Coastal Geomorphology of Great Britain

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Chapter 5

Beaches, spits, barriers and dunes – an introduction

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INTRODUCTION

The coasts of Britain support a wide variety of beach types and materials (Table 5.1). Some are sandy, but many include coarser material (granules, gravels, cobbles and occasionally boulders), often forming a steep upper beach behind a flat, sandy foreshore exposed at low tide, such as on the eastern shores of Dungeness, Kent (see GCR site report in Chapter 6) and at Ynyslas in Wales (Chapter 8). Others, such as Chesil Beach, Dorset and Spey Bay in Moray (Chapter 6), consist entirely of well-rounded beach gravel, in Britain often called 'shingle'. Shelly deposits, with the shells either intact or broken, or comminuted to shell grit and calcareous sand, also occur on British beaches, particularly on the Atlantic coasts, where extensive dune systems and the Scottish machair have formed from sediment derived from calcareous beaches. Chapter 7 of the present volume is devoted to sandy beach and dune sites, and Chapter 9 to machair beaches and dunes.

There have been beaches ever since the oceans first formed and coasts began to take shape along the margins of the land. Beach deposits are found in sedimentary formations of various geological ages, as in the Tertiary sediments of the London and Hampshire Basins. During the Quaternary Period, the 'emerged' or 'raised' beaches around Britain formed when the sea level was higher relative to the land, and have emerged as the result of land uplift, or a lowering of sea level, or some combination of the two processes. Beaches that formed on coastlines during low sea-level stages are now submerged on the sea floor, but few traces of these persist because of wave reworking or concealment by later sea-floor sediments. The present-day existing beaches began to form on the British coast about 6500 years BP, when the Holocene marine transgression (also known as the 'Flandrian' or 'Late Quaternary' marine transgression) brought the sea to a level where wave action shaped the present coastline, cutting back some parts and depositing sediment on others.

Beaches are also found along cliffed coasts – except where the cliffs plunge into deep water, or where the shore is too rocky and rugged to have retained a beach – but most occur on low-lying coasts, except where wave energy is weak and the shore has become marshy and muddy. Beaches can be regarded as occupying coastal compartments or sediment cells delimited by headlands that prevent longshore sediment movement where they extend into deep water (e.g. Portland Bill), and further restricted and subdivided by lesser promontories (e.g. Hengistbury Head) past which sand and gravel drift, particularly during stormy periods (Bray *et al.*, 1995).

Beaches are characterized by accumulation of sediments that extend from the point at which wave-accumulated sediments first apear (the lower limit of wave activity) to the upper limit of wave activity. Operationally, the intertidal zone co-incides with the visible beach, but depositional beach forms extend below this level. The intertidal zone is often characterized by a series of ridges and troughs of sediment culminating in a beach face affected by the uprush/swash and backwash of waves (see Figures 5.1 and 5.2).

Beaches may protect the land that lies behind

Table 5.1 Classification of beach structures based on their plan form (after Pethick, 1984); outline definitions are provided in the glossary of the present volume.

Rhythmic beach morphology	Cusps
	Crescentic bars
	Cell circulation topography
Shoreline beaches	Pocket beaches – swash-aligned (Davies, 1980)
	Open beaches – drift-aligned (Davies, 1980)
	Zeta-form or fish-hook beaches (Silvester, 1960; Swift, 1976)
	Combined swash and drift alignment
Detached beaches	Spits
	Cuspate forelands, nesses and tombolos
	Barrier beaches and islands

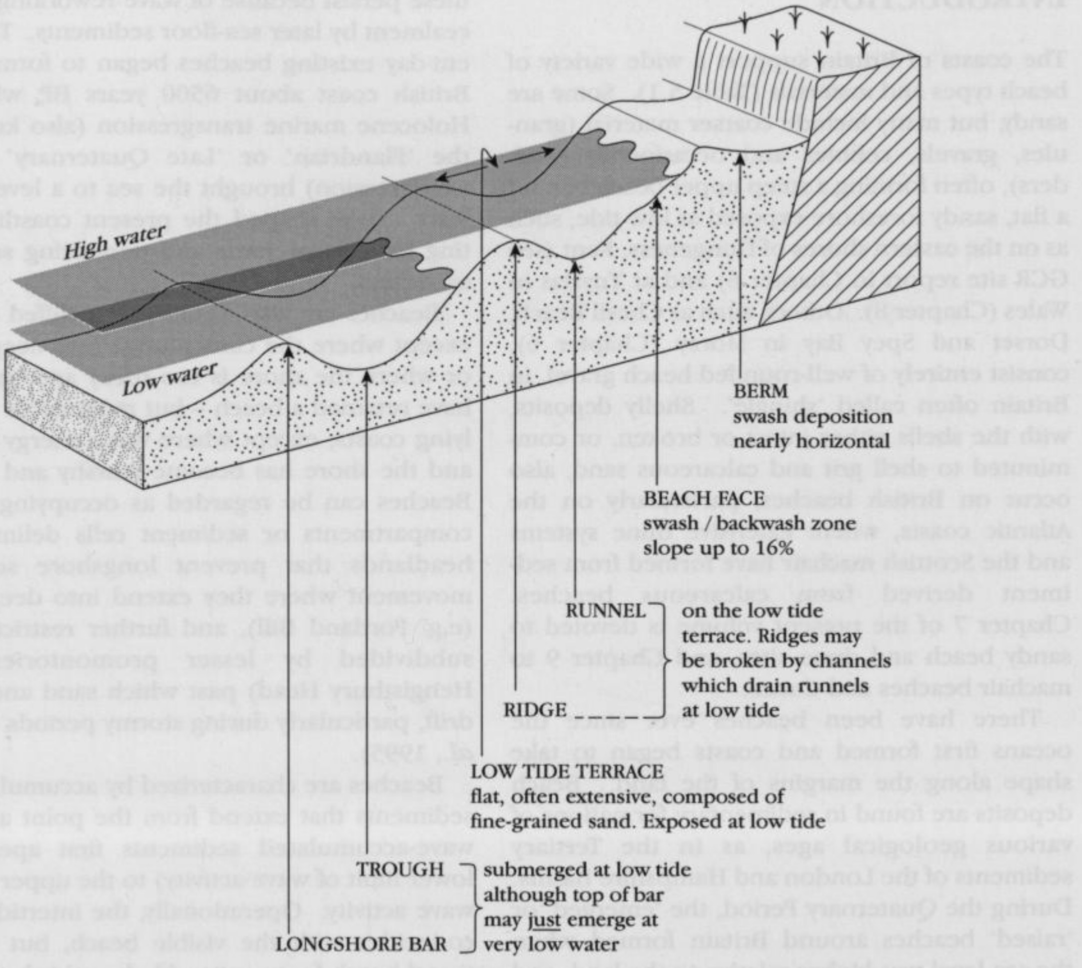


Figure 5.1 Beach morphology. Synonyms: The term 'ridge-and-runnel' is sometimes used for 'bar and trough'; 'ball and low' is the old name for 'bar and trough'; 'bar', 'offshore bar' etc., are old names for barrier islands, not to be confused with *longshore bar*; 'swash bar' is the old name for 'berm'; 'high-tide beach' is used for 'beach face'; 'low-tide beach' is used for the seaward edge of low-tide terrace. See also Figure 5.2. (After Pethick, 1984, p. 93.)

them from erosion by waves. Gravel (shingle) beaches are permeable, and absorb or reflect much wave energy, but where the sand supply has been sufficient to form wide sandy beaches with a very low transverse gradient, wave energy is dissipated (Figures 5.3 and 5.4). Many gravel beaches are on parts of the coast that receive high wave energy from occasional storm waves, but wave energy is also high on sandy beaches exposed to Atlantic swell and storm waves. The distribution of gravel (shingle) beaches and sandy beaches depends on the nature and sources of available beach material and the patterns of waves and currents that have delivered it to the coast (Figure 5.4).

PROVENANCE OF BEACH SEDIMENTS

The main sources of beach material are cliffs and rocky shores that are undergoing erosion, rivers that carry sediment down to the coast, particularly during floods, and the sea floor, although the relative importance of each source varies geographically (Figure 5.5). Some beach sediments are similar to those in rock formations exposed in the nearby cliffs and shore outcrops from which they have been derived. Beaches occupying coves on the south-west coast of England have a mineralogical composition indicating that they have been derived from nearby cliffs and coastal slopes (Stuart and Simpson,

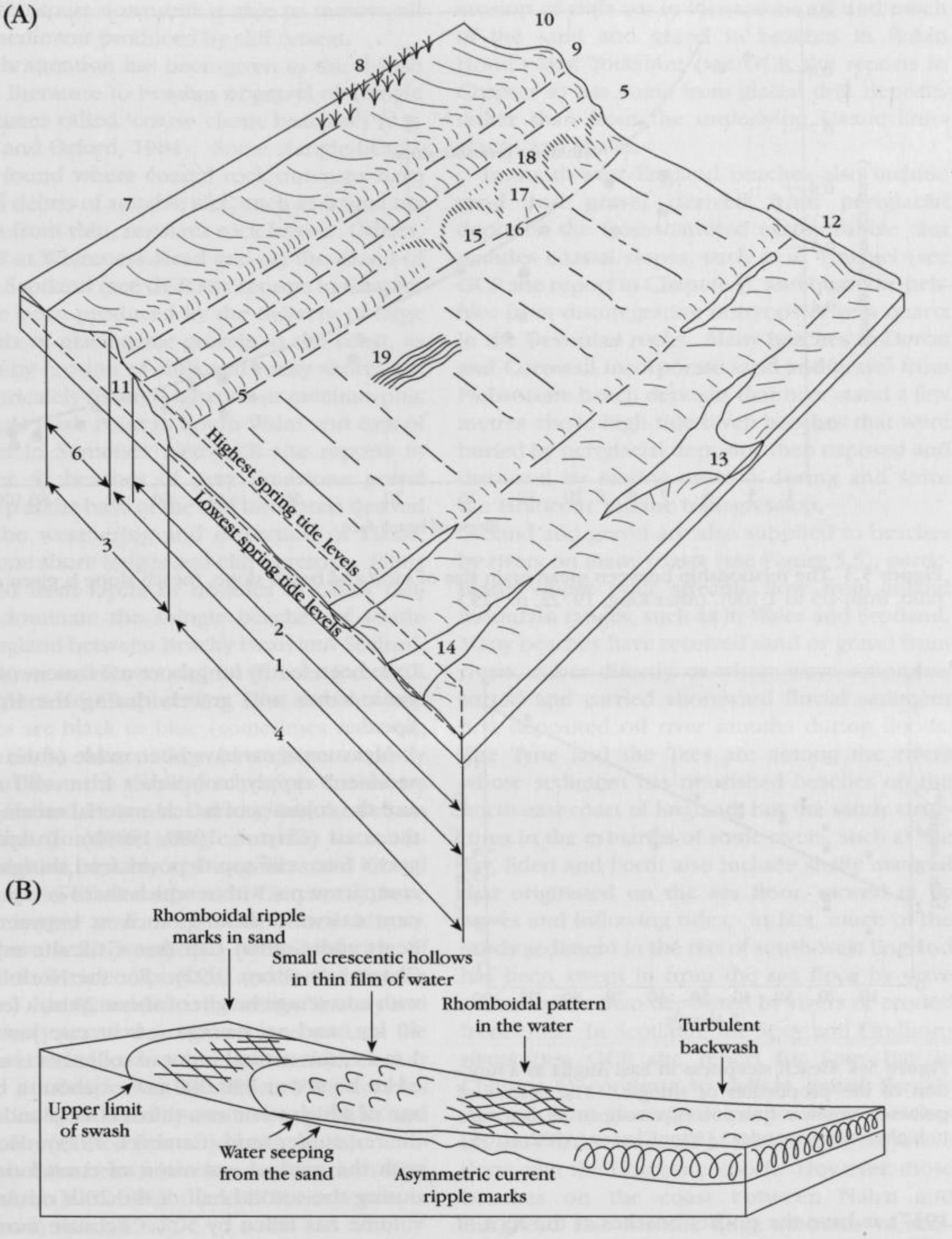


Figure 5.2 (A) Beach terminology: (1) beach, (2) shore, (3) upper beach (cordon littoral), (4) foreshore, (5) break of slope between upper beach and foreshore, (6) inner side of beach ridge, (7) lagoon, (8) marsh, (9) berms, (10) storm beach, (11) coastline, (12) ridges and runnels on the foreshore, (13) channel on foreshore, (14) pool in runnel of foreshore, (15) beach cusp, (16) apex of cusp, (17) bay of cusp, (18) horn of cusp, (19) ripple marks. (B) Formation of rhomboidal ripple marks. (After Fairbridge, 1968, p. 67.)

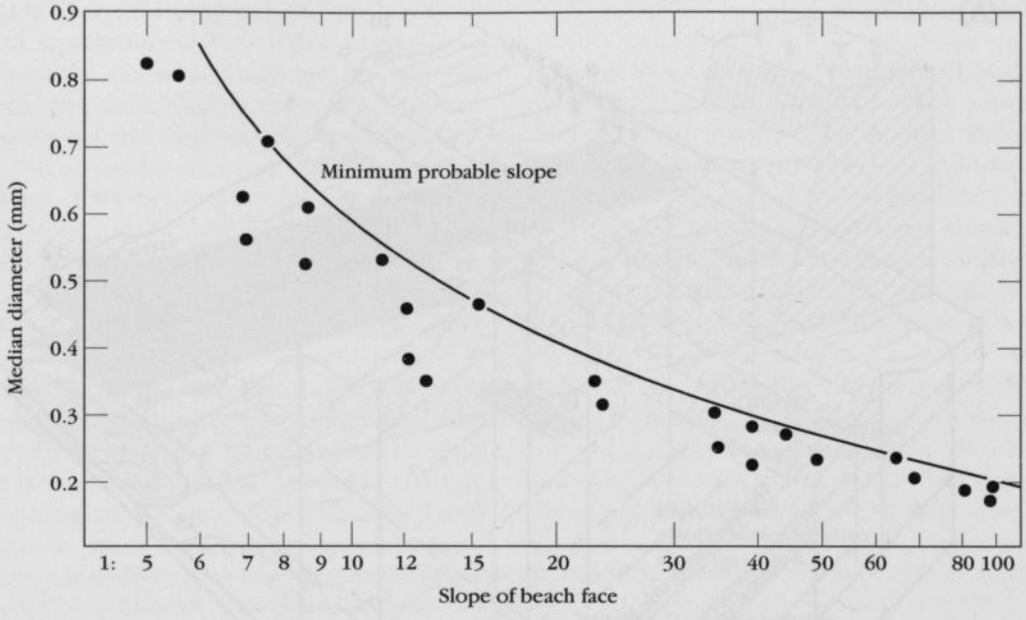


Figure 5.3 The relationship between mean grain size of sand and beach slope, (beach slope is given as a ratio, from 1:5 to 1:100). (After King, 1972a, p. 325.)

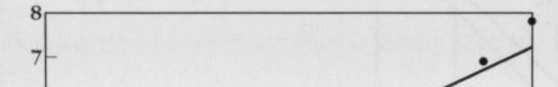


Figure 5.4 Beach steepness in East Anglia as a function of the proportion of shingle. The scatter of points is largely a function of variations in exposure to higher wave energies. (After Clayton, 1992, p. 64.)

1937) as have the pocket beaches at the foot of cliffs in Foula, Shetland. By contrast, many beaches on the south and east coasts of England contain quartz sand and flint gravel that have been either carried many kilometres along the coast by longshore drift, or brought onshore as sea levels rose. On the Moray coastline of Scotland, the present and emerged beaches of the Spey and Culbin (see GCR site reports in Chapters 6 and 11, respectively) beach system have been fed by longshore movement of glaciogenic sands and gravels during the Holocene Epoch.

Measurements have been made of the rates of sediment supply to beaches from cliff erosion and the volumes of beach material moving along the coast (Clayton, 1980, 1989b). In Lyme Bay, gravel from cliff-top deposits feed shingle beach compartments within which there is a predominant eastward drifting, such as between Lyme Regis and Golden Cap (see GCR site report in Chapter 4) (Bray, 1992). For the Norfolk cliffs, with an average height of about 20 m, a length of 40 km, and an average retreat rate just below 1 m a^{-1}, the natural input of sediment is estimated to be about 750 000 $m^3 a^{-1}$ about a century ago of which some two-thirds is sand and gravel, the remainder mud (Cambers, 1973). However, with the gradual extension of coastal defences during the second half of the 20th century, this volume has fallen by 50%. Because more than half of the sand and gravel leaves the cliff system via the beach and is transported by longshore drift to Great Yarmouth, some 40 km farther down the coast, the reduction in output has resulted in reduced beach volumes downdrift, leading to erosion there. The persistence of cliffs along the south and east coasts of Britain where the rocks are weaker indicates that in general a combination of offshore removal and longshore transport downdrift is able to remove all of the sediment produced by cliff retreat.

Much attention has been given in the British coastal literature to beaches of gravel or shingle (sometimes called 'coarse clastic beaches') (e.g. Carter and Orford, 1984). Some shingle beaches are found where coastal rock outcrops have yielded debris of suitable size, such as fragments broken from thin, resistant rock layers. Others, such as at Whiteness Head and on the island of Jura in Scotland (see GCR site reports in Chapter 6) have been produced by the delivery of large amounts of glaciogenic gravels to the coast, as well as by erosion of cliffs and rocky shores cut into intricately fissured igneous or metamorphic rocks. At Nash Point in South Wales and east of Watchet in Somerset (see GCR site reports in Chapter 4) beaches of grey limestone gravel piled up at the base of the cliff have been derived from the weathering and dissection of Liassic limestone shore ledges and cliff outcrops. Flints released from layers or nodules in Chalk outcrops dominate the shingle beaches of south-east England between Beachy Head and Seaford, Kingsdown and Dover and on Thanet (see GCR site reports in Chapter 4). Flint cobbles and pebbles are black or blue (sometimes retaining white rinds) where they have been recently released from the Chalk (such as on the shores below Ballard Down in Dorset), but the brown flints that dominate shingle beaches in south-east England, notably at Dungeness and Chesil Beach (see GCR site reports in Chapter 6), have had a longer and more complicated history. They have been weathered (with oxidation of ferrous to ferric compounds, and some leaching of silica) during residence in various Tertiary and Quaternary gravel deposits on land and on the sea floor during low sea-level phases before they arrived on the present coastline. Flint cobbles are gradually reduced by attrition to pebbles and sand, comminuted flint sand being a major constituent of the brown beaches on the south-west coast of the Isle of Wight (see GCR site report in Chapter 4) (Bird, 1997).

In much of Great Britain, sand and gravel eroded from offshore deposits or cliffs cut in Pleistocene glacial drift, for example on the Holderness coast, glaciogenic gravels and sand have been supplied to local beaches and drifted south to the spit at Spurn Head (see GCR site report in Chapter 8). Similarly, at Porth Neigwl in north Wales, a beach of sand backed by pebbles and cobbles has been derived from erosion of cliffs cut in Pleistocene till and much of the sand and gravel in beaches in Robin Hood's Bay, Yorkshire (see GCR site reports in Chapter 4) has come from glacial drift deposits rather than from the underlying Liassic limestones and shales.

In south-west England beaches also include sand and gravel derived from periglacial deposits, the frost-shattered earthy rubble that mantles coastal slopes, such as at Tintagel (see GCR site report in Chapter 3), and quartzite pebbles from disintegrating outcrops of vein quartz in the Devonian rocks. Many beaches in Devon and Cornwall incorporate sand and gravel from Pleistocene beach deposits that now stand a few metres above high tide level: beaches that were buried by periglacial deposits, then exposed and dissected by marine erosion during and since the Holocene marine transgression.

Sand and gravel are also supplied to beaches by rivers on many coasts (see Figure 5.5), particularly where swift streams flow from inland mountain ranges, such as in Wales and Scotland. Many beaches have received sand or gravel from rivers, either directly, or where wave action has sorted and carried shoreward fluvial sediment first deposited off river mouths during floods. The Tyne and the Tees are among the rivers whose sediment has nourished beaches on the north-east coast of England, but the sandy structures in the estuaries of some rivers, such as the Tay, Eden and Forth also include shelly material that originated on the sea floor, moved in by waves and inflowing tides. In fact, much of the sandy sediment in the rias of south-west England has been swept in from the sea floor by wave action rather than deposited by rivers or eroded from cliffs. In Scotland, the Spey and Findhorn rivers (see GCR site report for Spey Bay in Chapter 6) continue to deliver gravel (largely derived from glaciogenic deposits) to beaches on the north-east coast of Scotland as they have done over the Holocene Epoch. However, those beaches on the coast between Nairn and Burghead also include large amounts of sediment carried shorewards from once extensive glaciogenic deposits on the sea floor.

On some coasts, beaches have received wind-blown sand from the backshore dunes, such as at Cheswick Sands, north of Holy Island in Northumberland. On the north coast of Cornwall dunes have spilled from Constantine Bay across Trevose Head and supplied sand to the beach in Harlyn Bay (Bird, 1998). A similar process occurs at Balnakeil, in Sutherland (see GCR site report in Chapter 9), where winds drive sand eastwards from Balnakeil Bay over the peninsula of An Fharaid to cascade over a cliff and onto the shore at Flirum.

A great many beaches consist partly or wholly of sediment moved by waves from the sea floor during the Holocene marine transgression, and some still receive sea floor sediment. Sand and gravel that had been deposited by rivers, periglacial solifluction and melting glaciers on the emerged sea floor around Britain in Pleistocene times during low sea-level phases, together with weathered material from sea-floor rock outcrops, were reworked by waves and currents, and carried shoreward by wave action during the Holocene marine transgression to form beaches. This is considered to be the predominant source of sand and gravel on most Scottish beaches. This shoreward drifting is also the likely cause of a proto-gravel barrier at Chesil Beach, and contributed to the flint-dominated shingle beaches at Slapton Ley and Loe Bar near Porthleven in Cornwall (see GCR site reports in Chapter 6), which are now far from any shore sources of flint. The shingle at Slapton was carried onshore from a river terrace or beach gravel deposit on what is now the floor of Start Bay, and Reid and Flett (1907) suggested that the Loe Bar shingle came from Tertiary or Pleistocene deposits of flint gravel on the floor of Mount's Bay. Like many of Britain's shingle beaches these are now relict, no longer receiving gravel from the sea floor.

On some coasts wave action still moves sand and gravel from shallow sea-floor areas onto beaches. Johnson (1919) quoted John Murray's observation that shingle and chalk ballast gravel dumped by ships in water about 20 m deep 11 to 16 km off the north-east coast of England drifted onto the shore between Sunderland and Hartlepool. Various experiments have indicated that where the sea floor is gently sloping, sand can be moved shorewards by long ocean swell from a depth of up to 10 m (King, 1972a), and van Straaten (1959) found that waves moved sand onto beaches from a depth of 9 m. Shoreward drifting of sand and gravel is also indicated where shelly material (or other marine biogenic sediment, such as algae or foraminifera) are constituents of calcareous beaches, such as on the Atlantic coasts of Britain. In the Isles of Scilly (see GCR site report in Chapter 8), where cliffing is limited and sediment inflow from rivers is negligible, Barrow and Flett (1906) realized that the sand and gravel beach deposits had been carried in from the surrounding sea floor by wave action; they are calcareous beach sands with an admixture of quartzose sand from weathered granites on the sea floor. The same is true of many beaches on the Atlantic coasts of Britain, particularly the long curving white sandy beaches shaped by ocean swell on Sanday in Orkney and on the west coast of the Hebrides (see GCR site reports in chapters 8 and 9 respectively).

An extensive area of active coastal sand deposition occurs on the Northumbrian coast in the vicinity of Holy Island (see GCR site report in Chapter 11). Sand has been derived from shoals consisting of glaciofluvial drift deposits (including eskers), reworked and carried shoreward by wave action to form wide sandy beaches, generally backed by dunes that spread seawards as progradation continued. The prograding beach at Tentsmuir (see GCR site report in Chapter 7) in Fife has also been supplied with sand swept in from sea-floor shoals of glacial drift, but (at least in the northern part) also includes fluvial sand deposited off the mouth of the River Tay: the proportions of sand received from recent fluvial deposits and relict glacial deposits have not been determined. In recent decades the sandy shore at Holkham Bay in Norfolk has prograded as the result of inflow of sediment from the sea floor. Tràigh Mhór on the Hebridean island of Barra (see GCR site report for Eoligarry in Chapter 9) is a wide intertidal sandflat, which is a habitat for cockles *Cerastoderma edule*, and the adjacent beaches consist largely of in-washed cockle shells. Shelly beaches are also found on the Essex coast, such as at St Osyth Marsh (see GCR site report in Chapter 10), where there are no other sources of sand or gravel.

It is being recognized increasingly that the sediment sources of many British beaches are no longer as plentiful as they were earlier in the Holocene Epoch. In some cases this is because of recent coastal protection schemes that have reduced the sources of sediment from erosion, but in many others the reasons lie in an overall reduction of sediments sourced both from rivers and the seabed. Over Holocene times, the spread of vegetation resulted in river banks becoming more stabilized and fluvial sediment fluxes fell, a process that has recently been reinforced by artifical bank protection, so that rivers now contribute much less sediment to beaches than in earlier times. Similarly, glaciogenic seabed sediments were plentiful as the sea-level rise slowed at the end of the Holocene transgression about 6500 years ago. Since then a stable or only slowly rising sea level has resulted in the progressive reduction of offshore sediment volumes so that the seabed now supplies to the sediment budget only a small percentage of the previous amounts (Figure 5.5). Because of these reductions in the two major beach sediment sources, sediment fluxes to beaches have also reduced and consequently many beaches are now erosional (Hansom and Angus, 2001; Hansom, 2001). The implications of these reductions are described in the introduction to Chapter 9 since the machair dunelands of the Western Isles have been greatly affected by these changes in sediment economy.

Some beaches have received sediment from waste generated by coastal or hinterland mining and quarrying. In Cornwall the beaches at Par and Pentewan prograded during the past 200 years as the result of deposition of sand and gravel derived from mining waste brought down by rivers draining areas of tin and copper mining, and later china clay quarrying (Everard, 1962), and the beaches at Porthallow and Porthoustock have received in-washed gravel from quarry waste spilling over nearby cliffs (Bird, 1987). Beaches on the Durham coast have been augmented by the dumping of colliery waste (Carter, 1988). Near Workington in Cumbria there is a beach dominated by basic slag deposits from an old steelworks (Empsall, 1989), and beaches near ports may include pebbles from ships' ballast, such as at Charlestown in Cornwall and at Tentsmuir in Fife.

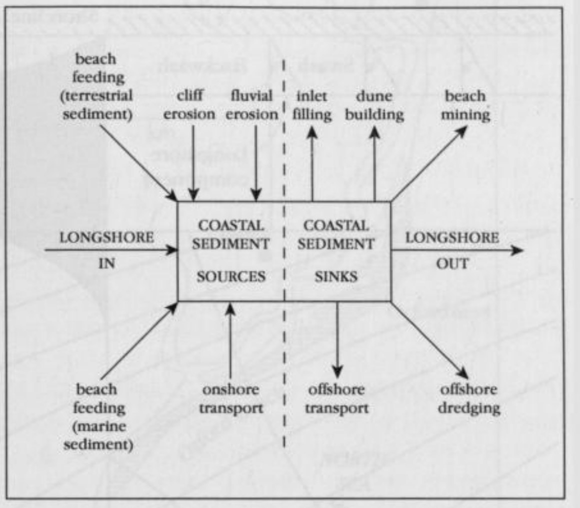


Figure 5.5 Sources and sinks of coastal sediment can be quantified to produce a sediment budget. Note the human element in the coastal sediment budget. (After Davies, 1980.)

COASTAL SEDIMENT MOVEMENTS

Apart from the western coasts, where beaches are exposed to Atlantic Ocean swell and storm waves, much of the British coastline faces narrow or enclosed seas, and variations in fetch (the extent of water across which waves may be generated by winds) and in wind, wave and tide regimes result in coastal sediment fluxes alongshore. Beach sediment moves alongshore when waves arrive at an angle to the beach, producing oblique swash followed by orthogonal backwash. Drifting of sand and gravel along the shore under such conditions can be readily observed from patterns of beach accumulation against groynes, or followed with the use of tracers, when identifiable materials placed on the beach move with the drifting beach material (Jolliffe, 1961). Oblique waves also generate longshore currents strong enough to transport sand, and sometimes gravel, along the coast in the nearshore zone (Figure 5.6). Coastal features that indicate the net direction of longshore drift include deflection of river mouths, such as at the mouth of the River Spey in Moray, Scotland, accretion at breakwaters, such as at Newhaven in Sussex and the growth of spits, for example, at Culbin in Moray and at Calshot Castle in Southampton Water.

In recent years it has been recognized that longshore sediment movement is also affected by currents produced by forced resonance within the nearshore. Such 'edge-wave' activity interacts with the incoming waves to produce longshore currents within circulation cells that result in the formation of beach cusps and other rhythmic forms. The currents produced by edge-wave activity can co-exist with longshore currents produced by oblique wave approach and may control the net transport of sediment. Together, the longshore currents that result from both processes usually increase from the shore to reach a maximum just beyond the mid-surf position (where the contribution from oblique waves reaches a maximum), before declining rapidly to zero outside the breaker zone (where

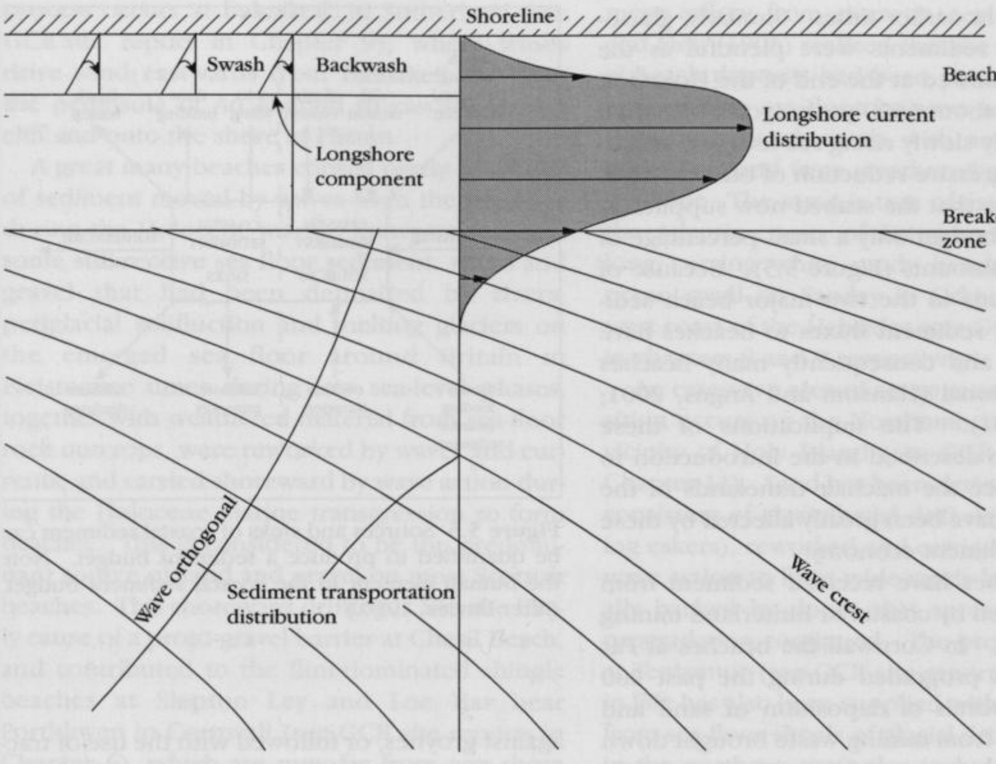


Figure 5.6 The run-up (oblique swash) and longshore current contributions to longshore or littoral drift. The amount of sediment moved alongshore depends on the wave energy component oblique to the shore. (After Fairbridge, 1968 and Komar, 1976.)

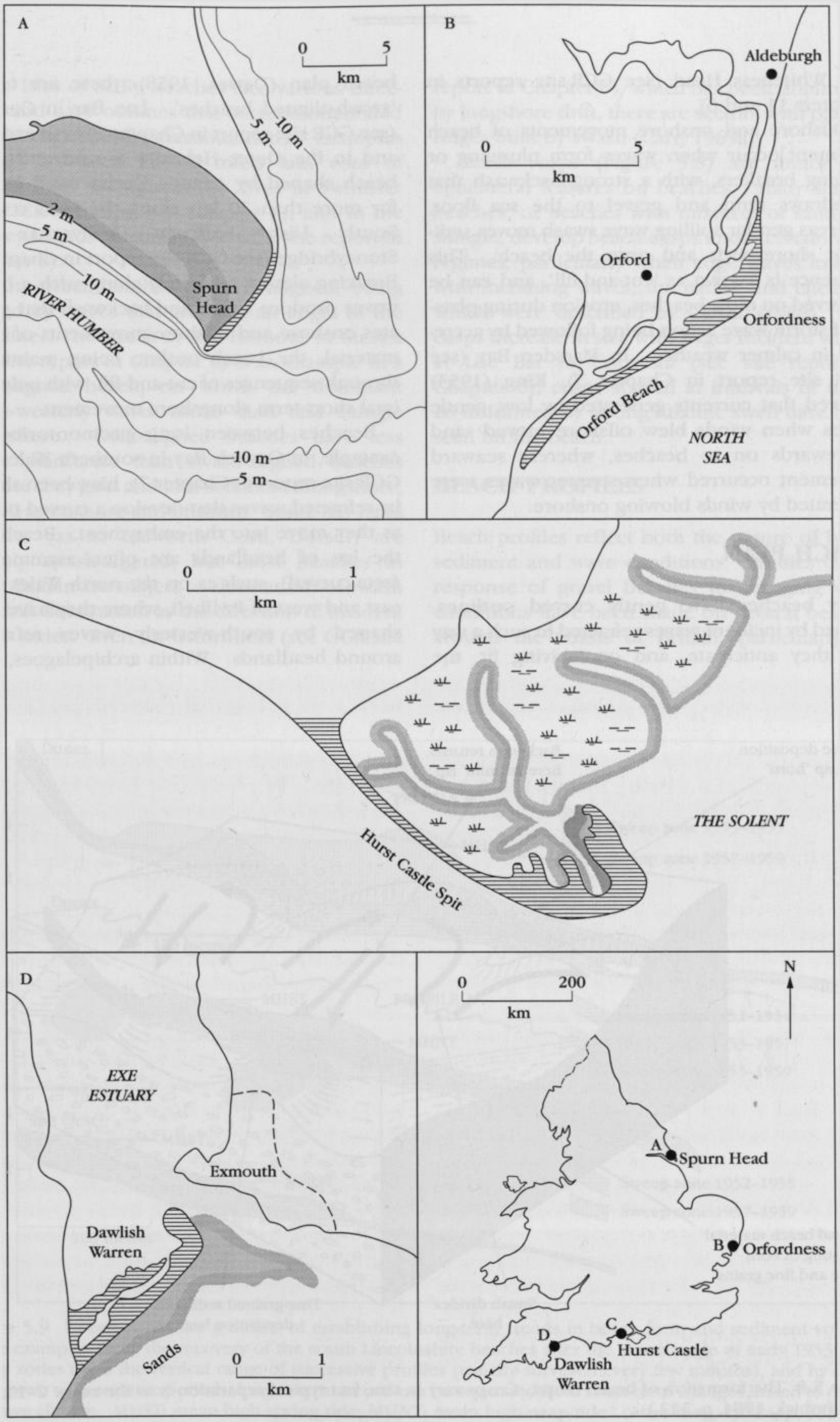
edge wave activity is negligible) (Trenhaile, 1997).

On the south coast of England the dominant waves are from the south-west, and are responsible for moving gravel eastward along the coast, such as between Bognor Regis and Rye in Sussex. The lobate foreland at Langney Point, near Eastbourne, and the cuspate foreland at Dungeness, east of Rye (see GCR site report in Chapter 6), have both been nourished with gravel that has travelled in this way. In Christchurch Bay sand and gravel beaches, supplied with sediment eroded from cliffs cut in gravel-capped Tertiary formations, have drifted eastward along the coast to accumulate in Hurst Castle Spit (see GCR site report in Chapter 6). On the Suffolk coast dominant north-easterly wave action has generated southward longshore drifting of shingle along Orfordness, and in Lincolnshire there is similar drifting of sand southwards to Gibraltar Point (see GCR site report in Chapter 8); (Figure 5.7).

Longshore drift usually alternates, moving sand or gravel first one way, then the other, as waves come in at different angles to the shore; this process can separate sand from gravel along the coast. On the south coast of England, beaches show alternations of eastward drift (by the dominant south-westerly waves) interrupted by westward drift (by weaker and less frequent south-easterly waves), resulting in a net eastward drift, such as on the north coast of Lyme Bay (Bird, 1989).

In the inner Moray Firth in Scotland, waves from the east are responsible for longshore drift to the west that has deflected river exits west and forced the migration of spits such as at Culbin

Figure 5.7▸ Some examples of English spits: (A) Spurn Head; (B) Orfordness; (C) Hurst Castle; and (D) Dawlish Warren. While the plan form of spits varies greatly, they all require an updrift sediment feed to form. In most cases, especially shingle spits, the sediment supply has now greatly decreased. (After Pethick, 1984, p. 108.)


A
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SEA
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Hurst Castle Spit
THE SOLENT
D
EXE
ESTUARY
Exmouth
Dawlish
Warren
Sands
0 1
km
0 200
km
N
A
Spurn Head
B
Orfordness
C
Hurst Castle
D
Dawlish
Warren

and Whiteness Head (see GCR site reports in chapters 11 and 6).

Offshore and onshore movements of beach sediment occur when waves form plunging or surging breakers, with a strong backwash that withdraws sand and gravel to the sea floor, whereas gentler spilling wave swash moves sediment shorewards and onto the beach. This sequence is known as 'cut-and-fill', and can be observed on most beaches, erosion during phases of storm wave action being followed by accretion in calmer weather. In Marsden Bay (see GCR site report in Chapter 7), King (1953) showed that currents generated by low, gentle waves when winds blew offshore moved sand shorewards on to beaches, whereas seaward movement occurred when steeper waves were generated by winds blowing onshore.

BEACH PLAN

Many beaches have gently curved outlines, shaped by incident waves refracted in such a way that they anticipate, and on arriving fit, the beach plan (Davies, 1958): these are termed 'swash-aligned beaches'. Loe Bar in Cornwall (see GCR site report in Chapter 6) is an example, and in the Outer Hebrides a sand and gravel beach shaped by Atlantic Ocean swell extends for more than 20 km along the west coast of South Uist, between Ardivachar and Stoneybridge (see GCR site report in Chapter 9). Breaking almost uniformly along such a beach, waves produce swash and backwash that generates onshore and offshore movements of beach material, the beach outline being maintained through sequences of cut-and-fill, with only minimal short-term alongshore movement.

Beaches between long promontories, for example, in Oxwich Bay in southern Wales (see GCR site report in Chapter 7), have been shaped by refracted waves that develop a curved outline as they move into the embayment. Beaches in the lee of headlands are often asymmetrical (zeta-curved), such as on the north Wales coast east and west of Pwllheli, where they have been shaped by south-westerly waves refracted around headlands. Within archipelagoes, such

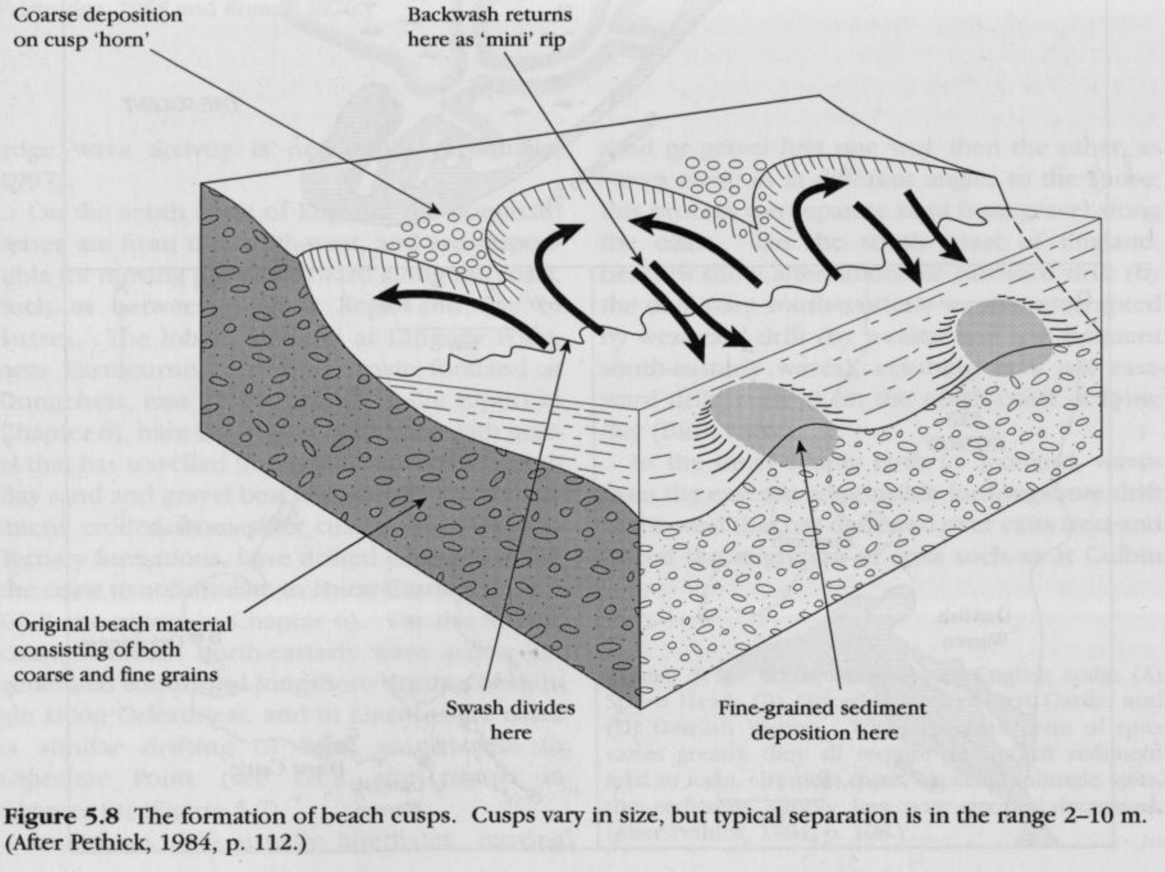

Figure 5.8 The formation of beach cusps. Cusps vary in size, but typical separation is in the range 2–10 m. (After Pethick, 1984, p. 112.)

as the Isles of Scilly, beaches face various directions and have outlines that become orientated at right angles to the maximum fetch. Examples of this are seen in the inlets and voes of Shetland, for example at the Ayres of Swinister (see GCR site report in Chapter 6), and in the Orkney Islands at Sanday (see GCR site report in Chapter 8).

Many other beaches are drift-aligned, being shaped by waves that arrive at an angle to the coastline. The beach at Rye Harbour in Sussex (see site report in Chapter 6) is an example of a drift-aligned beach, on which the dominant south-westerly waves move sand and shingle alongshore. Drift-aligned beaches have less stable planforms than swash-aligned beaches because they gain and lose sediment alongshore, as well as onshore and offshore. Some bay-head beaches (as in Lulworth Cove, Dorset) are entirely swash-aligned, but most beaches in Great Britain are subject to alternations of swash and drift domination as the direction of incident waves varies. Even on Orfordness (see GCR site report in Chapter 6), which has been dominated by longshore drift, there are sectors with parallel ridges built by swash (Carr, 1969a).

Beach cusps (Figure 5.8) are minor and ephemeral features on beaches. Many shingle beaches, or beaches with mixtures of sand and shingle, develop beach cusps under certain wave regimes, particularly when edge waves interact with incoming waves, the nature and effects of which were described by Carter (1988). The cusps increase in size with larger incident waves; at Loe Bar in Cornwall (see site report in Chapter 6), cusps spaced at intervals of up to 20 m formed by strong Atlantic swell have been seen on the beach.

BEACH PROFILES

Beach profiles reflect both the nature of beach sediment and wave conditions. Studies of the response of gravel beaches to changing wave conditions have been made on several beaches around the coasts of Britain, particularly on

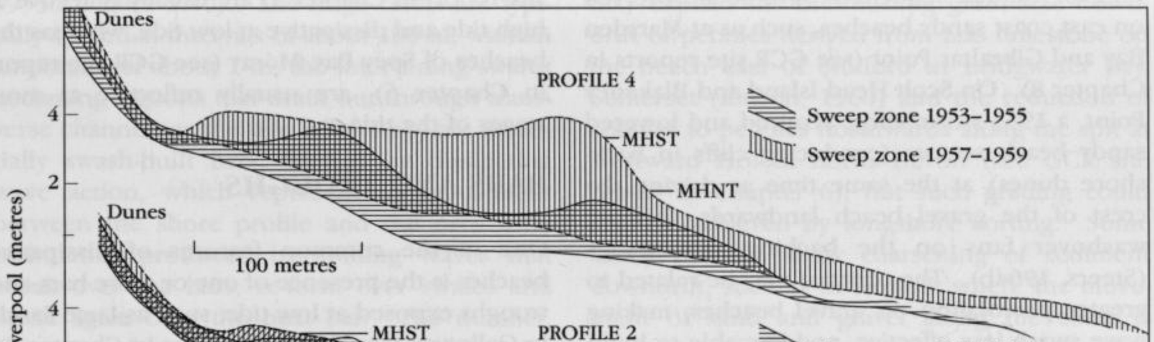

Figure 5.9 Sweep zones are a means of establishing long-term trends in beach form and sediment volume. These examples show the recovery of the south Lincolnshire beaches after the storm surge of early 1953. The sweep zones mark the vertical range of successive profiles (usually surveyed every few months), and by establishing two or more time periods, longer-term trends can be separated from short-term changes linked to changing wave climate. MHST: mean high spring tide; MHNT: mean high neap tide. (After King, 1972a, p. 359.)

Chesil Beach and Dungeness, but the dynamics of sandy beaches have received less attention in Britain than overseas, where sandy beaches are much more extensive.

There are contrasts in the response of gravel and sand beaches to alternations of cut-and-fill. In stormy episodes, waves reduce the gradient of the lower part of a gravel beach as strong backwash withdraws pebbles from the beach face, but the upper beach may be steepened and raised as gravel is carried shorewards by storm swash, forming a ridge or terrace known as a 'berm'. During calmer weather waves move finer nearshore gravel back onto the lower beach, restoring the swash-built lower slope, but leaving the steep upper beach unaffected.

The response of sandy beaches to these alternations of wave activity is a little different. On the sandy beaches at Ainsdale in Lancashire or Braunton Burrows in north Devon (see GCR site reports in Chapter 7), storm waves are almost entirely destructive, lowering and cutting back the beach, whereas berms are built by constructive wave action in calmer weather. Often swash-built sand bars are prominent at high and low tide levels, where wave action is more prolonged. Similar sequences have been observed on east coast sandy beaches, such as at Marsden Bay and Gibraltar Point (see GCR site reports in Chapter 8). On Scolt Head Island and Blakeney Point, a 1953 storm surge scoured and lowered sandy beach sectors (producing cliffs in backshore dunes) at the same time as driving the crest of the gravel beach landwards, forming washover fans on the backing saltmarshes (Steers, 1964b). The contrast may be related to greater percolation on gravel beaches, making wave swash less effective, and less able to build a berm than on sandy beaches. The outcome is that the outline in planform of a gravel beach is determined by storm waves, whereas sandy beaches are more influenced by the constructive waves and swell that arrive in calmer periods (Figure 5.9).

BEACH STATES

Analysis of incident wave regimes has shown that steep (> 3°) beaches (especially gravel beaches) tend to reflect waves, whereas gently sloping (generally sandy) shores dissipate their energy, the waves breaking and spilling across a wide surf zone (Wright and Short, 1984). Beaches may thus be described as exhibiting reflective or dissipative states (an intermediate category has also been recognized), and these can be defined using parameters related to wave power (Masselink and Short, 1993), and related to particular shore morphologies. These relationships are most clearly seen in low tidal range beaches, and on swash-dominated beaches, and are complicated on large tidal range and drift-aligned beaches by laterally migrating features such as lobes and bars.

Developed in Australia and the USA, this classification has been applied to beaches on various coastlines, but has so far been little used in Britain, perhaps because here gravel beaches are normally reflective, storm waves are more common than long swells, and tide ranges are relatively large. Nevertheless, swash-aligned beaches around Britain include some that are normally dissipative, such as the broad sandy beaches in the vicinity of Holy Island, and Lingay Strand in North Uist (see GCR site reports in chapters 11 and 9 respectively) and others (as on the Lancashire coast) that pass frequently from reflective to dissipative states in the course of cut-and-fill sequences. Some, such as the gravel-backed sandy beach at Porth Neigwl (see GCR site report in Chapter 4) are usually reflective at high tide and dissipative at low tide, whereas the beaches of Spey Bay, Moray (see GCR site report in Chapter 6), are usually reflective at most stages of the tide.

BARS AND TROUGHS

One of the common features of dissipative beaches is the presence of one or more bars and troughs exposed at low tide, such as Luce Sands in Galloway (see GCR site report in Chapter 7). A 'bar' is defined as a ridge or bank of sand (sometimes gravel) built up by wave action offshore and parallel to the coastline to a level where it is exposed at low tide but submerged at high tide. Where waves arrive obliquely, bars and troughs are aligned at an acute angle to the beach, such as on the shore at Porth Neigwl (see GCR site report in Chapter 4).

It should be noted that some coastal features called 'bar' as part of the place name (such as Loe Bar in Cornwall) are actually not bars *sensu stricto*, but *barriers* (see below).

The term 'ridge-and-runnel' has been used to describe multiple broad intertidal bars and swales running parallel to the coastline, as seen on the shores of South Lancashire (Gresswell,

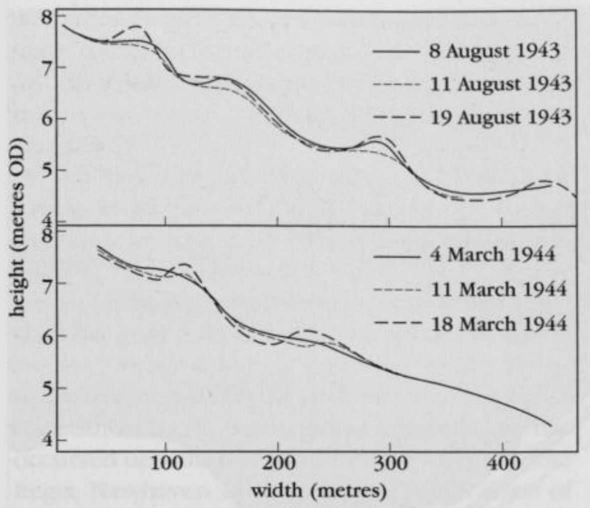

Figure 5.10 Profile of ridge-and-runnel beach (Blackpool). Ridge-and-runnel beaches occur where wide sandy beaches are dominated by local waves and swell is excluded, as here within the limited fetch of the Irish Sea. The short-period waves require a steep beach slope for equilibrium, and this is achieved through the formation of a series of ridges separated by runnels. (After King, 1972a, p. 342.)

1953b; Figure 5.10). The ridge crests are typically spaced at intervals of about 100 m, with an amplitude of about 1 m, the intervening swales becoming lagoons that drain out through transverse channels as the tide falls. They are essentially swash-built bars, formed by dissipating wave action, which represent an adjustment between the shore profile and the oscillatory turbulence produced by spilling waves that break over the bars, re-form over swales and break again over the next bar. The number, spacing and amplitude of multiple bars varies with the height and period of breaking waves, but bar topography, in turn, influences where and how incident waves break. The morphology of sand-bars and troughs changes in relation to variations in wave incidence and energy as the tide rises and falls. Similar sub-parallel bars and troughs off Gibraltar Point in Lincolnshire (see GCR site report in Chapter 8) differ from ridge-and-runnel in that they have been built by north-easterly waves and associated currents, the bars having grown southwards as intertidal spits (King and Barnes, 1964).

LATERAL GRADING

Some beaches show lateral grading of sediment, with finer-grained sediment towards one end and coarser towards the other. Chesil Beach (see GCR site report in Chapter 7) famously displays excellent longshore sorting, with small pebbles at the western end increasing in size to large cobbles at the south-eastern end (Carr and Blackley, 1974a; Figure 5.11). Beaches in Lyme Bay (Charmouth, Seatown) show similar lateral grading, while those on the Dorset coast east of Weymouth are graded in the opposite direction, possibly because the general dominance of south-westerly wave action on the south coast of England is replaced by south-easterly wave action in the lee of Portland Bill. There has been much discussion of the causes of lateral grading on beaches around Britain, but it should be noted that most beaches display only poor gradation and some no grading at all.

It is possible that lateral grading results from longshore sorting by oblique waves and associated currents, the coarser sediment being retained updrift as the more readily mobilized finer-grained sediment is carried downdrift. Alternatively, progressive downdrift reduction of initially coarse beach sediment by breakage and attrition may occur as it moves alongshore. This may explain the diminishing grain size downdrift of pebbles derived from Lias limestone on the beach east of Stolford in Bridgwater Bay, Somerset (Kidson, 1960) and the reduction of cobbles to pebbles northwards along the spit at Westward Ho! in north Devon (see GCR site report in Chapter 6), but such grading could also be achieved by longshore sorting. Some sandy beaches show coarsening of sediment downdrift, such as in Norfolk where the movement of sand and gravel along the coast is accompanied by preferential removal of sand to offshore bars (McCave, 1978a). Lateral grading can also result from alternations of longshore drift, the sorting of pebbles on Chesil Beach possibly as a result of the more frequent and stronger south-westerly waves carrying beach sediment eastwards and the less frequent and weaker south-easterly waves returning the finer-grained fractions westwards (Jolliffe, 1964). It has been suggested that beach sediment coarsens towards sectors of higher wave-energy, but this is not an explanation of lateral grading, unless it leads to sorting as the result of drifting from higher to lower wave-energy sectors. It is also possible that beaches like Chesil Beach may have originally developed at a lower sea level and have since been driven onshore retaining

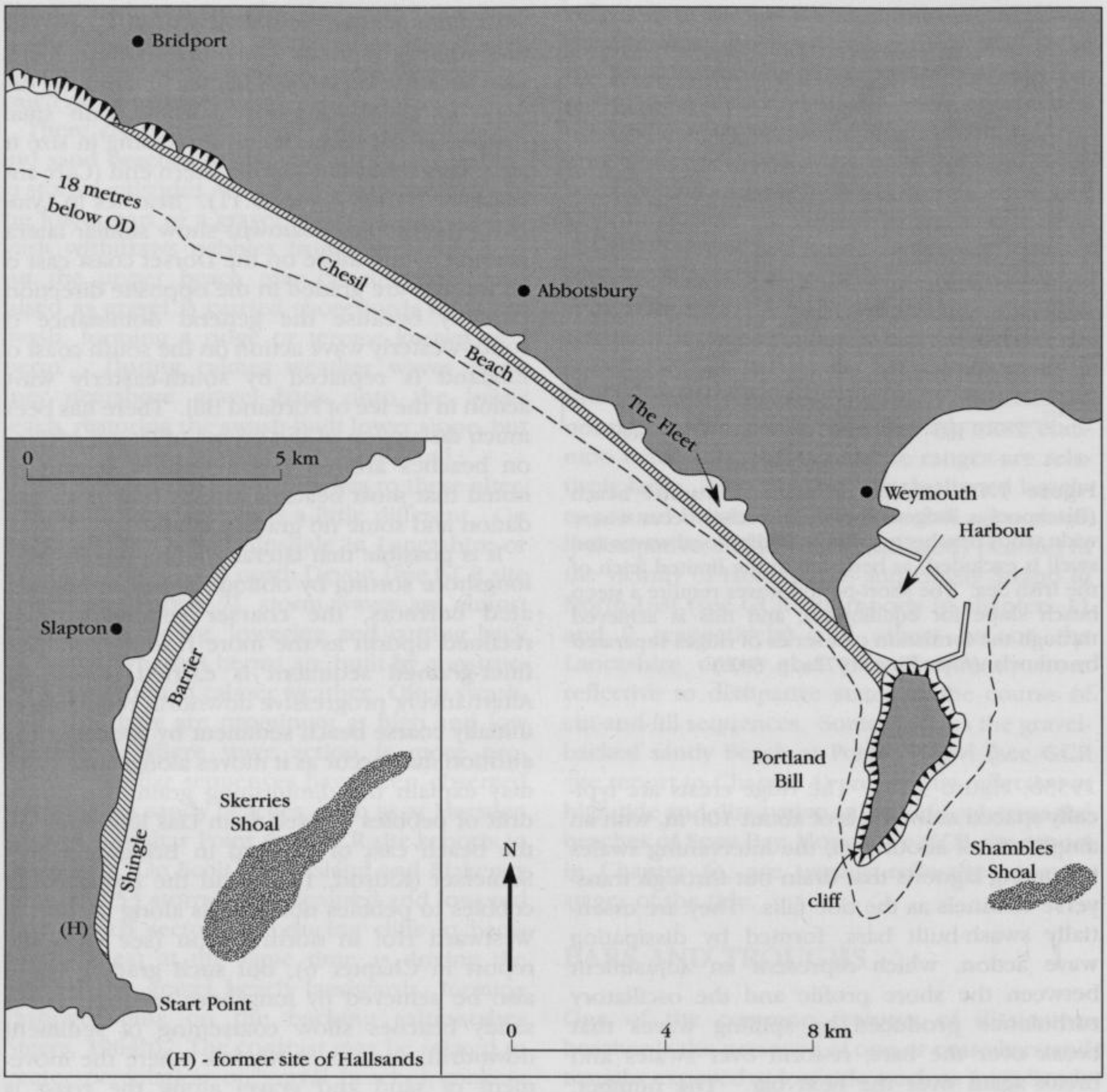

Figure 5.11 Coastal barriers enclosing coastal lagoons, Slapton, Devon and Chesil Beach, Dorset. Each of these barriers show gradation in pebble size along the barrier; coarse material is at the southern end of the Slapton barrier at Hallsands, and at the eastern end of Chesil Beach. (After Bird, 1984, p. 144.)

longshore gradation inherited from a more unidirectional wave regime than that of the present-day. The grading remains because of the lack of any new sediment that may 'dilute' the grading. Most beaches show poor lateral grading, however, and beaches such as Chesil Beach are the exception.

PROGRADING BEACHES

Progradation of beaches occurs where there is a continuing supply of sand and gravel from longshore or offshore sources, and a predominance of constructive wave action. Beaches also prograde on actively emerging coasts, stimulating shoreward drifting of sediment, such as in northern Britain where uplift due to postglacial isostatic rebound is continuing, for example, Morrich More (see GCR site report in Chapter 11). This has probably contributed to the extensive progradation on the sandy coasts bordering the Moray Firth at Culbin, Spey Bay and Whiteness Head, and in the Dornoch Firth (see GCR site reports in the present volume). A well-documented prograding beach occurs at Luce Sands, in Dumfries and Galloway, where a uni-directional wave approach sweeps sediment into a re-entrant trap (see GCR site report in Chapter 7)

Few beaches are naturally prograding in southern Britain, although local progradation occurs in estuaries and river mouths and on the ends of spits. The northern part of the sandy beach on South Haven Peninsula in Dorset (see GCR site report in Chapter 7) has advanced seawards, but this is largely due to accretion alongside a training wall built at the entrance to Poole Harbour in 1924. Similar local progradation has occurred updrift of harbour breakwaters at Lyme Regis, Newhaven and Rye on the south coast of England. There are prograding sandy beaches on the shores of Carmarthen Bay in southern Wales (see GCR site report in Chapter 11), where sand is being swept onshore from extensive shoals to form a beach that is over 1.6 km wide at low tide. Most sandy beaches in southern Britain are mainly undergoing erosion, although some are stable.

BEACH RIDGES

Sandy beach ridges originate as berms built by constructive wave action, whereas gravel beach ridges have been piled up by storm waves. On prograding coastlines multiple beach ridges (with intervening swales) may form, their height and spacing being determined by the rate of progradation (depending on available sources and patterns of sediment supply) and the upper swash limit of the waves that built them.

There are numerous roughly parallel shingle beach ridges on Dungeness (see GCR site report in Chapter 6), each marking a former coastline. It has been suggested that variations in the crest levels of these beach ridges may be indications of former sea levels. Lewis and Balchin (1940) found that the crests of some of the older shingle ridges on Dungeness were 2 to 3 m lower than those formed more recently along the eastern shore, possibly indicating that sea level had since risen, relative to the land. If a coast is emerging (as the result of land uplift or a falling sea level) the crest heights of successive beach ridges are likely to decline seawards, but there will also be variations related to differing swash limits in each constructional phase. On parts of the coast of Scotland that have been rising because of isostatic rebound following deglaciation, parallel shingle beach ridges have crests that decline seawards, such as in Spey Bay east of Lossiemouth (see GCR site report in Chapter 11; Comber, 1995), and on the west coast of Jura (see GCR site report in Chapter 6), (McCann, 1964).

Most beach ridge systems in Britain are swash-aligned, having been built parallel to the incoming waves, but sub-parallel beach ridges can also be formed by the successive addition of longshore spits, built by waves arriving at an angle to the shore. On the South Haven Peninsula in Dorset (see GCR site report in Chapter 7) during the past three centuries, the formation in stages of three broad sandy beach ridges (surmounted by dunes), traced from historical maps by Diver (1933), has included a component of northward longshore spit growth. The growth of Morrich More in Ross and Cromarty is related to the same process, the later stages of which can be charted using historical maps dating from 1730 to show a series of beach ridges capped by dunes and now separated by saltmarsh (see GCR site report in Chapter 11).

A particular kind of beach ridge is found on saltmarshes, particularly on the Essex coast near St Osyth (see GCR site report in Chapter 10), where storm surges have swept sand and shells up across the marshland, and left them as a ridge emplaced at the swash limit. Such ridges also occur in France near Dinard and are similar to the sandy ridges known as 'cheniers', deposited on marshes and deltaic plains in Louisiana and elsewhere. Their rarity in Britain could be due to the lack of river deltas and deltaic coastal plains, on which cheniers are typically found.

SPITS, TOMBOLOS AND CUSPATE FORELANDS

Spits are found where beaches diverge from the coastline. Their recent evolution can be traced from historical maps and aerial photographs, and various studies have related their shaping to incident wave regimes and the effects of occasional storm surges. Some spits are almost straight, like the southern part of Orfordness (see GCR site report in Chapter 6), where the mouth of the River Alde has been deflected nearly 17 km southwards, but most end in one or more recurves, representing earlier terminations, such as at Hurst Castle spit (Figure 5.12). Blakeney Point and Scolt Head Island are shingle spits with the remains of several former recurved

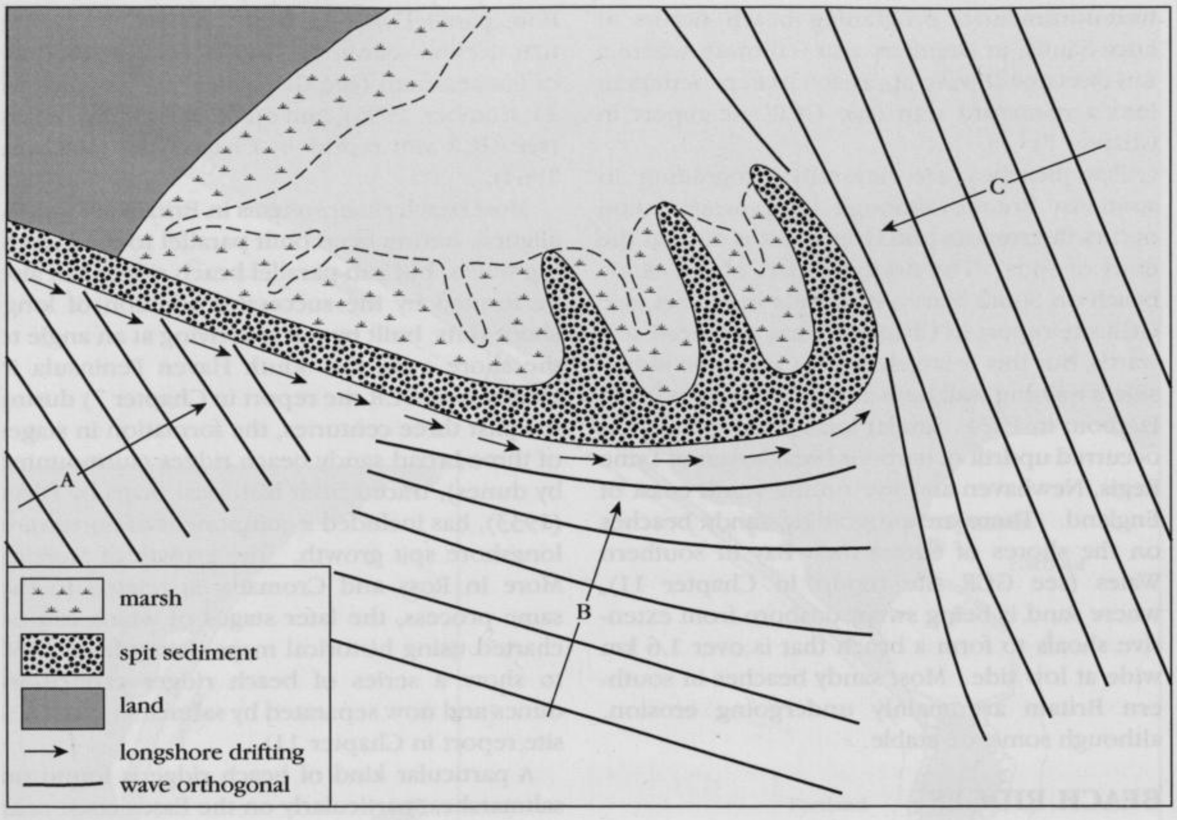

Figure 5.12 The shaping of a recurved spit, based on the outline of Hurst Castle Spit (see GCR site report in Chapter 6). Waves from A, arriving at an angle to the shore, set up longshore drifting which supplies sediment to the spit; waves from B and C determine the orientation of its seaward margin and recurved laterals respectively. (After King and McCullagh, 1971 and Bird, 1984, p. 148.)

terminations, which show that they have grown intermittently westwards, shaped by alternations of north-easterly and north-westerly wave action (see GCR site report for North Norfolk Coast in Chapter 11). These spits have been derived from morainic deposits at the margin of the Last Glacial ice-sheet (which crossed the Norfolk coastline in this area), the glacial drift deposits having been sorted and rearranged in the course of the Holocene marine transgression by wave- and tidal current-action.

Gravel beaches and beach ridges on the coast of Spey Bay and Burghead Bay in north-east Scotland have been supplied with gravel by the rivers Spey and Findhorn, carried westwards along the shore to form spits with recurves at their western ends, as the result of waves arriving from the north and north-east. Since the ongoing development of spits is linked to ongoing sediment supply to fuel distal accretion and spit extension, many are characterized by updrift erosion that may truncate earlier ridges or breach through the spit at the proximal end. The Bar, at Culbin in Moray, is a fine example of this process (see GCR site report in Chapter 11; Hansom, 1999). To the west, Whiteness Head (see site report in Chapter 6), on the southern shores of the Moray Firth, is a recurved spit of well-rounded gravel, derived from glacial drift deposits and similar to Blakeney Point in Norfolk. It has been built by westward longshore drifting and driven landward by storm surges so that the older recurves (projecting from the inner side) have been partly overrun (Steers, 1973).

The shaping of Hurst Castle spit (see GCR site report in Chapter 6) in relation to the direction of approach of dominant waves was demonstrated by Lewis (1931): it is exposed to south-westerly and southerly waves from the English Channel and easterly waves along the Solent, but is protected from south-easterly waves by the Isle of Wight. A computer simulation (SPIT-SIM) of the growth of this spit indicated the importance of constraints on the landward growth of the recurves (King and McCullagh, 1971). The main shingle bank has been driven landwards by storm surges, so that saltmarsh peat now crops out on the beach face (Nicholls and Webber, 1987a,c) (Figure 5.12).

On Rattray Head in Aberdeenshire, Scotland (see GCR site report for Strathbeg in Chapter 7) there is evidence of spit growth, first to the south-east, and later to the north-west, implying a reversal of longshore drifting, but it is possible that the sediment came in from the sea floor, and that the spits were largely swash-built. Paired spits of the kind seen at Poole, Christchurch and Pagham Harbours on the south coast of England (Robinson, 1955), and at Braunton Burrows (see GCR site report in Chapter 7), may result from a convergence of longshore drift produced by such alternations, but the entrance to Pagham Harbour was formed by the breaching of a shingle barrier in a 1910 storm. Paired spits can be shaped by waves refracted into the mouths of bays or estuaries (Kidson, 1963).

Tombolos are wave-built ridges of sand or gravel that link islands, or attach an island to the mainland. Some have formed as the result of the growth of a spit in the lee of an island until it reaches the mainland, others from the fusing of paired spits, and others as barriers (or augmented bars) built up across a strait. Stages in the evolution of tombolos can be seen in the Isles of Scilly (see GCR site report in Chapter 8), several of which are linked by depositional features of sand or shingle, some being partially submerged banks known as 'swashways'. On Samson, a sandy barrier links two former islands, and a shingle barrier ties Gugh to St Agnes. The curved shores of the sandy St Ninian's tombolo in the Shetland Islands (see GCR site report in Chapter 8) i have probably been shaped by a combination of refraction and diffraction of waves around St Ninian's Isle off the south-west coast of the Shetland mainland (Flinn, 1997).

Cuspate forelands (sometimes known as 'nesses') have formed by the deposition of beach sediment in protruding, more-or-less symmetrical, structures shaped by bi-modal wave-approach directions. Usually there is erosion on one side and longshore drifting round the point to an accreting shore on the other, such as on Dungeness, where the ridges have been truncated along the southern coastline (see Figure 6.43), and new ridges have formed on the prograded eastern shore. Dungeness probably originated as a spit on the coast off Rye about 5000 years BP, and has been built up and consolidated by waves arriving from the south-west and from the east, through the Strait of Dover (Lewis, 1932).

Morfa Dyffryn and Morfa Harlech (see GCR site reports in Chapter 8) are large cuspate lowlands on the north Wales coast, but they differ from Dungeness in that they originated from lobes of glacial drift, the margins of which were re-shaped by wave action, which built fringing beaches that are backed by dunes. Their points have grown northward as the result of erosion of sand and shingle from their southern shores and longshore drifting to the north.

The direction in which cuspate forelands migrate depends on wave patterns and local conditions. Winterton Ness on the north-east coast of Norfolk (see GCR site report in Chapter 8) is a lobate sandy foreland that has been migrating southwards as the result of erosion of its northern shore and accretion on its southern shore, supplied by longshore drift generated by the dominant north-easterly waves. In contrast, Benacre Ness (see GCR site report in Chapter 6), in a similar situation on the Suffolk coast, has been migrating northwards as the result of accretion on its northern side of sediment supplied by the predominant southward longshore drifting, and erosion on its southern side (Steers, 1964a). Migration of offshore shoals may also have influenced incident wave patterns and the evolution of these two nesses (Robinson, 1966). In Scotland, Buddon Ness at the mouth of the Tay has been built as a result of the seaward movement of sediment moved by the River Tay and the southwards movement of sediment on the outer coast. Falling sediment supply to the seaward coast had initiated chronic erosion, now arrested by artificial structures (see GCR site report for Barry Links in Chapter 7).

COASTAL BARRIERS

A coastal barrier is a prominent ridge or bank of sand or gravel built up by wave action to above high-tide level, backed by a lagoon or marsh. Some barriers (swash-aligned) have been built by waves arriving parallel to the coastline, with beach material supplied mainly by shoreward drifting from the sea floor; others (drift-aligned) have grown as longshore spits shaped by waves

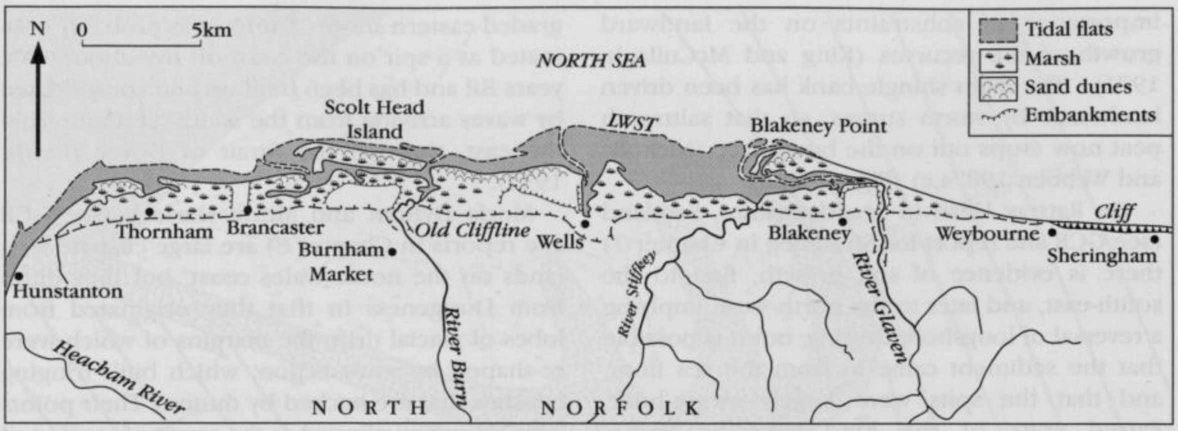

Figure 5.13 Coastal barriers backed by saltmarsh, North Norfolk Coast GCR site (see GCR site report in Chapter 11). The barriers and recurves carry sand dunes; behind are sheltered tidal inlets and extensive areas of saltmarsh, part of which has been reclaimed for grazing. (After Bird, 1984, p. 149.)

arriving at an angle to the coastline; and some are combinations of these two principal types. 'Barrier islands' are separated by transverse channels that are flooded at least at high tide.

The Loe Bar (see GCR site report in Chapter 6), near Helston in Cornwall, is an example of a swash-aligned barrier. It is 180 m wide, and consists largely of flint gravel and shingle moved from the sea floor, with only a small proportion derived from adjacent cliffs of slate and greenstone. The barrier is part of a beach that extends northwards from Gunwalloe to Porthleven, and runs across the mouth of a former ria, enclosing the lagoon known as the 'Loe Pool'. Loe Bar is sometimes overwashed by large waves from the south-west during storms, which have produced fans of gravel projecting into the lagoon.

Chesil Beach is another coastal barrier, consisting largely of pebbles that migrated shorewards from the sea floor during the Holocene marine transgression. It is essentially swash-aligned, but subject to alternations of longshore drift. It encloses a lagoon, The Fleet, the inner shore of which has low promontories and bays that have never been exposed to the open sea. Chesil Beach is migrating landwards, partly by occasional washover in storm surges, and partly because water driven through the permeable barrier by strong wave action forms gravelly fans spilling into The Fleet. Landward movement is confirmed by the presence of outcrops of lagoonal peat on the seaward slope of Chesil Beach.

In the Orkney and Shetland Islands there are many small gravel barriers, known as 'ayres', that have been deposited across the mouths of embayments to enclose, or partly enclose lagoons, known as 'oyces', which rise and fall with the tide. These are well represented in the Ayres of Swinister, Shetland, and in Central Sanday, Orkney (see GCR site reports in Chapter 6), where a complex series of protobarriers have evolved to form the present barriers enclosing tidal lagoons at Little Sea and Cata Sand.

Most British barriers are of gravel, which may be topped with sand dunes, but in Sandwood Bay (see GCR site report in Chapter 7) on the north-west coast of Scotland there is a wide swash-aligned, dune-capped, barrier beach built of sand that has moved in from the sea floor, enclosing a freshwater loch at the mouth of Strath Shinary, which is a glacial trough.

Barriers that originated as longshore spits are usually distinguished by the presence of recurves that mark former terminations, such as on the barrier island known as 'The Bar' on the Culbin coast (see GCR site report in Chapter 11), which formed during the 18th century, and has grown eastwards and westwards (Comber, 1995). Orfordness may be of composite origin: it has grown southwards as a longshore barrier backed by the deflected River Alde, but it includes parallel beach ridges formed during phases of swash-dominated progradation.

Scolt Head Island (see GCR site report for North Norfolk Coast in Chapter 11) is a good example of a barrier island consisting of shingle ridges, sandy intertidal areas and dunes, backed by saltmarshes (Figure 5.13). Its changing outlines have been much studied, particularly the evolution of Far Point, a western outgrowth in the form of a recurved spit (Steers, 1960). Although Walney Island (see GCR site report in Chapter 8) has the appearance of a barrier island it is actually a deposit of glaciofluvial gravel and till, cliffed on the seaward side, with dune-covered spits of sand and gravel that extend from either end.

COASTAL DUNES

British coastal dunes occupy an area of about 70 000 ha (Dargie, 2000) and occur on 7.4% of the coastline of Britain (Doody, 1989). Of this, the dune area of Scotland (*c.* 50 000 ha) far exceeds that of England (*c.* 11 900 ha) and Wales (*c.* 8100 ha). Scotland holds 71% of the British resource and has the largest and highest British dune systems (Dargie, 2000).

The dunes have formed where sand winnowed from a wide beach has been blown landwards and deposited on the coast above high-tide level, such as on the Ainsdale Dunes (see GCR site report in Chapter 7) in south-west Lancashire. The most extensive dune systems in Great Britain occur behind the sandy beaches of the Atlantic coasts of the Outer Hebrides, where ocean swell has formed wide, gently shelving beaches from which the prevailing westerly winds have blown sand onshore. High sand dunes have formed behind Tràigh Luskentyre and Tràigh Seilebost (see GCR site report for Luskentyre and Corran Seilebost in Chapter 9), Hebridean bays where broad sands are exposed at low tide on the south-western shore of the island of Harris. Other extensive and high dunes occur where plentiful sediment has been available in the past, such as between Aberdeen and Fraserburgh at the Forvie and Strathbeg GCR sites (see reports in Chapter 7). Exensive dune systems also occur at estuary mouths such as Barry Links and Tentsmuir (Forth of Tay); Culbin (Moray Firth); Morrich More and Dornoch (Dornoch Firth) (see GCR site reports in chapters 7 and 11)

Large dunes have also formed behind sandy beaches on the North Sea coast in the vicinity of Holy Island and in Lincolnshire, East Anglia and Wales. Some new dunes are forming behind prograding sandy beaches, but, more typically, where beach erosion is occurring, the seaward margins of coastal dunes are cliffed and receding. Since only a very few beaches in Britain are accreting, then most of the dune systems are erosional, as a result of both sea-level rise and a reduction in sediment supply.

There are several kinds of coastal dune topography (Figure 5.14). In an accreting sequence, the first colonizers of the small mounds of sand that accumulate around the flotsam of the high-water mark are salt-tolerant species such as sand couch *Agropyron junceiform* and sea rocket *Cakile maritima*. The presence of these pioneers serves to enhance sand deposition and the embryo dune grows to a foredune that may coalesce laterally to form a foredune ridge. The foredune ridge is built up immediately behind a sandy shore and held in place by vegetation, typically marram *Ammophila arenaria* or sea lyme grass *Leymus arenaria*. There has been much discussion of whether foredunes are initiated when vegetation colonizes wave-built berms of sand or gravel, or whether their original alignment depends on the growth of sand-trapping vegetation along a seed-bearing strandline of plant litter on the beach. As the dune continues to receive sand, and marram and other dune grasses are well equipped to cope with sand inundation, the foredune grows in height to produce a first dune ridge that is well covered with sand-trapping vegetation. Depending on the continuity and rate of sand accumulation, there may be several dune ridges formed in this way, although the farther from the sand source the more its sand supply is intercepted by the growth of dunes to seaward. Eventually, the older dunes become virtually stable with a dense ground vegetation cover, little new sand arriving and moribund stands of marram being progressively replaced by vegetation more suited to stable environments, such as mosses, lichens, a variety of grasses, and eventually shrubs and trees (Figure 5.14). At this stage the older dunes are susceptible to erosion if their vegetation cover is disrupted and many dunes show signs of such point-erosion, which leads to the development of blow-outs and the formation of parabolic dunes (Figure 5.15) However, a more serious type of erosion is the frontal erosion of the dune faces above the beach, since it leads to removal of younger parts of the dune system. Figure 5.14E shows the result of the latter type of erosion, and probably results because a combination of sea-level rise and reduction in sediment supply to the fronting beach forces the landward translation of the backshore into the

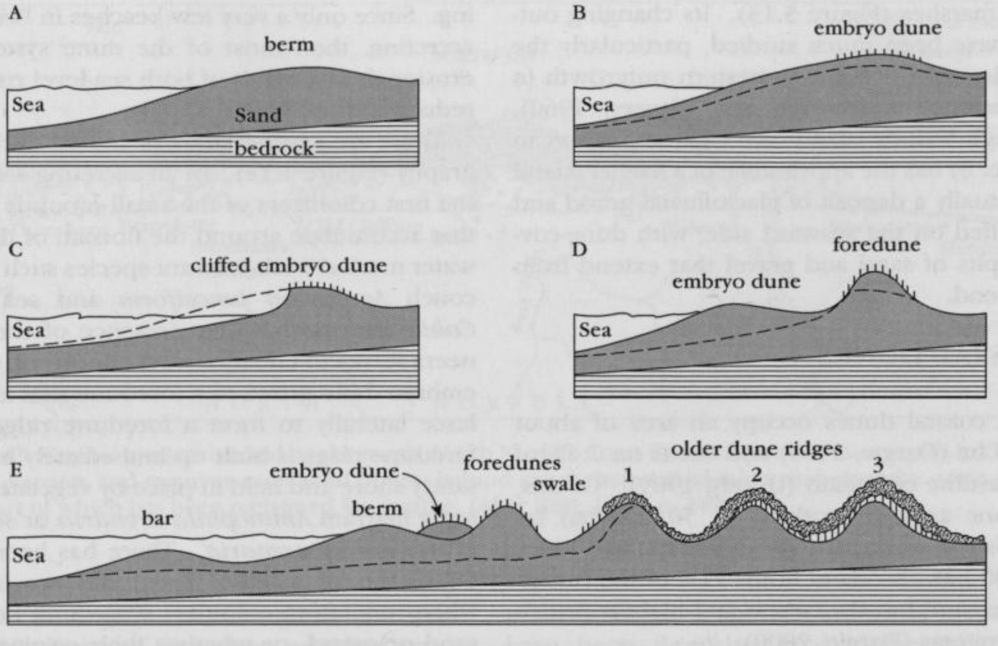

Figure 5.14 The formation of coastal sand dunes on a prograding coast (A–D). The older dunes farthest inland develop relatively mature soils and vegetation, and often the sand differs in colour from the younger dunes nearest the beach. The pecked line on E shows the effect that rising sea level and reduction in sediment supply has on sand dunes. Most of the dunes of Britain show such frontal erosion to a greater or lesser degree. Most dunes on the Scottish western and northern coastas are erosional. (Based on Hansom, 2001; Hansom and Angus, 2001, after Bird, 1984, p. 180.)

dune system. In Scotland, this latter situation is common and many mature dune systems have erosional edges characterized by steep sand faces (such as occurs at Dunnet in Caithness and at Barry Links in Tayside (see GCR site reports in Chapter 7). Dargie (2000) reports the extent of bare sand and mobile dune vegetation to total a mere 3.6% of the windblown sand extent of Scotland. Embryo and foredunes are thus rare.

Ranwell (1972) suggested a classification of dune systems that has been followed here for the sites in England and Wales (see Table 7.1). It is based on the combined effects of sand source, restrictions to longshore sand-movement and the geomorphological feature. Under this scheme, dunes are divided into two main groups: foreshore dunes, which are found most commonly on spits, nesses and offshore islands, and hindshore dunes, where most of the dune system lies on land behind the beach. In north-west Scotland, the dunes are dominated by 'machair', a flat sandy plain behind a narrow cordon of undulating dunes (Ritchie and Mather, 1984; see Chapter 9). Wind direction and speed affect the extent to which dunes (given an adequate and continuing supply of sand) can build in height. However, there are important differences in the dune patterns, well exemplified at Newborough Warren (see GCR site report in Chapter 11). Newborough Warren has a large reliable supply of sand and the coastal linear dunes have migrated inland. In contrast, Tywyn Aberffraw, a few kilometres to the north-west (see GCR site report in Chapter 7), has a distinctly different pattern of linear dunes that, despite their presence immediately behind the beach, have an alignment that is broadly perpendicular to the shore and which is associated with the development of parabolic dunes and blowthroughs. The time taken for a full cycle of linear dune construction and migration was estimated by Ranwell at about 80 years, and whilst this explains the particular features of Newborough Warren, it may also provide an insight into some of the separate zones found in other dunes such as Tywyn Aberffraw and South Haven Peninsula, Dorset (see GCR site reports in Chapter 7).

Many dunes are associated with the development of large accretional structures especially where there are extensive intertidal sandflats. Shingle or gravel spits, nesses and offshore bar-

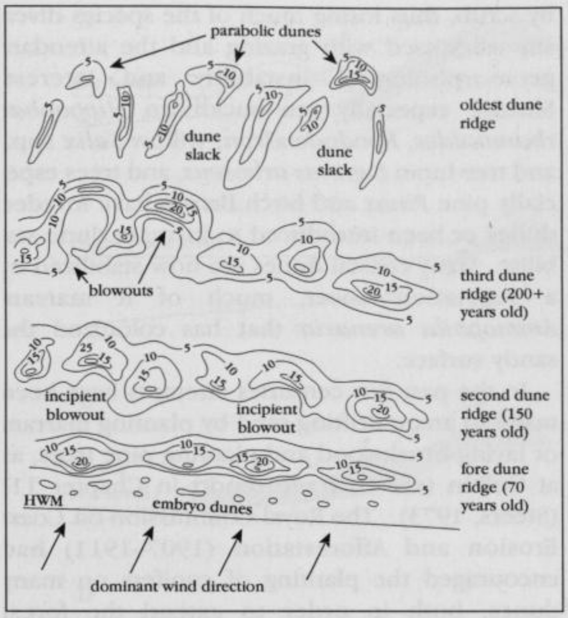

Figure 5.15 Sequential development of the dune ridges in a dune system. The blowthroughs of the second and third dune ridges eventually form into parabolic dunes in the older ridge. (After Pethick, 1984.)

rier structures have provided a base upon which sand beaches and dunes have developed. Particular examples occur on the distal ends of cobble spits at Westward Ho! and Ynyslas, on large estuary-mouth sand and shingle spits such as Spurn Head, Morfa Harlech and Morfa Dyffryn, on offshore islands for example around Lindisfarne, and on barrier beaches such as at Blakeney Point (North Norfolk Coast GCR site) and Pembrey (Carmarthen Bay GCR site). Extensive hindshore systems such as at Ainsdale, Lancashire, appear to have grown atop sandbanks that developed offshore. The dunes capping the emerged and modern sand ridges of Morrich More, Ross and Cromarty, may have developed in a similar way (see GCR site reports in the present volume).

Where the foundations of these dune systems rely primarily on longshore sediment transport, many are affected by erosion at their proximal end. This may result from up-drift coast protection structures (e.g. groyne-fields) or from reductions in the natural rate of longshore sediment supply brought about by changes in wave direction or changes in the nature of the sediments in the source region. For example, along parts of the west coast, the erosion of till and periglacial deposits has exposed hard-rock coasts and as a result the sediment supply is now much reduced. Similarly, estuarine sediment supply may be significantly reduced or enhanced as a result of changes in catchment management. Many dune systems rely on both continued positive sediment budgets of their foundation materials and of the sand supply. Offshore sand supplies have also reduced in volume as the Holocene supplies have become exhausted and longshore sediment supplies have been cut off or reduced.

Successive dune ridges may form on a prograding coast as parallel foredunes separated by dune swales. The evolution of parallel dunes can be traced at such sites as Tentsmuir in Fife or Winterton Ness in Norfolk (see GCR site reports in chapters 7 and 8) . As they are of increasing age landwards they can be used to study the evolution of soil profiles, the yellow or brown sand of recently formed dunes becoming grey or white on the older ridges as podzol profiles form and deepen. The rate of soil evolution depends on the nature of the sand and the type of colonizing vegetation: it is relatively slow on calcareous sands, but more rapid on quartzose sands as on South Haven Peninsula in Dorset (see site report in Chapter 7), where dunes formed within the past three centuries and colonized by heath vegetation already have white podzolic A horizons.

Coastal dunes are often interrupted by blowthroughs, which are unvegetated or sparsely vegetated hollows excavated by the wind, where sand has been driven landwards to form a looped ridge (Figure 5.15). There are good examples at Dunnet Bay (see GCR site report in Chapter 7). Blowthroughs can form naturally, during stormy periods when the seaward margin of the dunes is cut back by wave scour and the dune locally breached or overwashed. Some blowthroughs have originated where the dune vegetation has been depleted by grazing animals, by cutting, burning or trampling, or damaged by vehicles. Blowthroughs can grow into larger parabolic dunes with noses of sand advancing landwards and vegetated trailing arms on either side of a corridor formed by deflation. Parabolic dunes have been studied in the Sands of Forvie in Aberdeenshire, Scotland (see GCR site report in Chapter 7), where their development is accompanied by an adjustment between the dune morphology and the wind-flow patterns (Robertson-Rintoul, 1990). The orientation of parabolic dunes in relation to regional wind regimes has been demonstrated, for example on Barry Links in Angus (see GCR site report in Chapter 7), where they have SW–NE- trending axes (Landsberg, 1956).

Where onshore winds are strong and the vegetation cover sparse there is more general movement of sand landwards in the form of transgressive dunes, with sand spilling down a generally steeper leeward slope. These are well developed in Newborough Warren (see GCR site report in Chapter 11), where three successive sand ridges have formed and migrated inland at rates of up to 16.7 m a^{-1} (Ranwell, 1958), and in the Sands of Forvie (see site report in Chapter 7), where several roughly parallel E–W-trending sand ridges have been migrating north-eastwards within a corridor bounded by high N–S-trending dune ridges. It is not clear how these migrating sand ridges, separated by low-lying slacks, were initiated.

On Braunton Burrows (see GCR site report in Chapter 7) various dune forms, including fore-dunes, parallel ridges, swales, blowthroughs and parabolic dunes persist despite devegetation and damage during a phase of intensive military use. However, like Culbin, dune management has tended to take greater care of the vegetation than a geomorphologist might wish, and geomorphological diversity is lost if processes are arrested. There is similar diversity and dune fixing behind Luce Sands (see GCR site report in Chapter 7) on the southern side of the isthmus that links the Rhinns of Galloway to the mainland, where low parallel foredunes are backed by high transverse older dunes and many swales. Detailed surveys of such dunes, such as those by Single and Hansom (1994) at Luce Sands are necessary to determine rates and patterns of change. Kidson *et al.* (1989) made a photogrammetric survey of the Braunton Burrows dunes (scale 1:2500) in 1983 and used it to calculate volumes of gain and loss since an earlier survey in 1958.

Dune vegetation and habitats

Historically, many dunes were used as breeding grounds for rabbits, an activity recognized in the common usage of the terms 'burrows' or 'warren' in dune names. Grazing both by rabbits and other domestic animals has affected the vegetation of many dunes. The removal or absence of grazing often leads dunes to become dominated by scrub, thus losing much of the species diversity associated with grazing and the attendant geomorphological instability and interest. Shrubs, especially sea buckthorn *Hippophae rhamnoides*, *Rhododendron*, willow *Salix* spp., and tree lupin *Lupinus arboreus*, and trees especially pine *Pinus* and birch *Betula* have invaded dunes or been introduced to increase dune stability. Many coastal dunes are now stabilized by a vegetation cover, much of it marram *Ammophila arenaria* that has colonized the sandy surface.

In the past few centuries attempts have been made to arrest drifting sand by planting marram or laying brushwood and planting pine trees, as at Culbin (see GCR site report in Chapter 11) (Steers, 1973). The Royal Commission on Coast Erosion and Afforestation (1907–1911) had encouraged the planting of conifers on many dunes, both in order to extend the forest resource in Britain and to 'fix' dunes both as sea defences and to prevent them from invading agricultural land. Stamp (1947) commenting on the use of the British landscape described dunes as 'rarely providing land of high value' (p. 231), argued that afforestation was a safer use of many dunes than grazing and regarded the management of dunes as golf courses as obviating the 'risk of erosion' (p. 162).

The vegetation of dunes is significantly affected by the proportion of calcium carbonate to silica in the deposited sand (see Table 7.3), the hydrology of the dunes, climate (especially wind) and the ways in which dunes are managed.

The development of dunes in the Holocene Epoch

There is historical and archaeological evidence that coastal dunes have at times been more geomorphologically active, either because larger quantities of sand were arriving or the vegetation cover was sparser, so that bare and mobile dunes drifted more than they do now. At Skara Brae, in the Orkney Islands, dunes overran a Neolithic settlement about 4700 years BP. We know of its location only because it has since eroded out of a retreating dune face suffering frontal erosion. In Cornwall, drifting sand buried farms, villages and churches behind St Ives Bay and Perran Sands in medieval times, possibly as a result of destruction of vegetation that had previously fixed the dunes, or because

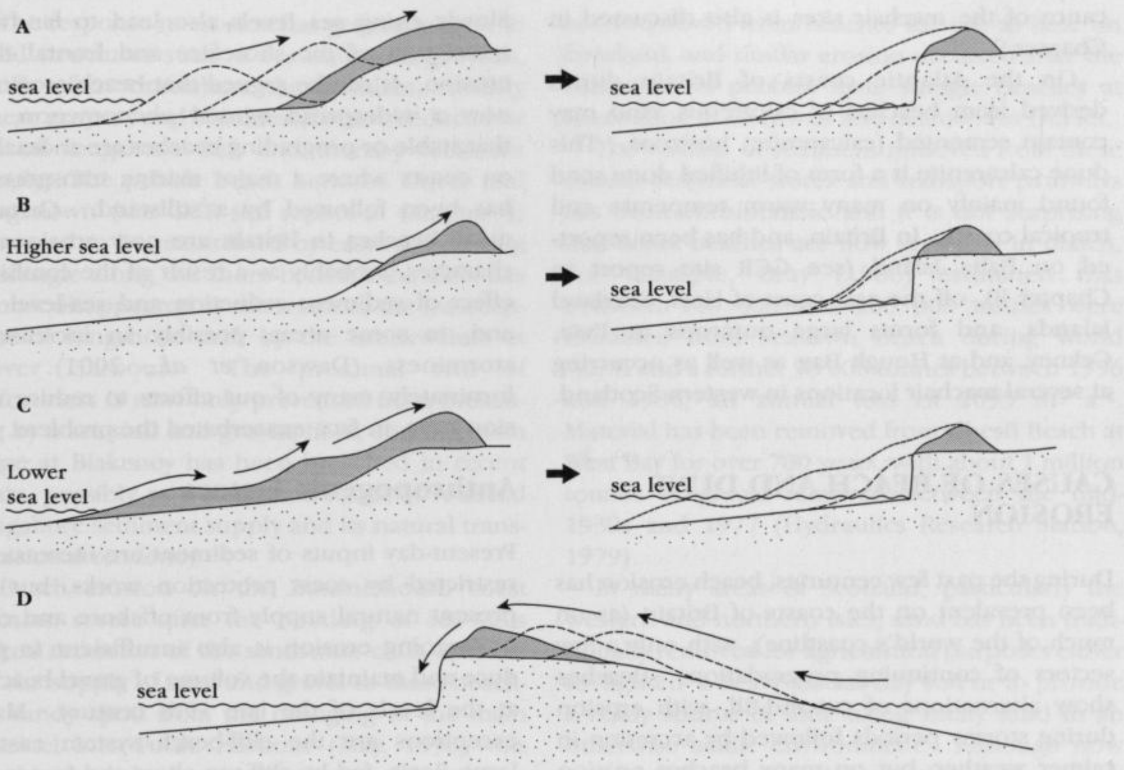

Figure 5.16 Ways in which cliff-top dunes may develop. (A) A transgressive dune truncated by cliff recession; (B) a dune formed at higher sea level stranded by cliff recession after a fall in relative sea level; (C) a dune formed during a lower sea level truncated by cliff recession as sea level rises; (D) a dune that has advanced from a neighbouring beach across a headland. (After Bird, 1984, p. 190.)

of a phase of stormier climate. Stormier conditions during the 17th and 18th centuries were responsible for the inundation of farmland by sand at Culbin in Moray, the subsequent instability resulting in dunes that exceed 45 m in height in Aberdeenshire and 30 m at Lady Culbin in Moray.

Dune fields where dunes have been blown up underlying rock surfaces, can reach altitudes in excess of 100 m on parts of the Highlands and Western Isles coast of Scotland. On some coasts dunes have migrated up and over cliffs. In the past few decades a climbing dune has been heaped against the Thanet cliffs near Foreness Point (see GCR site report for Joss Bay in Chapter 4). Some cliff-top dunes were built from sand blown up from the beach in this way, but the link has been removed by marine erosion (Figure 5.16). An example of this is seen at Upton and Gwithian Towans (see site report in Chapter 7) in Cornwall. The grassy Northam dunes at the northern end of the Westward Ho! cobble spit are also relict, having formed when there was a contiguous sandy beach from which westerly winds supplied sand. The dunes at Balnakeil in Sutherland formed in this way and now cascade over a headland onto the beach beyond (see GCR site report in Chapter 9).

Machair

On the coasts of Scotland there are areas of almost level, calcareous sandy plain, known as 'machair' (Ritchie and Mather, 1984). Typically these have developed behind a cordon of coastal dunes, such as at Eoligarry (see GCR site report in Chapter 9) on the northern part of the Hebridean island of Barra. The geomorphology of machair has been recently reviewed by Hansom and Angus (2001) and the machair GCR sites are described in Chapter 9. The machair sites have also been recognized for the contribution to wildlife conservation as a habitat 'type' protected by European law. This further significance of the machair sites is also discussed in Chapter 9.

On the Atlantic coasts of Britain dunes derived from beaches of calcareous sand may contain cemented (calcarenite) horizons. This dune calcarenite is a form of lithified dune sand found mainly on many warm temperate and tropical coasts. In Britain, and has been reported on Balta Island (see GCR site report in Chapter 8), off the east coast of Unst, Shetland Islands, and forms large outcrops at Evie, Orkney, and at Hough Bay, as well as occurring at several machair locations in western Scotland.

CAUSES OF BEACH AND DUNE EROSION

During the past few centuries, beach erosion has been prevalent on the coasts of Britain (as on much of the world's coastline), with only a few sectors of continuing progradation. Beaches show alternations of cut-and-fill, with erosion during stormy periods followed by accretion in calmer weather, but on many beaches erosion now chronically exceeds accretion. The reduction of beaches as buffer zones has led to erosion of formerly protected coastal land, and the introduction and extension of 'coastal defence' structures that often have further adverse effects on beaches, such as at Dawlish Warren in Devon (see GCR site report in Chapter 8).

Several causes of beach erosion have been identified, but further research is necessary to understand which of these have operated on particular sectors of coastline. Beaches lose sediment when it is carried along the coast in longshore drift or withdrawn to the sea floor during stormy periods. A beach is also depleted when sediment is swept landwards by wave action as washovers into estuaries and lagoons or onto coastal plains, or when winds blow sand from beaches to backshore dunes that are moving inland. Some beaches that prograded when sand or gravel moved in from the sea floor during the Holocene marine transgression (and for a period after the ensuing stillstand was established) are now being eroded because this source of sediment has diminished. This may be the explanation for beach erosion on the north coast of Cornwall, such as at Upton and Gwithian Towans, and at Braunton Burrows in Devon (see GCR site reports in Chapter 7). Slowly rising sea levels also lead to landward translation of the shoreface and frontal dune erosion. It can be argued that beach erosion is now a widespread natural phenomenon, and that stable or prograding beaches are anomalous on coasts where a major marine transgression has been followed by a stillstand. Certainly many beaches in Britain are now erosional in character, probably as a result of the combined effect of sediment reduction and sea-level rise and, in some areas, possibly an increase in storminess (Dawson *et al.*, 2001). Unfortunately, many of our efforts to reduce erosion have, in fact, exacerbated the problem.

Anthropogenic factors

Present-day inputs of sediment are increasingly restricted by coast protection works, but the present natural supply from offshore and cliffs undergoing erosion is also insufficient to produce and maintain the volume of gravel beaches at the levels of the late 19th century. Major exceptions are the cliff-beach system east of Lyme Regis, fed by cliff-top chert and transported by major landslides to the beach, and beaches fed by coarse, clastic, glacial sediments along parts of the upland coasts of Scotland. Many beaches have transgressed as Holocene sea level rose and have become compartmentalized by headlands (Hansom, 2001) or coast protection works.

At Dungeness, there is virtually no modern material feeding into the beaches. Longshore transport along its southern shore is removing and redistributing shingle from older parts of the structure and artificial beach feeding has helped maintain this transport stream since at least the 1950s. Even where there are chalk cliffs undergoing erosion that produce flints the present supply is insufficient to produce large fringing beaches. For example along the coast east of Dover, longshore transport has carried most of the 19th century fringing beach to a sink north of Deal. With further supplies from the west cut off by the harbour arms at Folkestone and Dover, the cliffs have become more erosionally active, but the supply of flint remains small.

The economic value of sand beaches as a major attraction for coastal recreation and tourism and the susceptibility of soft cliffs to erosion has led to the construction of extensive coast protection works to combat erosion at many coastal resorts.

The response to erosion has generally been to build structures such as sea-walls and groynes, which often exacerbate the problem, notably where groynes and breakwaters have reduced or cut off longshore drift and thereby sediment supply. The pebble beach between Dover and Kingsdown (see GCR site report in Chapter 4) that used to be maintained by eastward drifting of shingle along the shore beneath the cliffs has almost disappeared as the result of the interception of longshore drift by the breakwaters at Dover Harbour. The proximal end of Orfordness is now only prevented from breaching by a sea-wall and groyne-field, and the main ridge at Blakeney has been breached in recent years, possibly as a combined result of reduced longshore sediment supply and its natural transgressional tendency.

Beach erosion on the Bournemouth coast became severe after the building of sea-walls halted recession of the sandstone cliffs, and cut off the supply of sand and gravel to these beaches; sandy spoil from the dredging of the main channel into Poole Harbour (May, 1990) was used to feed the beach. Farther to the east, the sand spit at the mouth of Christchurch Harbour, which was formed by longshore sand transport from the erosion of Bournemouth's cliffs, now requires both walls and groynes along most of its length owing to reduced sediment supply.

At Spey Bay, Moray, the supply of fluvial gravels to the beach has further diminished as a result of bank protection in the River Spey and this has contributed to erosion and thinning of the beach, which protects the village of Kingston (Gemmell *et al.*, 2001a,b).

Sand and gravel extraction

Extraction of gravel has taken place from offshore banks, beaches and large landward deposits, such as Dungeness and Rye Harbour, to supply the considerable demand for aggregates. Elsewhere, deepening of nearshore water by the dredging of sand or gravel has been followed by beach erosion, such as at Hallsands (see GCR site report in Chapter 6) in Devon (Robinson, 1961).

In Cornwall and in the Hebrides, beaches have been depleted where calcareous sand has been removed from beaches for use as lime on farmland, and similar erosion occurred after the extraction of pebbles from shingle beaches at Gunwalloe in Cornwall and Seatown in Dorset.

The volume of sediment removed from these coastal sediment stores and transport pathways has been considerable and it is not surprising that some beaches are now seriously in deficit. For example, Bray (1986) estimated that between 100 000 and 200 000 tonnes were extracted from Seatown Beach during World War II and a further 50 000 tonnes between 1956 and 1986, an annual loss of 2095 m^3 a^{-1}. Material has been removed from Chesil Beach at West Bay for over 700 years, with about 1 million tonnes of gravel removed between the mid-1930s and 1977 (Hydraulics Research Station, 1979).

In many areas of Scotland, particularly the western and northern Isles, sand has been traditionally removed for agricultural purposes either to 'lighten' a heavy glacial clay soil or to provide a ready source of lime using shelly sand in an otherwise acidic environment. Although now much reduced, it is known that such activity continues in the more remote places, in spite of chronic beach and dune erosion in those areas.

Beach replenishment

In recent decades, more attention has been given to beach replenishment as a means to mitigate the effects of coastal erosion, using sand and gravel obtained from the sea floor or inland quarries, such as at Bournemouth, Weymouth, Sidmouth and Minehead in south-west England, or recycled from downdrift accumulations, such as at Rye in Sussex (Bird, 1996). The beach replenishment scheme at Spey Bay in Moray has successfully used the seawardmost gravel ridges of the Spey mouth gravel complex to recharge a depleted downdrift section (Gemmell *et al.*, 2001a,b). Although not on the same scale as replenishment programmes in North America or the Netherlands, the British examples suggest that such an approach represents an environment-friendly and sustainable way to manage beaches, particularly since traditional engineering approaches may cause negative side effects on adjacent coasts.