, reduces the rate of erosion of the headland, and limits the further extension of the platform. It has been hypothesised that wave-cut platforms cannot exceed 0.5 km in width.

Where there has been negative change in sea-level (page 81), former wave-cut platforms remain as **raised beaches** above the present influence of the sea (Figure 6.51).

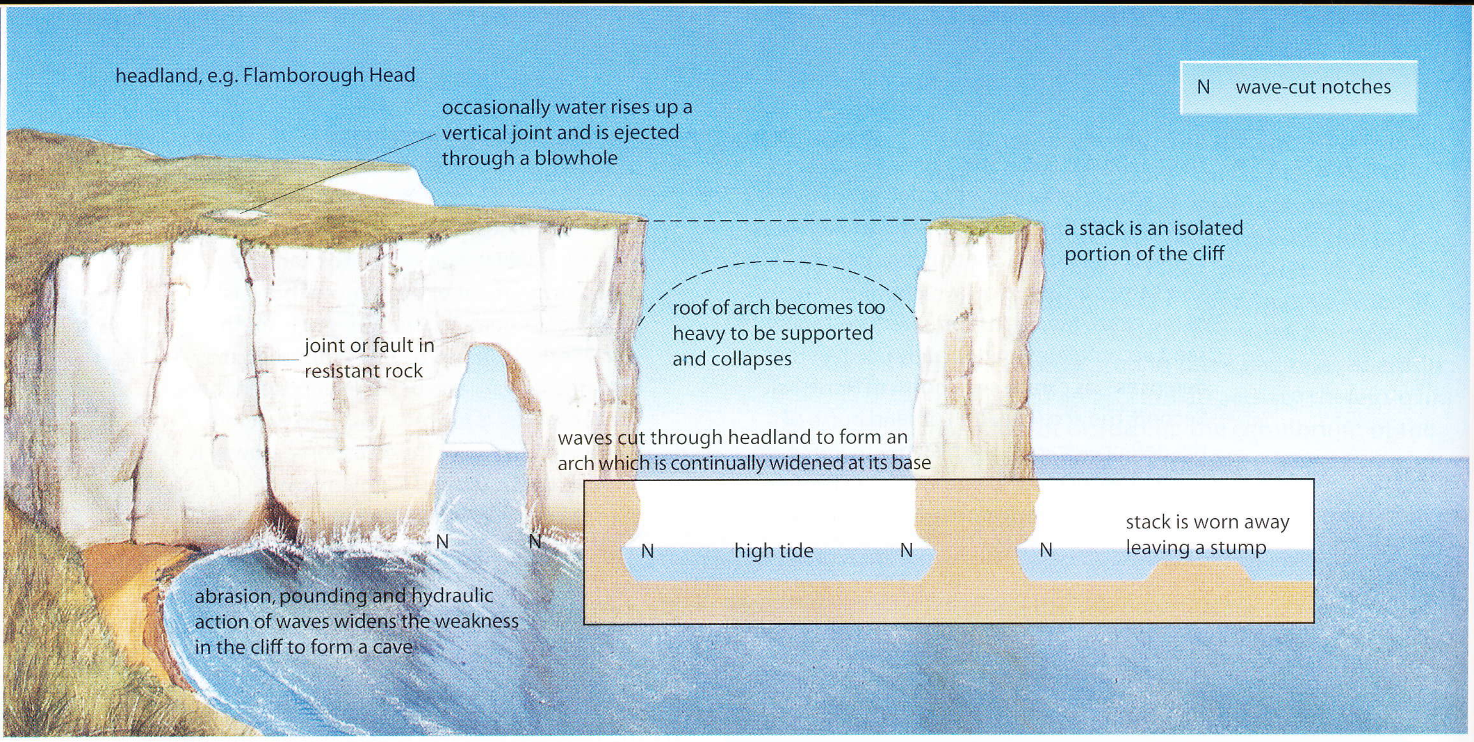


Figure 6.20

The formation of caves, blowholes, arches and stacks

Caves, blowholes, arches and stacks

Where cliffs are of resistant rock, wave action attacks any line of weakness such as a joint or a fault. Sometimes the sea cuts inland, along a joint, to form a narrow, steep-sided inlet called a **geo**, or at other times it can undercut part of the cliff to form a **cave**. As shown in Figure 6.20, caves are often enlarged by several combined processes of marine erosion. Erosion may be vertical, to form **blowholes**, but is more typically backwards through a headland to form **arches** and **stacks** (Figures 6.20 and 6.21).

These landforms, which often prove to be attractions to sightseers and mountaineers, can be found at The Needles (Isle of Wight), Old Harry (near Swanage) and Flamborough Head (Yorkshire, Figure 6.19), which are all cut into chalk, and at The Old Man of Hoy (Orkneys) which is Old Red Sandstone (Figure 8.12).

Figure 6.21

Icelandic coastline

Transportation of beach material

Up and down the beach

As we have already seen, flat, constructive waves tend to move sand and shingle up the beach, whereas the net effect of steep, destructive waves is to comb the material downwards.

Longshore (littoral) drift

Usually wave crests are not parallel to the shore, but arrive at a slight angle. Only rarely do waves approach a beach at right-angles. The wave angle is determined by wind direction, the local configuration of the coastline, and refraction at headlands and in shallow water. The oblique wave angle creates a nearshore current known as **longshore** (or **littoral**) **drift** which is capable of moving large quantities of material in a down-drift direction (Figure 6.22). On many coasts, longshore drift is predominantly in one direction; for example, on the south coast of England, where the maximum fetch and prevailing wind are both from the south-west, there is a predominantly eastward movement of beach material. However, brief changes in wind – and therefore wave – direction can cause the movement of material to be reversed.

Of lesser importance, but more interesting and easier to observe, is the movement of material along the shore in a zigzag pattern. This is because when a wave breaks, the swash carries material up the beach at the same angle as that at which the wave approached the shore. As the swash dies away, the backwash and any material carried by it returns straight down the beach, at right-angles to the waterline, under the influence of gravity. If beach material is carried a considerable distance, it becomes smaller, more rounded and better sorted.

Where beach material is being lost through longshore drift, the coastline in that locality is likely to be worn back more quickly because the buffering effect of the beach is lessened. To counteract this process, wooden breakwaters or **groynes** may be built (Figure 6.23). Groynes encourage the local accumulation of sand (important in tourist resorts) but can result in a depletion of material, and therefore an increase in erosion, further along the coast (Case Study 6A).

Figure 6.22

The effects of longshore drift

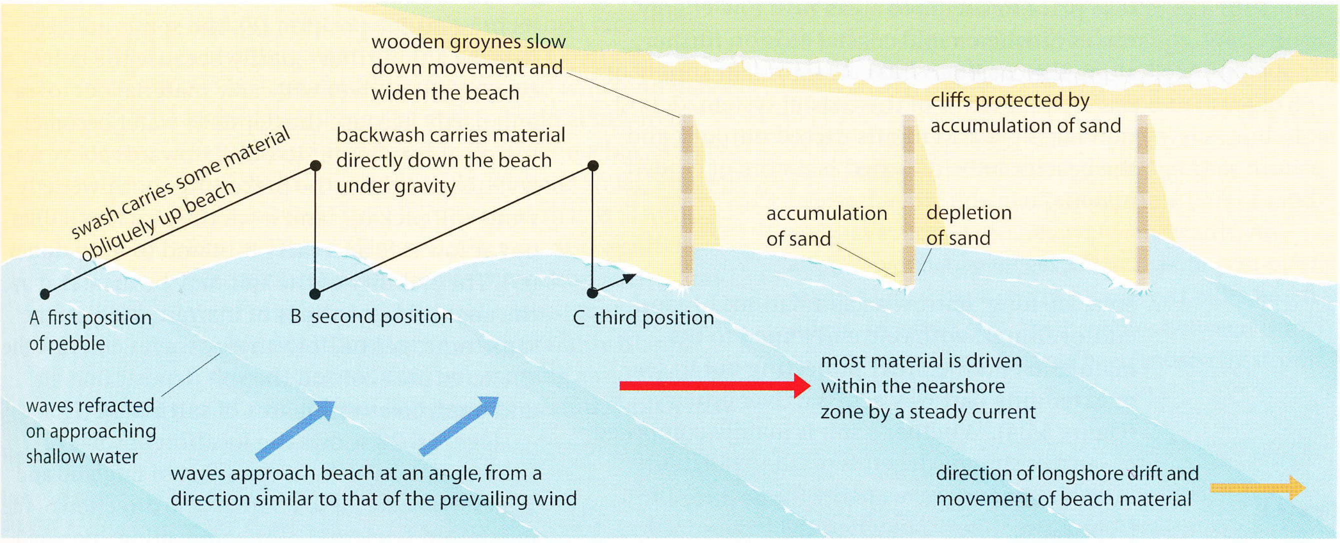


Figure 6.23

The effect of groynes on longshore drift, Southwold, Suffolk: this type of coastal management is usually undertaken at holiday resorts where sandy beaches are a major tourist attraction

Figure 6.24

A spit: Dawlish Warren at the mouth of the River Exe, Devon

Coastal deposition

Deposition occurs where the accumulation of sand and shingle exceeds its depletion. This may take place in sheltered areas with low-energy waves or where rapid coastal erosion further along the coast provides an abundant supply of material. In terms of the coastal system, deposition takes place as inputs exceed outputs, and the beach can be regarded as a store of eroded material.

Spits

Spits are long, narrow accumulations of sand and/or shingle with one end joined to the mainland and the other projecting out to sea or extending part way across a river estuary (Figure 6.24). Whether a spit is mainly composed of sand or shingle depends on the availability of sediment and wave energy (pages 145–146). Composite spits occur when the larger-sized shingle is deposited before the finer sands.

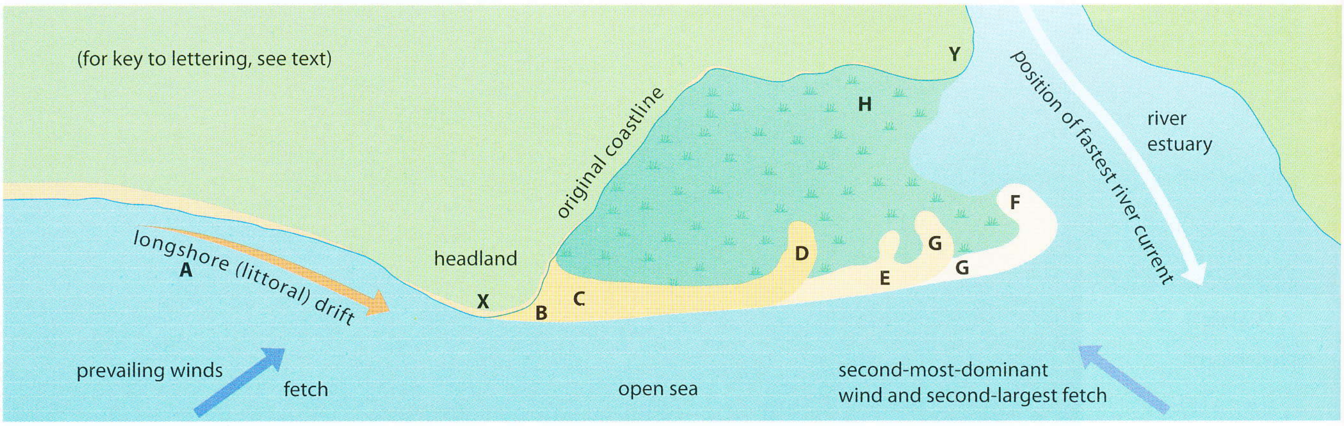
In Figure 6.25, the line **X–Y** marks the position of the original coastline. At point **A**, because the prevailing winds and maximum fetch are from the south-west, material is carried eastwards by longshore drift. When the orientation of the old coastline began to change at **B**, some of the larger shingle and pebbles were deposited in the slacker water in the lee of the headland. As the spit continued to grow, storm waves threw some larger material above the high-water mark (**C**), making the feature more permanent; while, under normal conditions, the finer sand was carried towards the end of the spit at **D**. Many spits develop a hooked or curved end. This may be for two reasons: a change in the prevailing wind to coincide with the second-most-dominant wave direction and second-longest fetch, or wave refraction at the end of the spit carrying some material into more sheltered water.

Eventually the seaward side of the spit will retreat, while longshore drift continues to extend the feature eastwards. A series of recurved ends may form (**E**) each time there is a series of storms from the south-east giving a lengthy period of altered wind direction. Having reached its present-day position (**F**), the spit is unlikely to grow any further – partly because the faster current of the river will carry material out to sea and partly because the depth of water becomes too great for the spit to build upwards above sea-level. Meanwhile, the prevailing south-westerly wind will pick up sand from the beach as it dries out at low tide and carry it inland to form **dunes** (**G**). The stability of the spit may be increased by the anchoring qualities of marram grass. At the same time, gentle, low-energy waves entering the sheltered area behind the spit deposit fine silt and mud, creating an area of **saltmarsh** (**H**).

Figure 6.28 shows the location of some of the larger spits around the coast of England and Wales. How do these relate to the direction of the maximum fetch and of the prevailing and dominant winds?

Figure 6.25

Stages in the formation of a spit



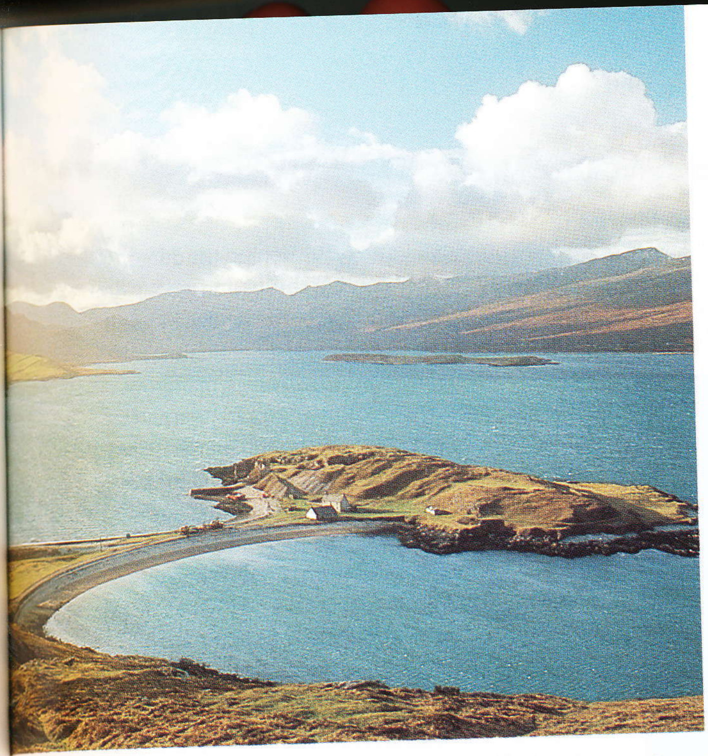


Figure 6.26

A tombolo: Loch Eriboll, Highland, Scotland

Figure 6.27

A bar: Slapton Ley, Devon

Tombolos, bars and barrier islands

A **tombolo** is a beach that extends outwards to join with an offshore island (Figure 6.26). Chesil Beach, in Dorset, links the Isle of Portland to the mainland. Some 30 km long and up to 14 m high, it presents a gently smoothed face to the prevailing winds in the English Channel.

If a spit develops in a bay into which no major river flows, it may be able to build across that bay, linking two headlands, to form a **bar**. Bars straighten coastlines and trap water in lagoons on the landward side. Bars, such as that at Slapton Ley, in Devon (Figure 6.27), may also result in places where constructive waves lead to the landward migration of offshore, seabed material.

Barrier islands are a series of sandy islands totally detached from, but running almost parallel to, the mainland. Between the islands, which may extend for several hundred kilometres, and the mainland is a tidal lagoon (Figure 6.29). Although relatively uncommon in Britain, they are widespread globally, accounting for 13 per cent of the world's coastlines. They are easily recognisable on maps of the eastern USA (Places 21), the Gulf of Mexico, the northern Netherlands, West Africa and southern and western Australia. Although their origin is uncertain, they tend to develop on coasts with relatively high-energy waves and a low tidal range. One theory suggests that they formed, below the low-tide mark, as offshore bars of sand and have moved progressively landwards. An alternative theory suggests that rises in post-glacial sea-level may have partly submerged older beach ridges. In either case, the breaches between the islands seem likely to have been caused by storm waves.

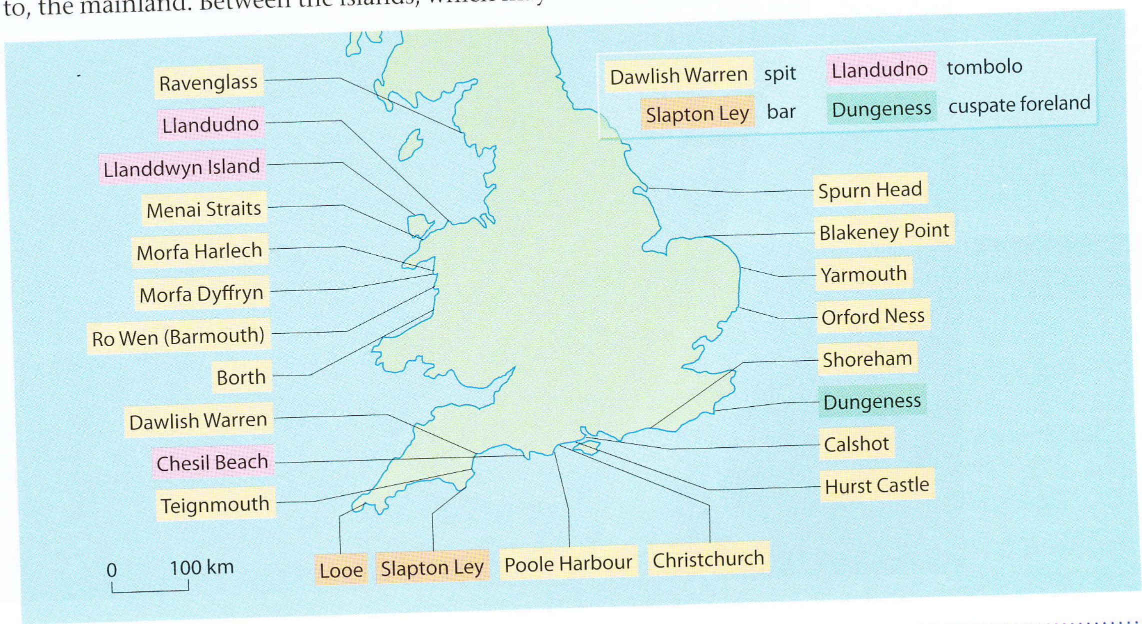


Figure 6.28

Location of some major spits, tombolos and bars in England and Wales

Places 21 Eastern and southern USA: barrier islands

Barrier islands have a unique morphology, flora and fauna. The smooth, straight, ocean edge is characterised by wide, sandy beaches which slope gently upwards to sand dunes which are anchored by high grasses (Figure 6.30). Behind the dunes, the 'island' interior may contain shrubs and woods, deer and snakes, insects and birds. The landward side is punctuated by sheltered bays, quiet tidal lagoons, saltmarshes and, towards the tropics, mangrove swamps. These wetlands provide a natural habitat for oysters, fish and birds. Although barrier islands form the interface between the land and the ocean, they seem fragile in comparison with the power that the wind and sea brings to them. It is virtually impossible for a tropical storm or hurricane to move ashore without first crossing either of the two longest stretches of barrier islands in the world: either that which extends for 2500 km from New Jersey to the southern tip of Florida (Figure 6.29); or the one stretching for 2100 km along the Gulf Coast states to Mexico.

Barrier islands are subject to a process called 'wash over'. This process, which might occur up to 40 times in some years, is when storm waves carry large quantities of sand over the island from the seaward face to the landward side. This results in the seaward side being eroded and pushed backwards. The landward marshes and mangrove swamps become suffocated, and the tidal lagoons are narrowed. From a human viewpoint, barrier islands form an essential natural defence against hurricanes and their storm-force waves.

Figure 6.29

Barrier islands off North Carolina, USA, taken from the Apollo spacecraft (X = position of Figure 6.30)

Figure 6.30

Barrier island on Core Banks, looking south (see X on Figure 6.29 for location)

Sand dunes

Sand dunes are a dynamic landform whose equilibrium depends on the interrelationship between mineral content (sand) and vegetation.

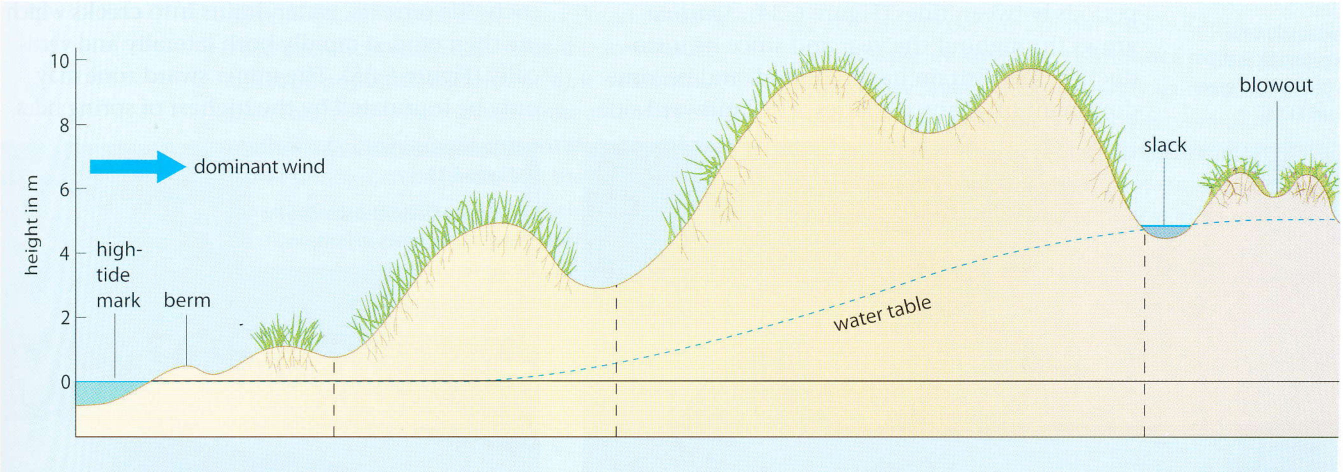
Longshore drift may deposit sand in the inter-tidal zone. As the tide ebbs, the sand will dry out allowing winds from the sea to move material up the beach by saltation (page 183). This process is most likely to occur when the prevailing winds come from the sea and where there is a large tidal range which exposes large expanses of sand at low tide. Sand may become trapped by seaweed and driftwood on berms or at the point of the highest spring tides. Plants begin to colonise the area (Figure 11.10), stabilising the sand and encouraging further accumulation. The regolith has a high pH value due to calcium carbonate from seashells.

Embryo dunes are the first to develop (Figure 6.31). They become stabilised by the growth of lyme and marram grasses. As these grasses trap more sand, the dunes build up and, due to the high rate of percolation, become increasingly arid. Plants need either succulent leaves to store water (sand couch), or thorn-like leaves to reduce transpiration in the strong winds (prickly saltwort), or long tap-roots to reach the water table (marram grass). As more sand accumulates, the embryo dunes join to form **foredunes** which can attain a height of 5 m (Figures 6.31 and 6.32). Due to a lack of humus, their colour gives them the name **yellow dunes**. The dunes become increasingly grey as humus and bacteria from plants and animals are added, and they gradually become more vegetation-covered and acidic. These **grey (mature) dunes** may reach a height of 10–30 m before the supply of fresh sand is cut off by their increasing distance from the beach (Figure 11.11). There may be several parallel ridges of old dunes (as at Morfa Harlech, Figure 6.33), separated by low-lying, damp slacks. Heath plants begin to dominate the area as acidity, humus and moisture content all increase (Figure 11.9). Paths cut by humans and animals expose areas of sand. As the wind funnels along these tracks, **blowouts** may form in the now **wasting dunes**. To combat further erosion at Morfa Harlech, parts of the dunes have been fenced off and marram grass has been planted to try to re-stabilise the area and to prevent any inland migration of the dunes.

The above idealised scheme can be interrupted at any stage by storms or human use. If the supply of sand is cut off, then new embryo dunes cannot form and yellow dunes may be degraded so that it is the older, grey dunes that line the beach.

Figure 6.31

A transect across sand dunes, based on fieldwork at Morfa Harlech, North Wales



	Embryo	Fore or yellow dunes	Grey dunes and dune ridges	Wasting dunes with blowouts
Dune height (m)	1	5	8–10	6–8
Percentage of exposed sand	80	20	less than 10	over 40 on dunes
Humus and moisture content	very little humus, mixed salt and fresh water	some humus, very little moisture, fresh water	humus increases inland, water content still low, fresh water	high humus, brackish water in slacks
pH	over 8	slightly alkaline	increasingly acid inland: pH 6.5–7	acid: pH 5–6
Plant types	sand couch, lyme grass	marram, xerophytic species	creeping fescue, sea spurge, some marram, cotton grass, heather	heather, gorse on dunes, *Juncus* in slacks

Figure 6.32

Embryo and foredunes at Morfa Harlech, North Wales (refer also to Figures 11.10 and 11.11)

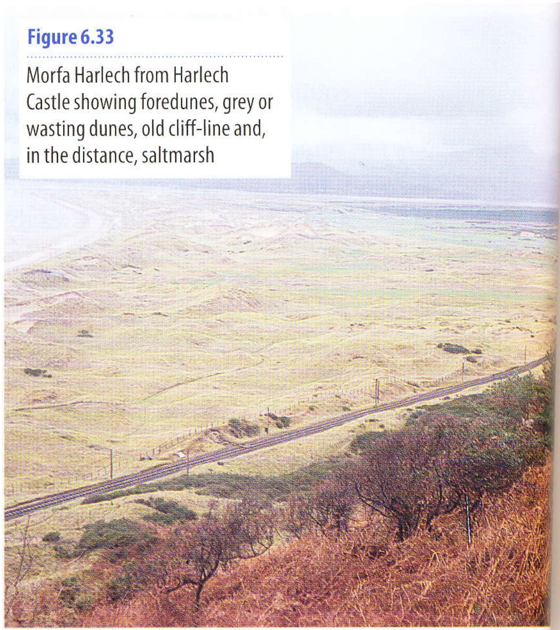


Figure 6.33

Morfa Harlech from Harlech Castle showing foredunes, grey or wasting dunes, old cliff-line and, in the distance, saltmarsh

Saltmarshes

Where there is sheltered water in river estuaries or behind spits, silt and mud will be deposited either by the gently rising and falling tide or by the river, thus forming a zone of **inter-tidal mudflats**. Initially, the area may only be uncovered by the sea for less than 1 hour in every 12-hour tidal cycle. Plants such as algae and *Salicornia* can tolerate this lengthy submergence and the high levels of salinity. They are able to trap more mud around them, creating a surface that remains exposed for increasingly longer periods between tides (Figure 6.34). *Spartina* grows throughout the year and since its introduction into Britain has colonised, and become dominant in, many estuaries. The landward side of the inter-tidal mudflats is marked by a small cliff (Figure 11.12), above which is the flat **sward zone**. This zone may only be covered by the sea for less than 1 hour in each tidal cycle (Figure 6.12). Seawater collects in hollows which become increasingly saline as the water evaporates. The hollows often enlarge into **saltpans** (Figure 11.13) which are devoid of vegetation except for certain algae and the occasional halophyte (page 291). As each tide retreats, water drains into **creeks** which are then eroded rapidly both laterally and vertically (Figure 6.35). The upper sward zone may only be inundated by the highest of spring tides.

Figure 6.34

Llanrhidian saltmarsh, Gower peninsula, South Wales (refer also to Figures 11.13 and 11.14)

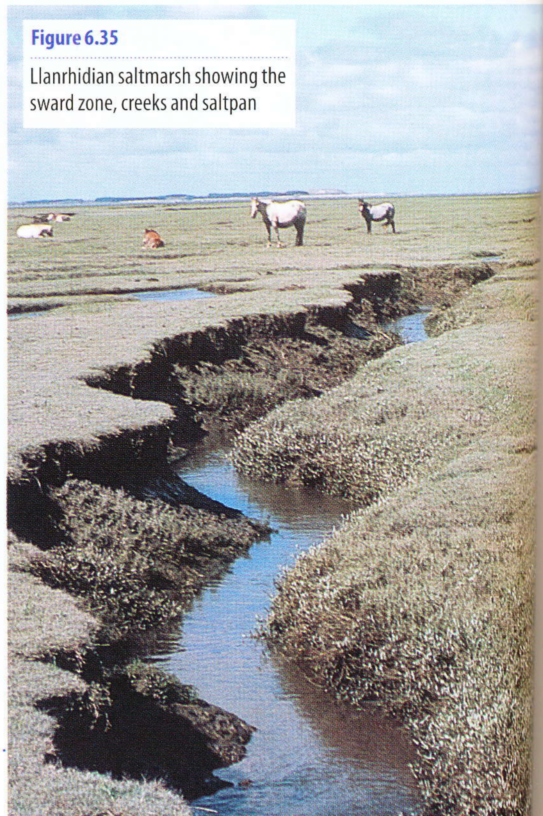


Figure 6.35

Llanrhidian saltmarsh showing the sward zone, creeks and saltpan

Framework 6 Sampling

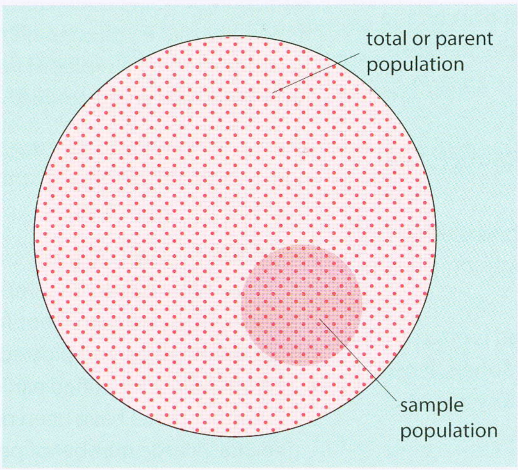


Figure 6.36

A sample population in relation to the total population

Why sample?

Geographers are part of a growing number of people who find it increasingly useful and/or necessary to use data to quantify the results of their research. The problem with this trend is that the amount of data may be very expensive, too time-consuming, or just impracticable to collect – as it would be, for example, to investigate everybody's shopping patterns in a large city, to find the number of stones on a spit, or to map the land use of all the farms in Britain.

Sampling is the method used to make statistically valid inferences when it is impossible to measure the **total population** (Figure 6.36). It is essential, therefore, to find the most accurate and practical method of obtaining a **representative sample**. If that sample can be made with the minimum of bias, then statistically significant conclusions may be drawn. However, even if every effort is made to achieve precision, it must be remembered that any sample can only be a close estimate.

Sampling basics

Most sampling procedures assume that the total population has a **normal distribution** (Figure 4.16a) which, when plotted on a graph, produces a symmetrical curve on either side of the mean value. This shows that a large proportion of the values are close to the average, with few extremes. Figure 6.37 shows a normal distribution curve and the **standard deviation** (page 247) – the measure of dispersion from the mean. Where most of the values are clustered near to the mean, the standard deviation is low.

The larger the sample, the more accurate it is likely to be, and the more likely it is to resemble the parent population; it is also more likely to conform to the normal distribution curve. While the generally accepted minimum size for a sample is 30, there is no upper limit – although there is a point beyond which the extra time and cost involved in increasing the sample size do not give a significant improvement in accuracy (an example of the law of diminishing returns, page 462).

Figure 6.37 shows that, in a normal distribution, 68.27 per cent of the values in the sample occur within a range of ±1 standard deviations (SDs) from the mean; 95 per cent of the values fall within ±2 SDs; and 99 per cent within ±3 SDs. These percentages are known as **confidence limits**, or **probability levels**. Geographers usually accept the 95 per cent probability level when sampling. This means that they accept the chance that, in 5 cases out of every 100, the true mean will lie outside 2 SDs to either side of their sample mean.

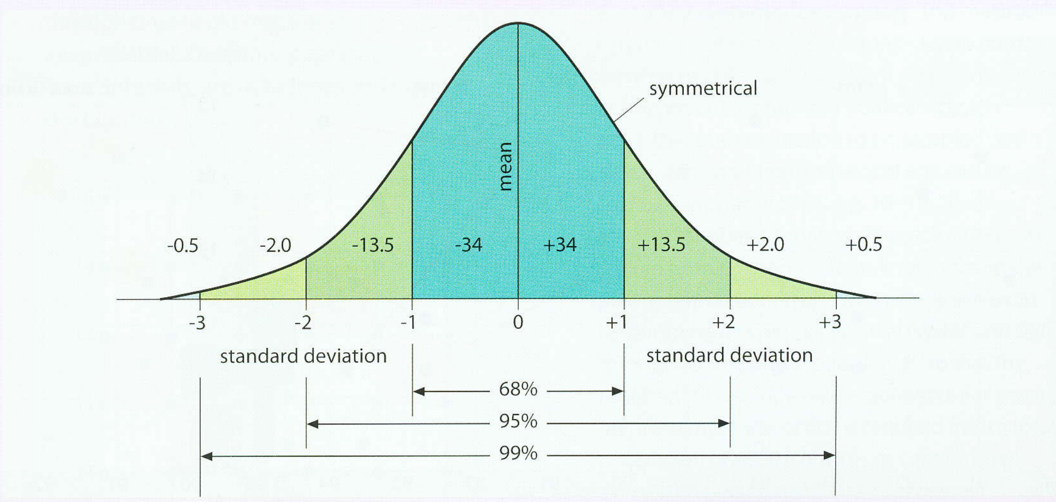


Figure 6.37

A normal distribution showing standard deviations from the mean

Sampling techniques

Several different methods may be used according to the demands of the required sample and the nature of the parent population. There are two major types, with one refinement:

- **Random sampling** This is the most accurate method as it has no bias.
- **Systematic sampling** This method is often quicker and easier to use, although some bias or selection is involved.
- **Stratified sampling** This method is often a very useful refinement for geographers; it can be used with either a random or a systematic sample.

Part of a random number table

9271	0143	2141	9381
1498	3796	4413	1405
6691	4294	6077	9091
9061	1148	9493	1940
2660	7126	7126	4591
3459	7585	4897	8138
6090	7962	5766	7228
2191	9271	9042	5884

Random sampling

Under normal circumstances, this is the ideal type of sample because it shows no bias. Every member of the total population has an equal chance of being selected, and the selection of one member does not affect the probability of selection of another member. The ideal random sample may be obtained using **random numbers**. These are often generated by computer and are available in the form of printed tables of random numbers, but if necessary they can be obtained by drawing numbers out of a hat. Random number tables usually consist of columns of pairs of digits. Numbers can be chosen by reading either along the rows or down the columns, provided only one method is used. Similarly, any number of figures may be selected – six for a grid reference, four for a grid square, three for house numbers in a long street, etc. Using the grid shown in Figure 6.38, the random number table given above yields eight 6-figure grid references: 927114; (986691 has to be excluded because the grid does not contain these numbers); 906126; etc.

One feature of a genuine random sample is that the same number can be selected more than once – so remember that if you are pulling numbers from a hat, they should be replaced immediately after they have been read and recorded.

There are three alternative ways of using random numbers to sample areal distributions (patterns over space) (Figure 6.38).

1. **Random point** A grid is superimposed over the area of the map to be sampled. Points, or map references, are then identified using random number tables, and plotted on the map. The eight points identified earlier (in the random number table) have been plotted on Figure 6.38a. A large number of points may be needed to ensure coverage of the whole area – see Figure 6.40.
2. **Random line** Random numbers are used to obtain two end points which are then joined by a line, as in Figure 6.38b which uses the same eight random points, in the order in which they occurred in the table. Several random lines are needed to get a representative sample (e.g. lines across a city to show transects of variation in land use).
3. **Random area** Areas of constant size, e.g. grid squares or quadrats, are obtained using random numbers. By convention, the number always identifies the south-west corner of a grid square. If sample squares one-quarter the size of a grid square are used, together with the same sample points, their locations are as shown on Figure 6.38c – note that the point in the north-east cannot be used because part of the sample square lies outside the study area. This method can be used to sample land-use areas or the distribution of plant communities over space.

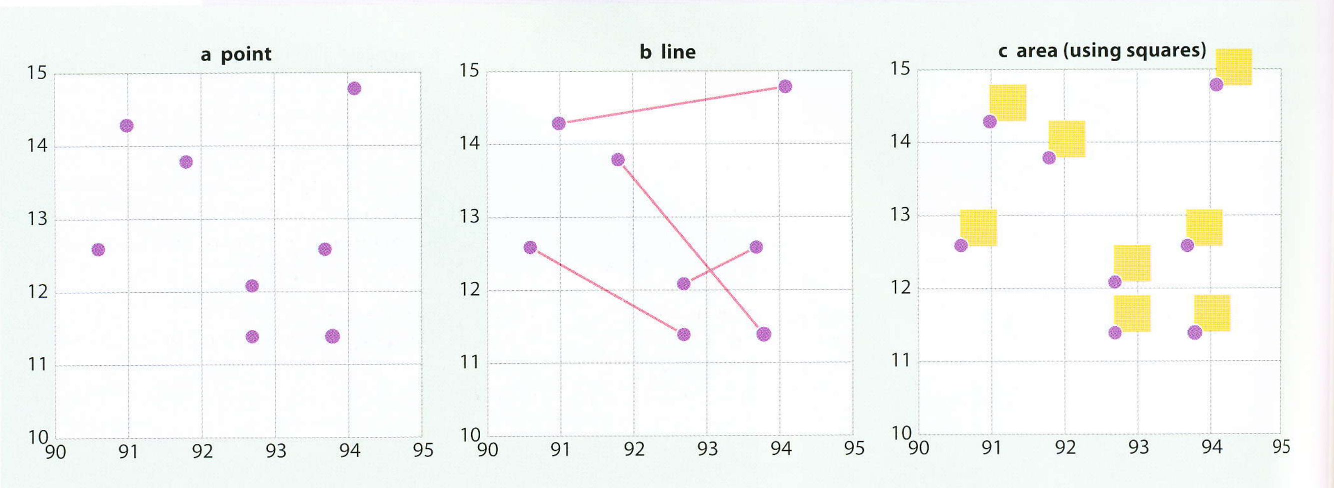


Figure 6.38

Random sampling using point, line and area techniques

The advantages of random sampling include its ability to be used with large populations and its avoidance of bias. Careful **sample design** is needed, however, to avoid the possibility of achieving misleading results, for example when sampling small populations, and when sampling over a large area. Also, when used in the field, it may involve considerable time and energy in visiting every point.

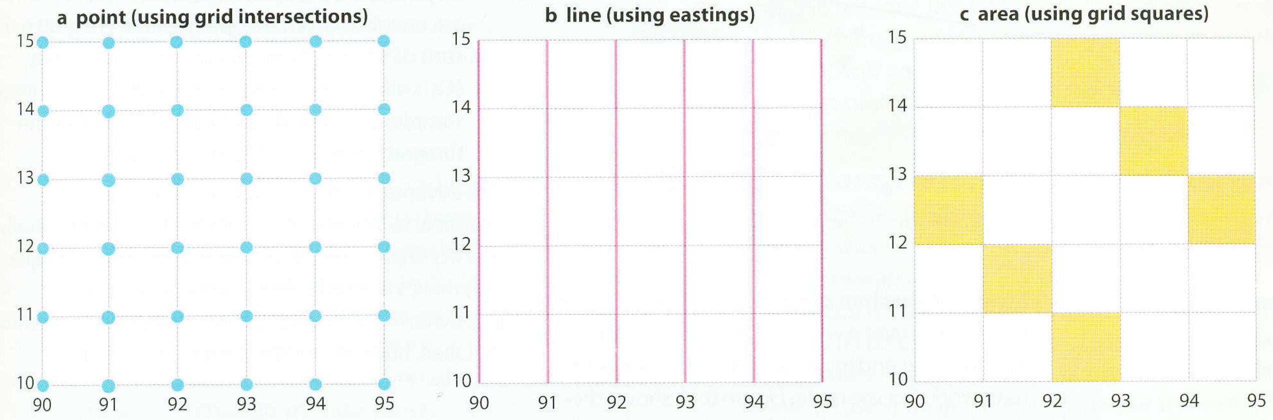


Figure 6.39

Systematic sampling using point, line and area techniques

Systematic sampling

A systematic sample is one in which values are selected in a regular way, e.g. choosing every 10th person on a list, or every 20th house in a street. This can be an easier method in terms of time and effort than random sampling. Like random sampling, it can be operated using individual points, lines or areas (Figure 6.39).

1 **Systematic point** This can show changes over distance, e.g. by sampling the land use every 100 m. It can also show change through time, e.g. by sampling from the population censuses (taken every 10 years).
2 **Systematic line** This may be used to choose a series of equally spaced transects across an area of land, e.g. a shingle spit.
3 **Systematic area** This is often used for land-use sampling, to show change with distance or through time (if old maps or air photographs are available). Quadrats, positioned at equal intervals, are used for assessing plant distributions.

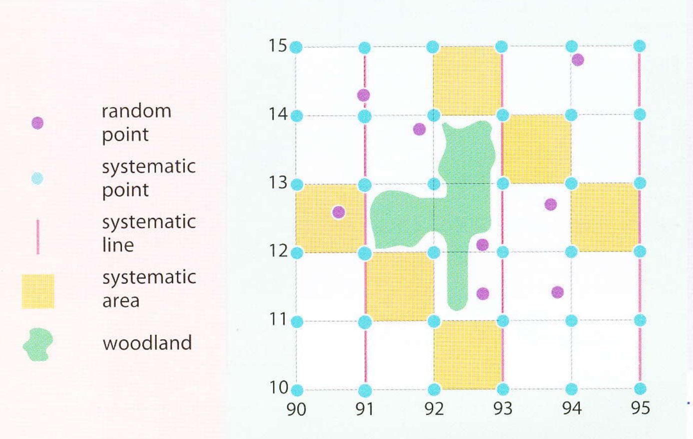


Figure 6.40

Poor sample design and selection can lead to inaccurate results: an area of woodland is completely missed in this example

The main advantage of systematic sampling lies in its ease of use. However, its main disadvantage is that all points do not have an equal chance of selection – it may either overstress or miss an underlying pattern (Figure 6.40).

Stratified sampling

When there are significant groups of known size within the parent population, in order to ensure adequate coverage of all the sub-groups it may be advisable to stratify the sample, i.e. to divide the population into categories and sample within each. Although categorising into groups (layers or strata) may be a subjective decision, the practical application of this technique has considerable advantages for the geographer. Once the groups have been decided, they can be sampled either systematically or randomly, using point, line or area techniques.

1 **Stratified systematic sampling** This method can be useful in many situations – when interviewing people, sampling from maps, and during fieldwork. For example, in political opinion polls, the total population to be sampled can be divided (stratified) into equal age and/or socio-economic groups, e.g. 10–19, 20–29, etc. The number interviewed in each category should be in proportion to its known size in the parent population. This is most easily achieved by sampling at a regular interval (systematically) throughout the entire population, so that the required total sample size is obtained. For example, if a sample size of 800 is required from a total population of 8000 (i.e. a 10 per cent sample), every 10th person would be interviewed.

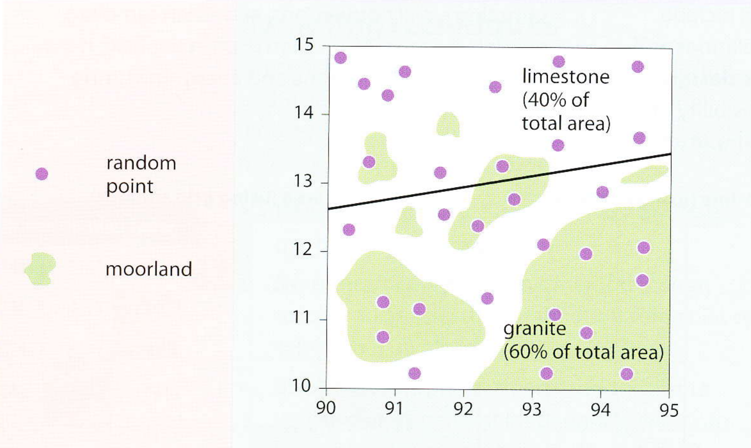


Figure 6.41

A random point sample, stratified by area

2 Stratified random sampling This method can be used to cover a wide range of data, both in interviewing and in geographical fieldwork and map work. For example, Figure 6.41 shows the distribution of moorland on two contrasting rock types: granite occupies 60% of the total area and limestone 40%. To discover whether the proportion of moorland cover varies with rock type, the sampling must be in proportion to their relative extents. Thus, if a sample size of 30 points is derived using random numbers, 18 are needed within the granite area (18 is 60 per cent of 30) and 12 within the limestone area (12 is 40 per cent of 30). If it was decided to area sample, 18 quadrats would have to fall within the granite area, and 12 in the limestone.

The advantages of stratified sampling include its potential to be used either randomly or systematically, and in conjunction with point, line or area techniques. This makes it very flexible and useful, as many populations have geographical sub-groups. Care must be taken, however, to select appropriate strata.

Changes in sea-level

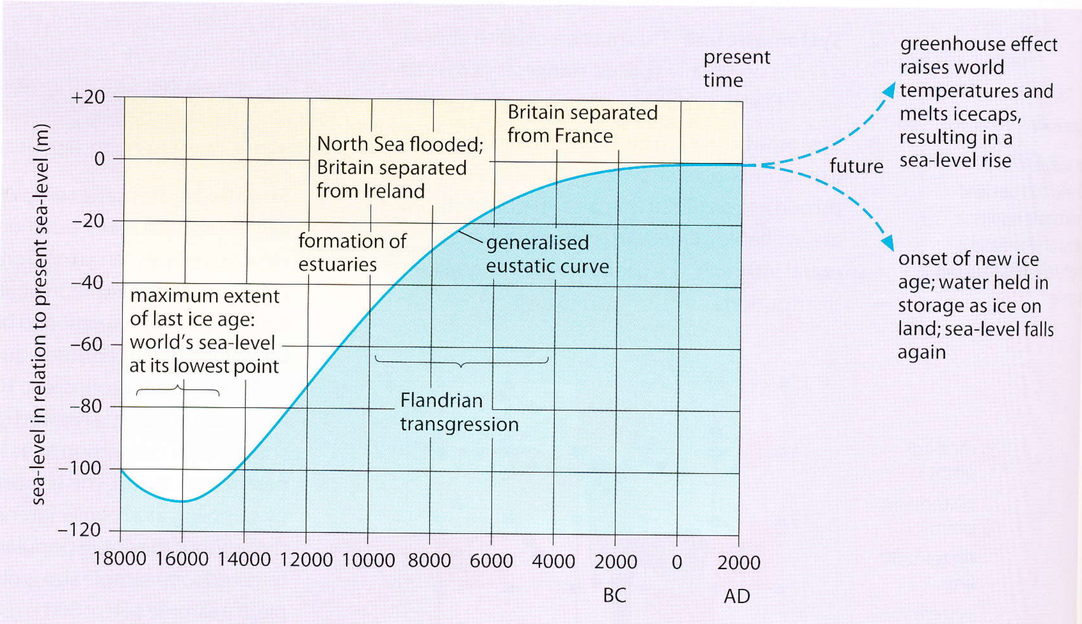
Although the daily movement of the tide alters the level at which waves break onto the foreshore, the average position of sea-level in relation to the land has remained relatively constant for nearly 6000 years (Figure 6.42). Before that time there had been several major changes in this mean level, the most dramatic being a result of the Quaternary ice age and of plate movements.

During times of maximum glaciation, large volumes of water were stored on the land as ice – probably three times more than today. This modification of the **hydrological cycle** meant that there was a worldwide, or **eustatic** (glacio-eustatic, page 123), fall in sea-level of an estimated 100–150 m.

As ice accumulated, its weight began to depress those parts of the crust lying beneath it. This caused a local, or **isostatic** (glacio-isostatic, page 123), change in sea-level.

Figure 6.42

Eustatic changes in sea-level since 18 000 BC



The world's sea-level was at its minimum 18 000 years ago when the ice was at its maximum (Figure 6.42). Later, as temperatures began to rise and icecaps melted, there was first a eustatic rise in sea-level followed by a slower isostatic uplift which is still operative in parts of the world today. This sequence of sea-level changes may be summarised as follows:

1 Formation of glaciers and ice sheets. Eustatic fall in sea-level gives rise to a negative change in base level (page 81).
2 Continued growth of ice sheets. Isostatic depression of the land under the ice produces a positive change in base level.
3 Ice sheets begin to melt. Eustatic rise in sea-level with a positive change in base level.
4 Continued decline of ice sheets and glaciers. Isostatic uplift of the land under former ice sheets results in a negative change in base level.

During this deglaciation, there may have been a continuing, albeit small, eustatic rise in sea-level but this has been less rapid than the isostatic uplift so that base level appears to be falling. Measurements suggest that parts of north-west Scotland are still rising by 4 mm a year and some northern areas of the Gulf of Bothnia (Scandinavia) by 20 mm a year (Places 23, page 166). The uplift in northern Britain is causing the British Isles to tilt and the land in south-east England to be depressed. This process is of utmost importance to the future natural development and human management of British coasts (Figure 6.56).

Tectonic changes have resulted in:

- the uplift (**orogeny**) of new mountain ranges, especially at destructive and collision plate margins (pages 17 and 19)
- local tilting (**epeirogeny**) of the land, as in south-east England, which has increased the flood risk, and in parts of the Mediterranean, leading to the submergence of several ancient ports and leaving others stranded above the present-day sea-level
- local volcanic and earthquake activity, as in Iceland.

Landforms created by sea-level changes

Changes in sea-level have affected:

- the shape of coastlines and the formation of new features by increased erosion or deposition
- the balance between erosion and deposition by rivers (page 81) resulting in the drowning of lower sections of valleys or in the rejuvenation of rivers, and
- the migration of plants, animals and people.

Landforms resulting from submergence

Eustatic rises in sea-level following the decay of the ice sheets led to the drowning of many low-lying coastal areas.

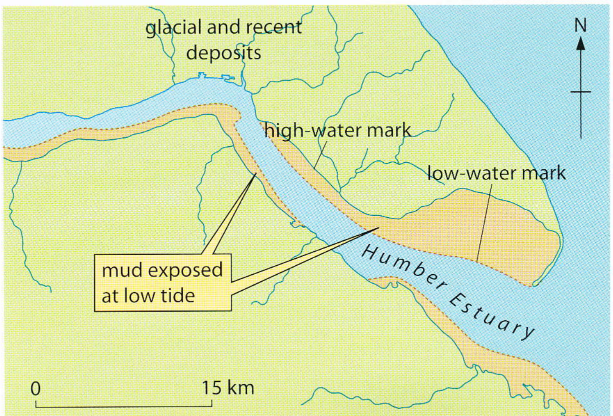
Estuaries are the tidal mouths of rivers, most of which have inherited the shape of the former river valley (Figure 6.45). In many cases, estuaries have resulted from the lower parts of the valleys being drowned by the post-glacial rise of sea-level. Being tidal, estuaries are subject to the ebbs and flows of the tide, and usually large expanses of mud are revealed at low tide (Figure 6.43). Many estuaries widen towards the sea and narrow to a meandering section inland (Figure 6.44).

Estuaries are affected by processes that are very different from those at work along rivers and coasts, because of particular features.

- **Residual currents** are created by the mixing of fresh water (from rivers) and saline water (sea water brought in by the tides). Mixing tends to take place only when discharge and velocities are high; otherwise the fresh river water, being less dense, tends to rise and flow over the saline water.
- **Tidal currents** have a two-way flow associated with the incoming (flood) and outgoing (ebb) tide.
- Continuous variations in both **discharge** and **velocity** resulting from the tidal cycle. Tidal velocities are highest at mid-tide and reduce to zero around high and low water. Times of zero velocity result in the deposition of fine-grained sediments, especially in upper estuary channels, which form mudflats and saltmarsh.

Figure 6.43

The Humber estuary



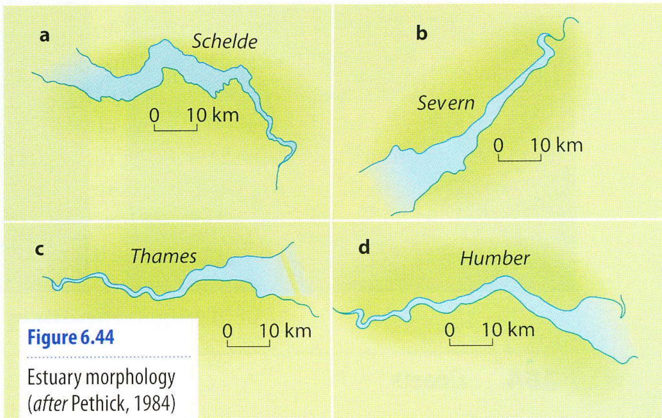


Figure 6.44

Estuary morphology (*after* Pethick, 1984)

Classification of estuaries

a **According to origin** This traditional method divides estuaries into different shapes but on the basis of their river valley origins.

- **Drowned river valleys**, resulting from post-glacial rises in sea-level, includes most estuaries.
- **Rias**, formed when valleys in a dissected upland are submerged, are one type of drowned river valley (Places 22).
- **Dalmatian coasts** are similar to rias except that their rivers flow almost parallel to the coast, in contrast to rias where they flow more at right-angles, e.g. Croatia.
- **Fiords**, formed by the drowning of glacial troughs (page 113), are extremely deep and steep-sided estuaries (Places 22).
- **Fiards** are drowned, glaciated lowland areas, e.g. Strangford Lough, Northern Ireland.

b **According to tidal process and estuary shape** This modern approach, supported by Pethick, acknowledges that it is tidal range that determines the tidal current, the residual current velocities and, therefore, the amount and source of sediment.

- **Micro-tidal** estuaries, which have a tidal range of less than 2 m, are dominated by freshwater river discharge and wind-driven waves from the sea. They tend to be long, wide and shallow, often with a fluvial delta or coastal spits and bars.
- **Meso-tidal** estuaries have a tidal range of between 2 m and 4 m. This fairly limited range means that, although fresh water has less influence, the tidal flow does not extend far upstream and the resultant shape is said to be stubby, with the presence of tidal meanders in the landward section.
- **Macro-tidal** estuaries have a tidal range in excess of 4 m and a tidal influence that extends far inland. They have a characteristic trumpet shape (Figure 6.44) and long, linear sand bars formed parallel to the tidal flow.

Places 22 Devon and Norway: a ria and a fiord

Kingsbridge estuary

During the last ice age, rivers in south-west England were often able to flow during the warmer summer months (compare Figure 5.14), cutting their valleys downwards to the then lower sea-level (page 163). When, following the ice age, sea-levels rose (Figure 6.42), the lower parts of many main rivers and their tributaries were drowned to form sheltered, winding inlets called **rias**. The Kingsbridge estuary (Figures 6.45 and 6.46) is a natural harbour produced by the drowning of a dendritic drainage system (Figure 3.50b). The deepest water is at the estuary mouth, a characteristic of a ria, with depth decreasing inland. The result is a fine natural harbour with an irregular shoreline and, at low tide, 800 hectares of tidal creeks and mudflats.

Apart from south-west England, rias are also found in south-west Wales, south-west Ireland, western Brittany and north-west Spain.

Figure 6.45
Kingsbridge estuary

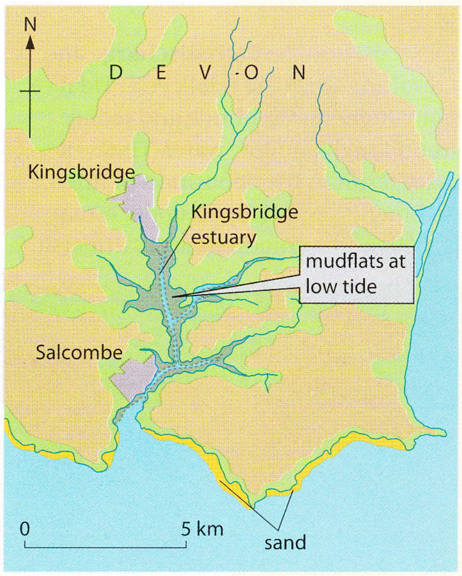


Figure 6.46
Kingsbridge estuary looking north

Sognefjorden

Fiords (fjords) such as Sognefjorden (the Sogne Fiord) were formed by glaciers eroding their valleys to form deep glacial troughs (page 113). When the ice melted, the glacial troughs were flooded by a eustatic rise in sea-level (page 163) to form long, deep, narrow inlets with precipitous sides, a U-shaped cross-section, and hanging valleys (Figure 4.21). Glaciers seem to have followed lines of weakness, such as a pre-glacial river valley or, as suggested by their rectangular pattern, a major fault line (Figure 6.47). Unlike rias, fiords are deeper inland and have a pronounced shallowing towards their seaward end. The shallow entrance, comprising a rock bar, is known as a **threshold**.

The Sognefjorden extends 195 km inland and, at its deepest, has a depth of 1308 m (Figure 6.48). One description of the Sognefjorden is given in Figure 6.49.

Apart from Norway, fiords are also found on the west coasts of the South Island of New Zealand, British Columbia, Alaska, Greenland and southern Chile.

Figure 6.47

Location of Sognefjorden

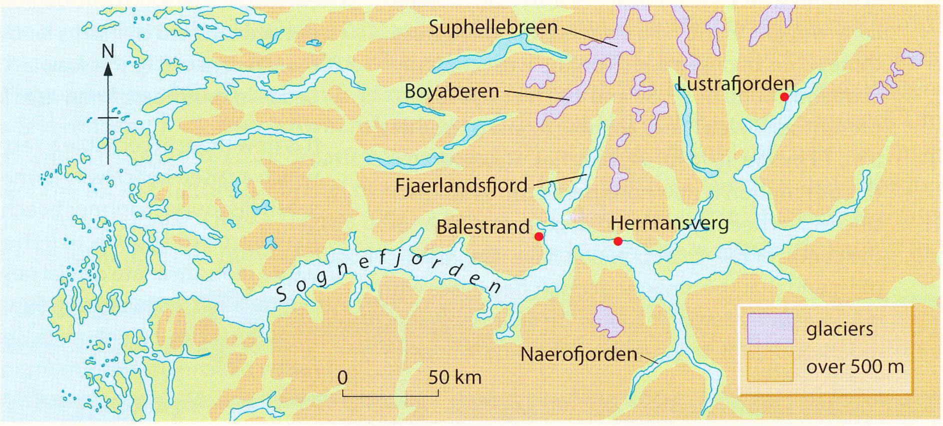


Figure 6.48

Sognefjorden

Figure 6.49

Extract from *Blue Ice*, a novel by Hammond Innes

As we sailed up the fjord, the wind died away leaving the water as flat as glass. The view was breathtakingly beautiful. Mountains rose to snow-covered, jagged peaks. The dark green of the pines covered the lower slopes, but higher up the vegetation vanished leaving sheer cliffs of bare rock which seems to rise to the blue sky. In the distance, on a piece of flat land, was Balestrand, with a steamer moving to the quay. Beyond was the hotel on a delta of green and fertile land.

'Isn't it lovely?' Dahler said. 'It is the sunniest place in all the Sogne Fjord. The big hotel you see is built completely of wood. Here the fjord is friendly, but when you reach Fjaerlandsfjord you will find the water like ice, the mountains dark and terrible, rising to 1300 metres in precipitous cliffs. High above you will see the Boya and Suphelle glaciers, and from these rivers from the melting snow plunge as giant waterfalls into the calm, cold, green coloured fjord.'

Figure 6.50

Erosion surfaces (marine peneplanation) at St David's, Dyfed, South Wales

Landforms resulting from emergence

Following the global rise in sea-level, and still occurring in several parts of the world today, came the isostatic uplift of land as the weight of the ice sheets decreased. Landforms created as a result of land rising relative to the sea include erosion surfaces and raised beaches.

Erosion surfaces In Dyfed, the Gower peninsula (South Wales) and Cornwall, flat planation surfaces dominate the scenery. Where their general level is between 45 m and 200 m, the surfaces are thought to have been cut during the Pleistocene period when sea-levels were higher – hence the alternative name of **marine platforms** (Figure 6.50).

Raised beaches As the land rose, former wave-cut platforms and their beaches were raised above the reach of the waves. Raised beaches are characteristic of the west coast of Scotland (Figure 6.51). They are recognised by a line of degraded cliffs fronted by what was originally a wave-cut platform. Within the old cliff-line may be relict landforms such as wave-cut notches, caves, arches and stacks (Figure 6.52). The presence of such features indicates that isostatic uplift could not have been constant. It has been estimated that it would have taken an unchanging sea-level up to 2000 years to cut each wave-cut platform. (This evidence has been used to show that the climate did not ameliorate steadily following the ice age.)

Places 23 Arran: raised beaches

The Isle of Arran is one of many places in western Scotland where raised beaches are clearly visible. Early workers in the field claimed that there were three levels of raised beach on the west coast of Scotland, found at 25, 50 and 100 feet above the present sea-level. These are now referred to as the 8 m, 15 m and 30 m raised beaches. However, this description is now considered too simplistic, since it has been accepted that places nearest to the centre of the ice depression have risen the most and that the amount of uplift decreases with distance from that point. Thus, for example, the much-quoted '8 m raised beach' on Arran in fact lies at heights of 4–6 m. Where the raised beach is extensive, there is a considerable difference in height between the old cliff on its landward side and the more recent cliff to the seaward side, e.g. the 30 m beach in south-east Arran rises from 24 to 38 m.

It is now more acceptable to estimate the time at which a raised beach was formed by carbon-dating seashells found in former beach deposits, rather than by referring solely to its height above sea-level (i.e. to indicate a 'late glacial raised beach' rather than a '100 ft/30 m beach'). Figure 6.53 is a labelled transect, based on fieldwork, showing the two raised beaches in western Arran.

Figure 6.51

Raised beaches on the Isle of Arran: the lower one relates to the younger '8 m beach'; the upper one to the older '30 m beach'

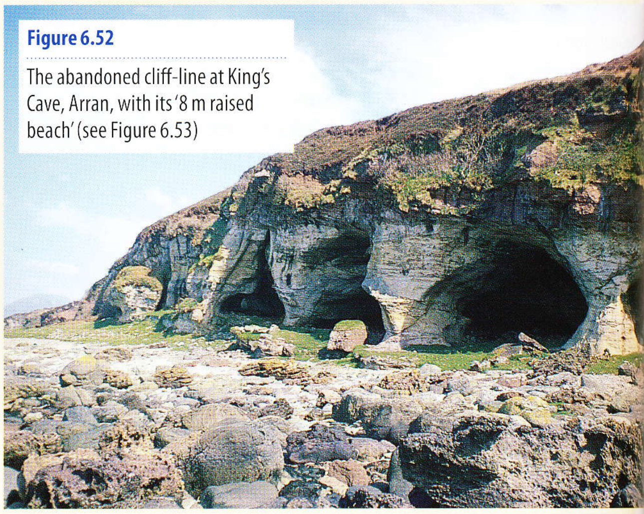


Figure 6.52

The abandoned cliff-line at King's Cave, Arran, with its '8 m raised beach' (see Figure 6.53)

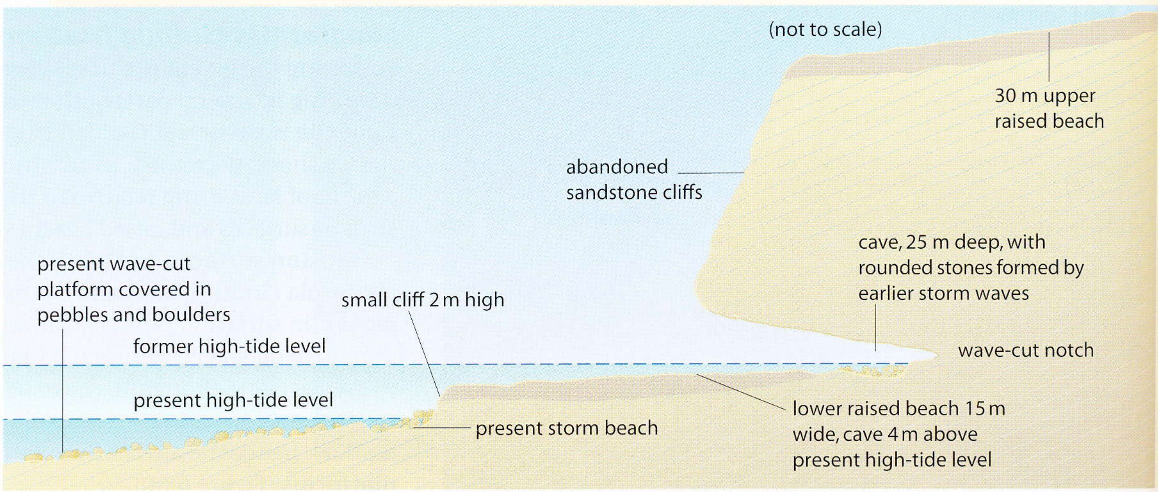


Figure 6.53

Diagrammatic transect across raised beaches of Arran

Figure 6.54

A concordant (Pacific) coastline: Lulworth Cove, Dorset

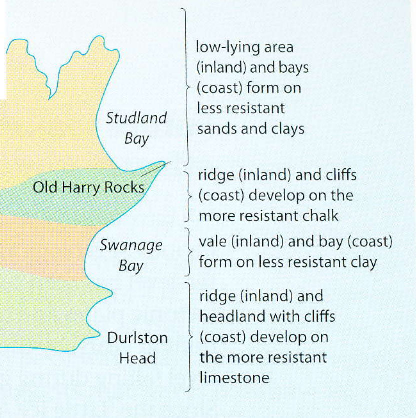


Figure 6.55

A discordant (Atlantic) coastline: Swanage Bay, Dorset

Rock structure

Concordant coasts and **discordant coasts** are located where the natural relief is determined by rock structure (geology). They form where the geology consists of alternate bands of resistant and less resistant rock which form hill ridges and valleys (page 199). Concordant coasts occur where the rock structure is parallel to the coast, as at Lulworth Cove, Dorset (Figure 6.54). Should there be local tectonic movements, a eustatic rise in sea-level, or a breaching of the coastal ridge, then summits of the ridge may be left as islands and separated from the mainland by drowned valleys. These can be seen on atlas maps showing Croatia/the former Yugoslavia (Dalmatian coast) or San Francisco and southern Chile (Pacific coasts). Discordant coasts occur where the coast 'cuts across' the rock structure, as in Swanage Bay, Dorset (Figure 6.55). Here the ridges end as cliffs at headlands, while the valleys form bays.

Framework 7 Classification

Why classify?

Geographers frequently utilise classifications, e.g. types of climate, soil and vegetation, forms and hierarchy of settlement, and types of landform. This is done to try to create a sense of order by grouping together into classes features that have similar, if not identical, characteristics into identifiable categories. For example, no two stretches of coastline will be exactly the same, yet by describing Kingsbridge estuary as a ria, and Sognefjorden as a fiord (Places 22), it may be assumed that their appearance and the processes leading to their formation are similar to those of other rias and fiords, even if there are local differences in detail.

How to classify

When determining the basis for any classification, care must be taken to ensure that:

- only meaningful data and measures are used
- within each group or category, there is the maximum number of similarities
- between each group, there is the maximum number of differences
- there are no exceptions, i.e. all the features should fit into one group or another, and
- there is no duplication, i.e. each feature should fit into one category only.

As classifications are used for convenience and to assist understanding, they should be easy to use. They should not be oversimplified (too generalised), or too complex (unwieldy); but they should be appropriate to the purpose for which they are to be used.

No classification is likely to be perfect, and several approaches may be possible.

An example

The following landforms have already been referred to in this book:

> arch; braided river; corrie; delta; esker; hanging valley; knickpoint; moraine; raised beach; rapids; spit; wave-cut platform.

Can you think of at least three different ways in which they may be categorised? The following are some possibilities:

a Perhaps the simplest classification is a two-fold division based on whether they result from erosion or from deposition.

b They could be reclassified into two different categories: those formed under a previous climate (i.e. relict features) and those still being formed today.

c The most obvious may be a three-fold division into coastal, glacial and fluvial landforms.

d A more complex classification would result from combining either **a** and **b**, or **a** and **c**, to give six groups.

Future sea-level rise and its effects

We have already seen (page 162) that over long periods of geological time (tens of millions of years) sea-level has been controlled by the movement of tectonic plates and over shorter periods (the last million years) by the volume of ice on the land (sea-level falling during glacials, rising in interglacials). Since the 'Little Ice Age' in the 17th century, when glaciers in alpine and arctic regions advanced, the world has slowly been warming. This warming helps to explain why global sea-levels are now some 20 cm higher than they were a century ago and why they are rising by 2 mm a year.

The fact that sea-level is continuing to rise, and at an accelerating rate, is due almost entirely to two factors:

1 **Thermal expansion** Since 1961, the average temperature of the global ocean has increased to depths of over 3000 m and the sea is now absorbing more than 80 per cent of the heat added to the climatic system through global warming. Such warming causes seawater to expand, contributing significantly to sea-level rise.

2 **Melting ice** A less significant, but increasing, contribution is from melting ice – mainly alpine glaciers, including the 1500 or so in the Himalayas – and, to a lesser extent as yet, polar ice sheets and ice caps.

Global sea-level rose at a rate of 1.8 mm/yr between 1965 and 2005 and by 3.1 mm/yr between 1993 and 2005. Some computer models are suggesting that between 1990 and 2090 it could be as high as 3.7 mm/yr, increasing to 5 mm/yr by 2100 (Figure 6.57). Other models have suggested a greater 'Doomsday' scenario with sea-levels rising by 8 mm/yr by the end of this century (one has even suggested 16 mm/yr). Whichever prediction eventually proves to be the most accurate, sea-level rise will have serious consequences:

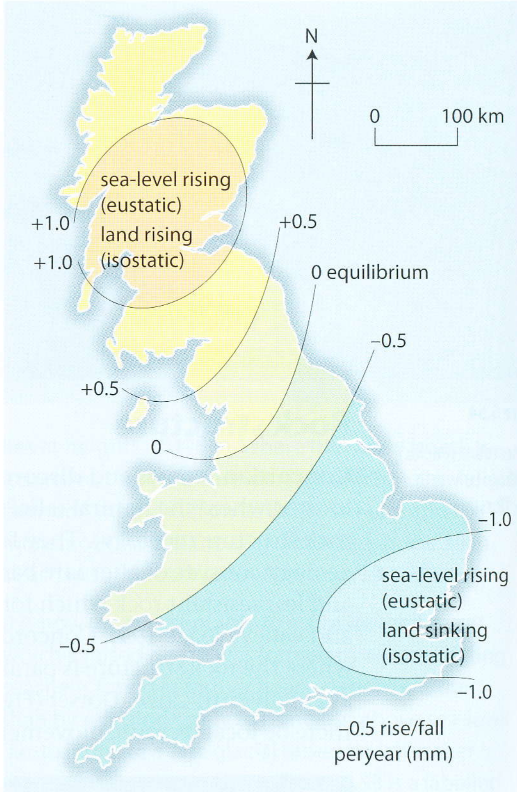


Figure 6.56

Relative sea-level (RSL): the combined net effect of sea and land surface changes

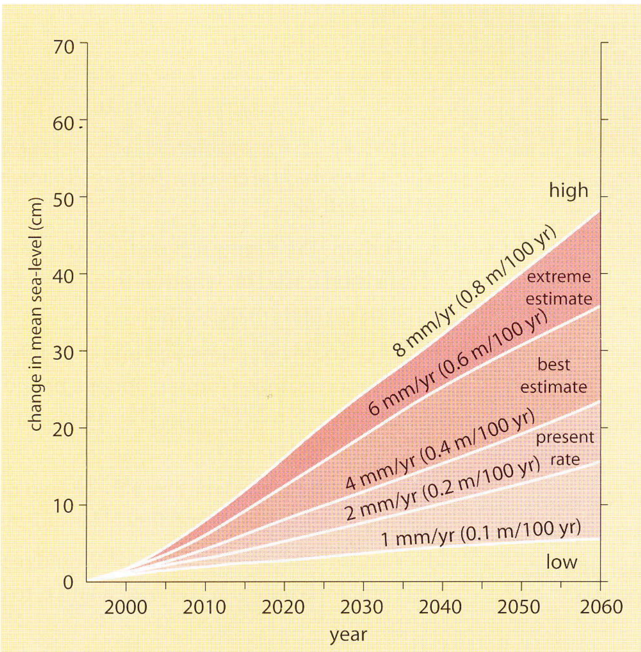


Figure 6.57

Projections of future sea-level rise resulting from global warming: the extreme values cover the 95 per cent probability range (*after* Clayton, 1992)

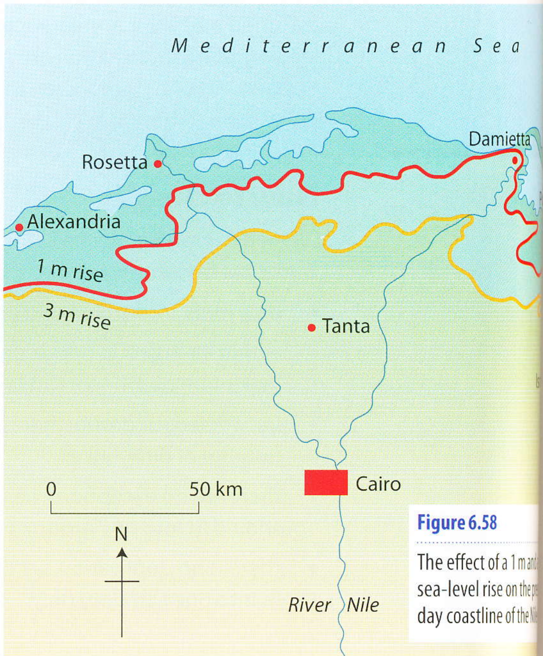


Figure 6.58

The effect of a 1 m a… sea-level rise on the p… day coastline of the N…

- Storm surges, tsunamis, higher tides and larger waves will cause more damage.
- An increase in the frequency and severity of coastal flooding would inundate numerous coastal settlements such as Tokyo, Shanghai, Lagos, London, Bangkok, Kolkata, Hong Kong and Miami, causing the displacement of large centres of populations as well as destroying industry and farmland (Figure 6.58). At present over 65 million people live in annual flood-risk areas, 50 million of those in danger of storm surges. A rise of 1 m in the next 100 years would inundate one-quarter of the land area of Bangladesh, affecting nearly 70 per cent of its population.
- Several low-lying ocean states such as the Maldives in the Indian Ocean and Tuvalu and the Marshall Islands in the Pacific are likely to be inundated.
- There will be an increase in coastal erosion and expensive coastal defences will need to be built and maintained.
- Various coastal ecosystems will be threatened, including sand dunes, saltmarshes, mangrove swamps, coral reefs and coral islands, which may not be able to adapt quickly enough if the rise is too rapid.
- Some sea-life species will migrate to cooler waters.

Larger waves

Mid-Atlantic waves that eventually pound the western coasts of the British Isles have increased in height over the last 30 years. Oceanographers have found that the mean height of these waves in winter has risen from 4 m to 5.3 m. Added to that, the mean height of the largest and most destructive type of wave has risen from 8 m to 11 m. This suggests that waves now have far more energy than they did in 1980 and while they may be a potential form of renewable energy, at present they undermine cliffs, strip sand from beaches and threaten coastal defences (Figure 6.59).

Freak waves of 15 m and over in height were in the past considered to be a marine myth. Opinions began to change when workers on off-shore oil-rigs reported that waves of that height occurred fairly frequently. Two orbiting satellites launched by the European Space Agency in 2000 were given the task of recording and plotting these so-called freak waves. Radar sensors on the satellites soon showed that freak waves were relatively common and, within one period of three weeks, a team of land-based observers noted the existence of more than ten waves of over 25 m spread across the various oceans. Freak waves may explain the sudden disappearance of ships, some as large as oil-tankers.

Figure 6.59
Some impressive waves
a North Cape, Norway – note the relative size of the people
b A wave breaking over a lighthouse, Seaford, Sussex

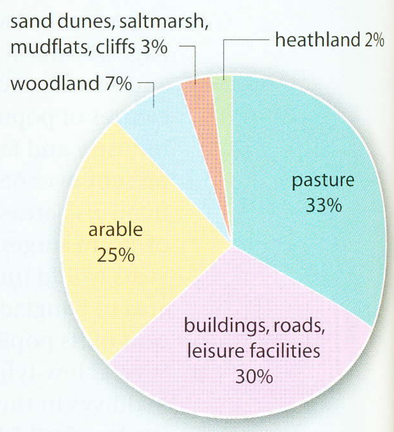
Coastal management in the UK

A The need for management

Although Britain's coasts are rarely affected by extreme events such as the Indian Ocean tsunami (Places 4), storm surges as in the Bay of Bengal (Places 19) or the tropical storms in Central America and Florida (Places 31, page 238), large stretches are under threat from one or more sources (Figure 6.60). Much of Britain's coastline is used for human activity and although in some more remote places there is often a demand from only one or two main land users, in many others there is competition for, and conflict over, land use (Figure 6.61). Combining the threats posed by:

- natural events such as flooding and erosion, and
- human demands that include settlement, economic activities and recreational use

there is a continuing need for a national, sustainable management plan. Such a plan has to consider on the one hand the rapidly increasing costs of providing new defences and maintaining both new and existing defences, and on the other hand the need to protect people and property.



- 23% of the UK lies within 10 km of the coast.
- 17.2 million people live within this coastal zone.
- 35% of UK manufacturing and electricity production is close to the coast.
- Most of the coastline is used for recreational purposes, especially walking.
- Coasts attract larger number of specialist groups (ornithologists, geologists, school parties).

Figure 6.61 Coastal land use

Figure 6.60 Threats to Britain's coasts

Threat	Examples
Increased risk of flooding	
rising sea-level linked to global warming	estuaries, south-east England
higher high tides	Thames estuary
risk of increased number of storm surges	southern North Sea
Increased risk of erosion	
larger waves (generating more energy)	western Britain
human activity (use of footpaths, building on cliff-tops)	Yorkshire, East Anglia
Overuse and/or misuse	
settlements and economic development	estuaries
leisure and tourism (caravan and car parks, golf courses)	close to large urban areas

Who is responsible for coastal management?

The Department for Environment, Food and Rural Affairs (DEFRA) has overall responsibility for coastal defences in England, although the Environment Agency has powers to reduce flooding in tidal waters. In order to protect the coast, DEFRA has to produce a **shoreline management plan (SMP)**. To do this, it is necessary to understand coastal processes in any given stretch of coastline. It would be impossible to achieve this for the whole British coastline, so it has been divided into a number of separate units referred to as 'coastal cells' (Figure 6.62); there are eleven for England and Wales. The location and size of each of these cells is defined so that coastal processes within each individual cell are totally self-contained, and changes

Figure 6.62 Coastal cells around the coasts of England and Wales

taking place within that cell do not significantly affect the coastline of adjacent cells.

Two basic principles in SMP production are that:

- natural processes should not be interfered with unless it is necessary to protect life or property
- all schemes must be economically viable and undergo a cost–benefit analysis to ensure that they make good use of public money.

What are the options?

A shoreline management plan has, for each coastal cell, four defence options:

- Do nothing, other than monitor and review.
- Hold the existing defence line by maintaining or changing the standard of protection.
- Advance the existing defence line.
- Retreat the existing defence line by realigning the coast, i.e. **managed retreat**.

SMPs are developed by groups of people that include planners, engineers, geomorphologists and others with special local knowledge.

How has the coast been protected in the past?

Traditional sea defences, now referred to as **hard defences** (Figure 6.63), involved the construction of distinctive features:

- Concrete sea walls were often built, in the 19th century, at holiday resorts. They created more space for promenades and leisure amenities and protected hotels from storm waves.
- Groynes, usually of wood, were constructed at right-angles to the coastline. They helped to reduce the force of the waves and trapped material being moved along the coast by longshore drift (Figure 6.23). This helped to widen beaches and to reduce the removal of beach material.
- Concrete breakwaters protected small harbours from strong wave action.

More recently it has been realised that:

- concrete sea walls absorb, rather than reflect, wave energy and so now they are often curved at the top (bullnose) to divert waves
- groynes, by trapping sand, cause the loss of replacement material further along the coast, increasing the problem elsewhere.

More recent hard defences include:

- wooden slatted revetments, constructed parallel to the coast, which dissipate the force of waves
- concrete blocks, known as rip-rap, which also absorb the power of waves
- offshore breakwaters and reefs which reduce wave energy but still allow some longshore drift (Figure 6.70).

Most of the earlier schemes, apart from being unsustainable, were not environmentally friendly, either visually or in relation to local habitats (ecosystems), and were expensive to build and to maintain. Wherever possible they are being replaced or supplemented by **soft defences**. Soft defences include:

- the use of beach replenishment at the base of cliffs and sea walls where lost sand and shingle is replaced (although such replacement is expensive and needs to be maintained for long periods)
- cliff stabilisation, either by inserting pipes to remove excess water or by planting vegetation to reduce mass movement.

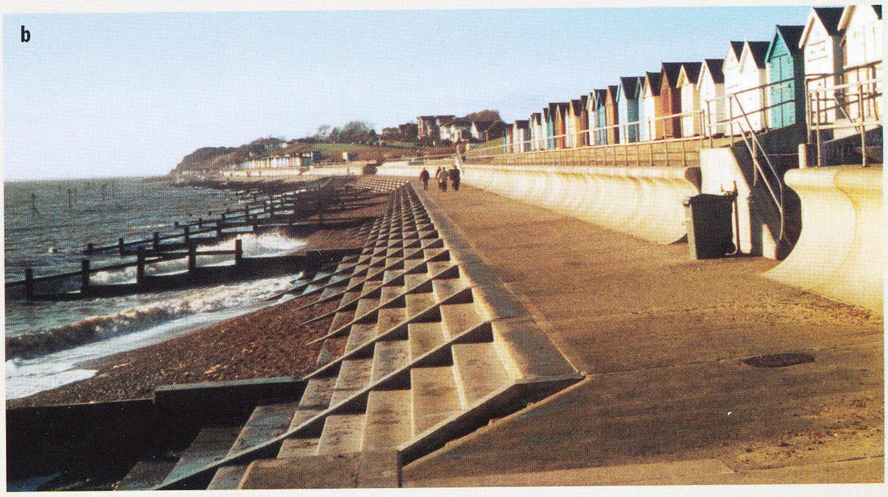


Figure 6.63

Coastal defences
a Rip-rap
b Groynes and a bullnose sea wall
c Revetments

B Coastal management schemes in East Anglia

Erosion has always been a major problem along much of the coast of Norfolk (Figure 6.64) while further south flooding is the major hazard in Suffolk and Essex (Places 19). Present-day shoreline management plans (SMPs, page 170) must aim to strike the seemingly impossible balance between protecting the coastline at a viable cost and minimising the disruption of natural processes and nearby defence schemes. In north Norfolk, hard engineering solutions are now less in favour than softer options. In Suffolk and Essex controversy has arisen over SMP proposals to re-align parts of the coastline in a 'managed retreat'. This case study considers several specific places and their problems.

Aldeburgh and East Lane Point, Suffolk

Aldeburgh, in Suffolk, at the northern end of Orford Ness (Figures 6.28 and 6.65), was protected by a sea wall and timber groynes to reduce the loss of beach material. Six streets to the east of the town have been lost to the sea since the 16th century, and the only visible remains of the former village of Slaughden, 1 km to the south, are a Martello tower and what is now a marina.

Following the partial failure of the sea wall in 1988, Anglian Water and the National Rivers Authority (now the Environment Agency) devised a £4.9 million plan to provide sea defences that would also protect the tidal freshwater areas of the River Alde immediately to the west of the town. The existing sea wall was extended at its base in the section considered most threatened. Several 10-tonne rock blocks were placed in front of the sea wall to absorb the wave energy; 200 m of wall originally protecting the northern end of Orford Ness was demolished, and a rock armour bank put in its place. A total of 24 new groynes were built, stretching south beyond the Martello tower (Figure 6.66), and 75 000 m^3 of shingle were deposited as beach replenishment. More rocks were brought in to make a 400 m bank between the existing sea wall to the south and the shingle bank. The scheme was completed in 1992. It took into account the risk that storm damage could cause to an important natural area.

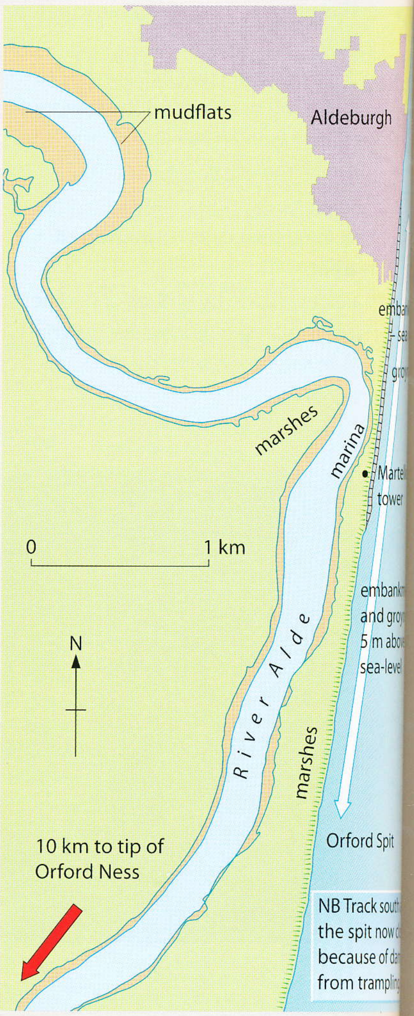
In 2004 there were increasing fears that Aldeburgh could become an island and that the Suffolk coastline as far south as Felixstowe could change if the sea broke through obsolete defences during the next winter's storms. At greatest immediate risk is East Lane Point, near Bawdsey, south of Aldeburgh (Figure 6.67). Much of the land behind the Point is considered by the government to be a 'non-viable flood defence area' as it does not reach the requisite number of points required for funding under the new DEFRA scoring system mainly because the area is sparsely populated. A spokesperson for DEFRA stated that 'there will never be sufficient money available for every coastal defence need and so priority must go to protecting people and their property'.

Figure 6.64

Erosion near Overstrand, Norfolk

Figure 6.65

Aldeburgh's sea defences



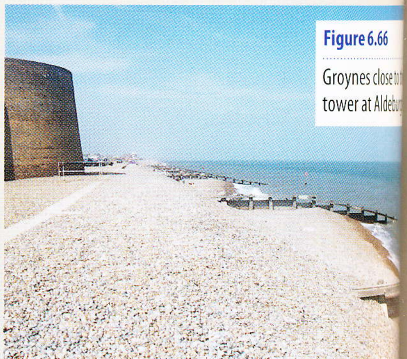


Figure 6.66

Groynes close to tower at Aldeburgh

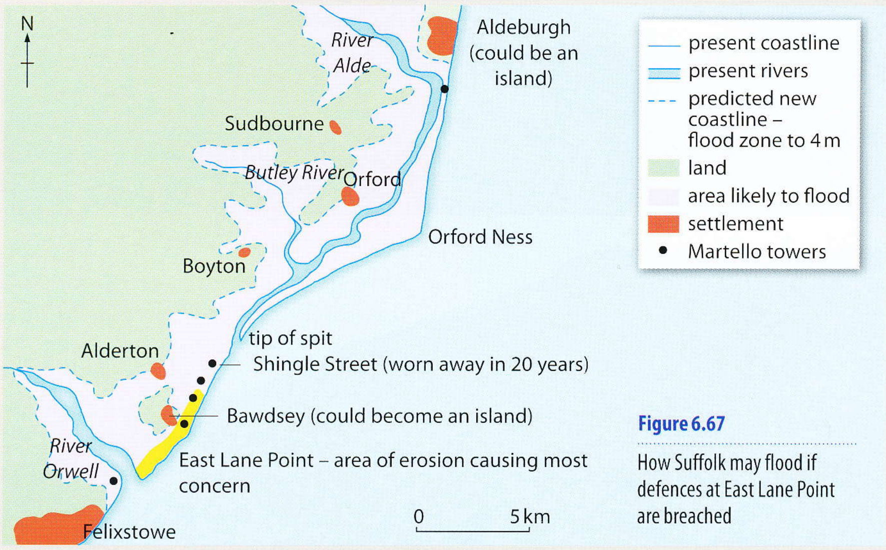


Figure 6.67

How Suffolk may flood if defences at East Lane Point are breached

Sea Palling, Norfolk

Much of the Norfolk coastline from Cromer southwards to Great Yarmouth is protected by expensive coastal defences. At Sea Palling the beach is backed by sand dunes which, in earlier times, helped provide a natural defence. Behind these are 6000 ha of land used for settlement, farming and (this area being part of the Norfolk Broads) tourism and wildlife. In 1953 a storm surge (Places 19) broke through the coastal defences, flooding large areas and, at Sea Palling itself, washing away houses and drowning seven people.

Following the flood, a sea wall was constructed in front of the dunes (Figure 6.68) and there was some replenishment of beach material. However, by the 1990s the beach in front of the sea wall had narrowed due to the removal of material southwards by longshore drift during times of northerly and easterly gales, a process that led to an increase in wave energy. Following the severe winter storms of 1991, rip-rap was positioned against the sea wall as a temporary measure.

In 1992 a beach management strategy was introduced with the conditions that it would not significantly affect adjacent coastal areas, it would have minimal environmental impacts and it would be cost-effective. Over 150 000 tonnes of rock were placed in front of the wall to prevent further undermining and 1.4 million m^3 of replenishment sand were added in front of the rock. The major part of the scheme was the construction of four offshore reefs designed to reduce incoming wave energy and to protect the beach while at the same time allowing some longshore drift so as not to deplete the supply of sand to beaches further along the coast (Figure 6.69). These reefs were completed in 1995 but almost immediately presented a problem that had not been predicted: sand began to accumulate in the sheltered lee of the reefs, leading to the formation of tombolos (page 155 and Figure 6.70) which in turn interrupted the process of longshore drift. To try to overcome this problem, the next five reefs to be built were shorter (to reduce areas of shelter behind them), lower (to allow more overtopping waves) and closer together (to prevent erosion in the gaps). A further five are planned 3 km to the south.

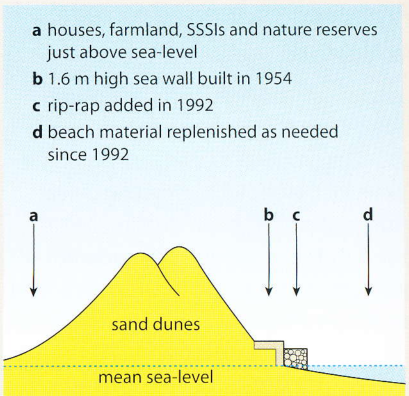


Figure 6.68
Sea defences 1954–92

Figure 6.69
Artificial reefs at Sea Palling

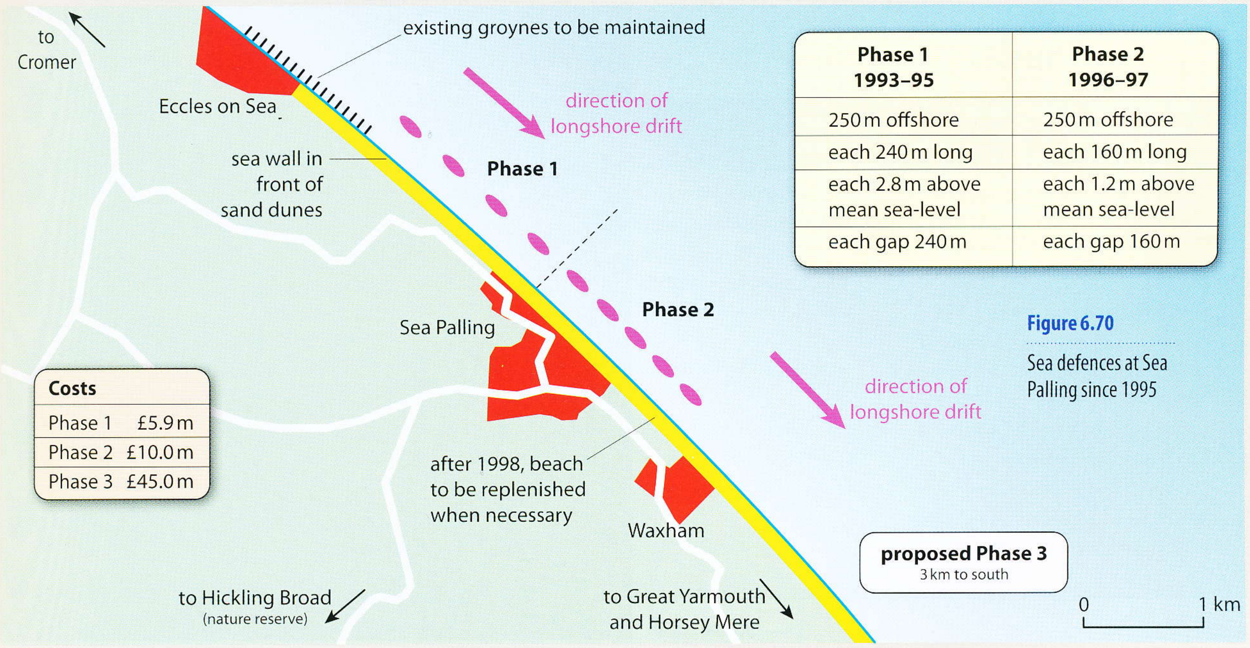


Figure 6.70
Sea defences at Sea Palling since 1995

Coastal management in the UK

Proposed 'managed retreat' in Norfolk

Controversial plans by Natural England to flood parts of Norfolk emerged in early 2008. The proposal, if accepted, would see Britain for the first time admitting defeat in the battle to maintain all of its coastal defences. Experts doubt if the present defences can cope with the rising sea-level resulting from global warming and the sinking of south-east England, and the plan to 'realign the coast' in a 'managed retreat' is the less expensive and more practical option. This would involve building a new sea wall further back from the present coastline, at a cost of a fraction of that of trying to maintain the existing defences. The Environment Agency, in response, stated that it is committed to 'holding the present line' of sea defences for the next 50 years, although it admitted that that option was becoming increasingly difficult and more expensive, while DEFRA said it was committed to the sustainable protection of people and property here in Norfolk and elsewhere.

Should the scheme go ahead, it would mean allowing the sea, over a period of time, to breach 25 km of the north Norfolk coast between Eccles on Sea and Winterton-on-Sea. In time the sea would create an area of saltwater lake and salt-marsh covering 65 km^2 (Figure 6.71). Over the next 50 years or so this lake would eliminate six villages: four on the coast (Eccles on Sea, Sea Palling, Waxham and Horsey) and two inland (Hickling and Potter Heigham). The lake would also inundate about 600 houses, many hectares of good-quality arable farmland and five fresh-water lakes that currently form part of the Norfolk Broads, including the tourist area of Hickling Broad (Figure 6.72) and the rare fauna and flora of Horsey Mere.

Opponents to the plan claim that it would mean in the short term making their properties unsaleable and, in the long term, relocating hundreds of people and paying them compensation. A millennium of history would vanish under the waves and with it villages like Hickling, which is mentioned in the Domesday Book, and Sea Palling, which the sea failed to destroy in the 1953 flood. Churches and other buildings listed by English Heritage would also be lost.

Proposers suggest that the plan is more economically sustainable than present policies and that a newly created saltmarsh could be used by farmers for cattle grazing, it could act as a buffer zone helping to dissipate wave energy, it would provide storage for excess water during times of storm surges, and provide a welcome haven for wildlife when little of Britain's original salt-marsh ecosystem remains (page 175). They also claim that experiments have shown that a sea wall can costs £5000 a metre to build and maintain, whereas an inland retreat of 80 m, allowing a saltmarsh to form a buffer against tides and waves, only costs £400 a metre to build and maintain.

Natural England claim that the 'surrender' option is only one of several possibilities, but it considers the issue to be so important that it is time to open discussions and to encourage debate. No final decision has been made about the plan.

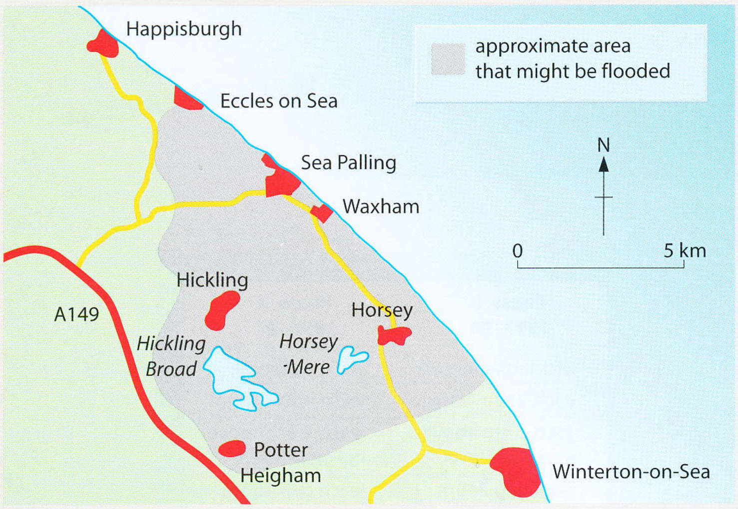


Figure 6.71
Proposed area of flooding on the north Norfolk coast

Figure 6.72
Hickling Broad

Sand dunes and saltmarsh

Large tracts of the coast of East Anglia consist either of sand dunes (pages 157 and 290) or saltmarsh (pages 158 and 291). Both are fragile ecosystems that are under threat and receive less attention and management than they deserve and need.

As we have seen, sand dunes fringe much of the Norfolk coast, either backing sandy beaches (Figure 11.10) or stabilising spits such as that at Blakeney Point. Sand dunes are under threat from:

- the rising sea-level which attacks the embryo and foredunes (Figure 6.32), narrowing beaches and thus depriving them of their source material
- excavation for sand by construction companies
- people either walking along paths within them, especially where they form part of a coastal footpath, or playing (or sheltering from the wind) in blow-outs.

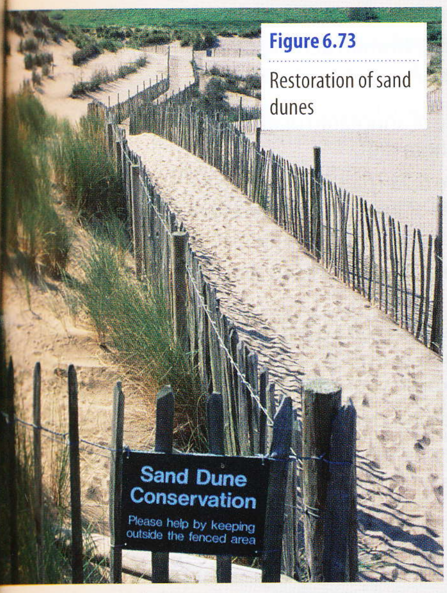


Figure 6.73

Restoration of sand dunes

Where human influence is limited, the ecosystem can repair itself, but where it is severe the damage may be irreversible. One solution is to fence off selected areas to allow time for recovery (Figure 6.73).

Saltmarsh develops behind coastal spits as at Blakeney Point (Figure 11.14) but is most extensive in the river estuaries of Suffolk and Essex (Figure 11.13). Saltmarsh has been under threat since Saxon times when parts were drained around the present-day Norfolk Broads. Essex was said to have 30 000 ha of saltmarsh in 1600, yet 400 years later only 2500 ha remain. This remaining saltmarsh supports around two million wildfowl and wading birds in winter and is a habitat for rare species of plants, birds and insects. Currently another 100 ha/yr of saltmarsh is being lost across England alone due to the rising sea-level and human activity. However, there are several plans in Essex to recreate more saltmarsh to provide alternative habitats for wildlife, to act as a buffer zone against the larger waves, and as storage for surplus water during storm surges or as the mean high-tide level rises. The most ambitious and expensive project (£12 million) is being undertaken by the RSPB, which intends to break the sea walls (Figure 6.74) around Wallasea Island, near Southend, changing 730 ha of farmland back into a mosaic of saltmarsh, creeks and mudflats – although these will only be covered by 50 cm of water at high tide.

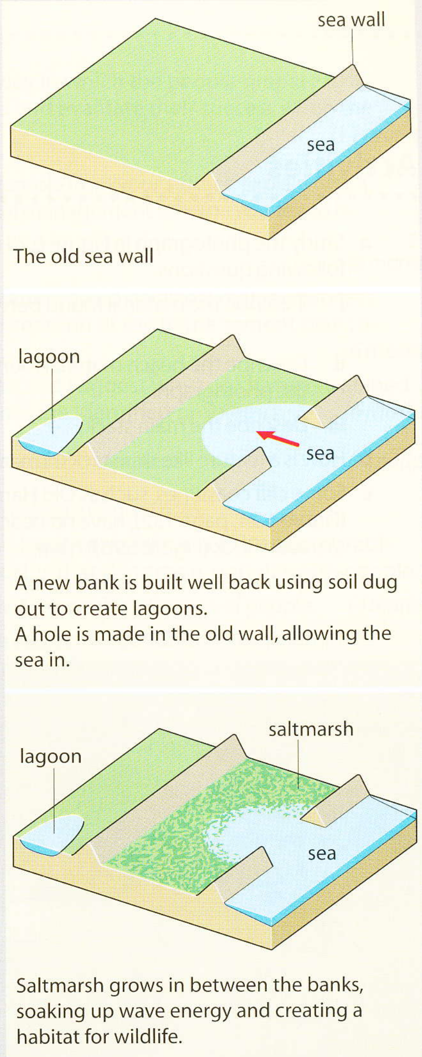


Figure 6.74

Breaching of an old sea wall to create a saltmarsh

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Sea-level changes (Antrim coast): www.ehsni.gov.uk/natural/earth/geology.shtml

Questions & Activities

Activities

1 a Study the photograph in Figure 6.75 and answer the following questions.

i Describe the material found between the two stacks. *(3 marks)*

ii Describe the beach material found in the foreground of the photograph. *(3 marks)*

iii Describe the main stack. *(4 marks)*

b How is a feature like this stack formed? *(6 marks)*

c Some cliff coastlines, such as Old Harry Rock near Swanage (Figure 6.21, page 152), have no beach while others, such as Marsden Rock (Figure 6.75), have.

Suggest a reason for this difference. *(4 marks)*

Figure 6.75 Marsden Rock

d Marine erosion is concentrated at the base of a cliff.

Suggest two ways in which the rest of the cliff is eroded. *(5 marks)*

2 a Making good use of diagrams, describe **two** landforms that may be found on a beach. *(6 marks)*

b Why are large stones and boulders found at the **back** of a beach? *(4 marks)*

c Making good use of diagrams, explain how sand and other material is moved along a beach by the action of waves. *(5 marks)*

d Why are shingle beaches steeper, on average, than sandy beaches? *(5 marks)*

e How and why may human activity change this marine transport process? *(5 marks)*

3 a Making good use of annotated diagrams, explain the process of longshore drift. *(5 marks)*

b i Study Figure 6.23 (page 153). Suggest, with reasons, the direction of longshore drift on this coastline. *(3 marks)*

ii Why were the sea defences put along this shoreline? *(6 marks)*

iii What effect would you expect there to be further down the coast as a result of the building of these sea defences? Explain your answer. *(6 marks)*

c Choose **one** landform created by marine deposition.

Describe the size and shape of the landform and suggest how marine deposition has helped to create it. *(5 marks)*

Exam practice: basic structured questions

4 a What is meant by each of the following terms used in relation to the effects of waves on a coastline:

i abrasion (sometimes called corrasion)

ii attrition

iii hydraulic action? *(6 marks)*

b Explain how the processes identified in **a** cause a cliff to change its shape. *(6 marks)*

c Study Figure 6.17 (page 150).

i Describe and suggest reasons for the shape of the cliff shown in the photograph. *(6 marks)*

ii Although there are houses on top of this cliff it has been decided not to attempt to protect this coastline. Suggest **two** reasons for this decision. *(7 marks)*

5 a Explain the terms 'eustatic' and 'isostatic' used when studying sea-level change. *(4 marks)*

b Explain how:

i an ice age

ii one other mechanism could cause sea-level change. *(7 marks)*

c Choose **one** landform that has been created by or significantly changed by a fall in sea-level.

Describe the landform and explain the role of sea-level change in its formation. *(7 marks)*

d Choose **one** landform that has been created or changed significantly by a rise in sea-level. Describe the landform and explain the role of sea-level change in its formation. *(7 marks)*

6 a Study Figure 6.25 on page 154.

Why has saltmarsh formed at H? *(6 marks)*

b Explain the meaning of:

i dominant wind

ii embryo dune. *(4 marks)*

c Explain how sand dunes go through a series of stages from the appearance of berms to the formation of grey (or mature) dunes. *(15 marks)*

Exam practice: structured questions

7 a On a coastline with cliffs, deposition can cause the shape of the coastline to change. Suggest where there will be deposition on such a coastline and the reasons for deposition there. *(10 marks)*

b i Study Figure 6.75. Draw an annotated diagram to identify the main features of the landform in the photograph. *(5 marks)*

ii With reference to evidence from the photograph, explain how marine processes may have created this landform *(10 marks)*

8 a With reference to one or more examples of cliff coastlines, explain how marine and sub-aerial processes have combined to shape the cliffs. *(12 marks)*

b i Identify and describe **two** ways in which people can manage the erosion of a cliff foot. *(6 marks)*

ii Evaluate the success of one of these management strategies. *(7 marks)*

9 a Choose two of the following micro-morphological features of a beach: berm; beach cusps; ridge and runnels; longshore bar.

For each feature that you have chosen:

i Making use of annotated diagrams, describe its shape and location on a beach. *(6 marks)*

ii Explain how it is formed. *(10 marks)*

b What effect do storm waves have on a beach profile? *(9 marks)*

c Describe **one** method you could use to survey the profile of a beach. *(5 marks)*

10 a Using an annotated diagram only, explain the process by which beach material is moved along the coastline. *(5 marks)*

b Choose **one** landform that is created when beach material is deposited. Name and describe the landform.

Explain the processes by which the landform is created. *(10 marks)*

c Why do people try to reduce the movement of beach material on some coastlines? Suggest and explain **two** methods for reducing such movement. *(10 marks)*

11 a Using your own case studies, choose **two** examples of hazards that occur on marine coasts. For each hazard:

i Identify the hazard and its location. *(2 marks)*

ii Explain how the action of the sea leads to danger on the coast. *(12 marks)*

b Describe **one** way in which the people prepare to face marine hazards and evaluate their success when the danger occurs *(11 marks)*

12 a Using an example from your studies, explain why a particular coastal management scheme was felt to be necessary. *(6 marks)*

b Describe the planning and decision-making process involved in the creation of the management plan for the area. *(6 marks)*

c Outline the plan and suggest why the changes outlined should overcome the identified problem/s. *(6 marks)*

d Evaluate the success of the project. *(7 marks)*

13 Study the sand dune area in Figure 6.76.

a i Identify and locate **one** feature of the photograph which indicates that this area is popular with people.

Explain how it shows the presence of people. *(4 marks)*

ii Explain **one** piece of evidence from the photograph which shows that this popularity is causing damage to the environment. *(4 marks)*

b i Suggest **one** possible effect of the environmental damage caused in this area. *(7 marks)*

ii Explain how conservation work could overcome the damage done to this sand dune belt. *(10 marks)*

Figure 6.76
Damaged sand dunes at Gower, Wales

Exam practice: essays

14 'The interface between the sea and the land is an area of conflict in nature and for people.' Using examples, explain this statement. *(25 marks)*

15 Discuss possible causes of future changes in sea-level and explain how these changes might produce both short-term and long-term effects on the physical and human environment. *(25 marks)*

16 Choose **one** system of coastal classification. Describe and explain the principles on which it is based and, making use of examples, describe some of the problems of applying your classification system to cover all coastal areas. *(25 marks)*

17 Discuss the arguments for and against the managed retreat of parts of the coastline in the UK. Evaluate the strength of these arguments as they apply to **one or more** areas that you have studied. *(25 marks)*

18 'Coastal sand dunes form some of the most important defences against the sea, so every effort should be made to conserve and strengthen our dune systems.'

Evaluate this statement. *(25 marks)*