Chapter 1 Introduction to coastal geomorphology of Great Britain

This volume summarizes the results of the site evaluation and selection programme of Britain's coastal regions that was undertaken between 1980 and 1990 as part of the Geological Conservation Review (GCR), although the site evaluation phase of the Review is ongoing. With the aim of representing the highlights of Britain's coastal geomorphology, 99 sites (see (Figure 1.2)) were selected eventually for this part of the GCR, to be considered for long-term conservation under British law.

The descriptions of the GCR sites in this book are intended not only to justify why it is important to conserve geomorphologically important parts of our coast, but also to demonstrate the major contribution that British sites have made, and continue to make, in developing our understanding of coastal geomorphological processes and the features that they create.

Organization of this volume

In the following sections of Chapter 1, an overview of coastal research is followed by an introduction to the coastal geomorphology of Great Britain — discussing geomorphological processes and their controls (a glossary of geomorphological and technical terms is provided at the back of this book). There is a brief discussion of the impact of coastal management and engineering on the environment, and the chapter concludes with details of the rationale and methods of selection of the coastal geomorphology GCR sites.

Most of the GCR sites described in the present volume are dominated by one coastal landform, especially in terms of their associated research significance, and this is the basis of their arrangement into chapters. This has the advantage that each set of landforms can be introduced in terms of our understanding of coastal geomorphological processes and the linked landforms. However, while cliff site descriptions are divided into 'hard-rock' (Chapter 3) and 'soft-rock' (Chapter 4), one chapter (Chapter 2) serves to introduce them. Similarly, whereas it is convenient to separate out into successive chapters groups of sites representing gravel ('shingle') beaches, sandy beaches, and spits and tombolos, it is simpler to cover all three chapters (6–8) by a single introduction (Chapter 5). There follow chapters on machair (9), and saltmarshes (10), each with their own introduction. Finally the selected GCR sites include a number that are complex in their assemblage of linked geomorphological forms, and so they have been grouped into a final chapter (11) with the title 'Coastal Assemblages'.

Coastal research in Britain

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With its geologically varied coastline and high-energy coastal regime, much coastal research has been stimulated in Britain over the past two hundred years. Books describing the landforms and scenery of the British Isles have paid considerable attention to the coast, and descriptions of many British sites have found their way into textbooks about coastal forms and processes as archetypal exemplars. Steers has published two very valuable descriptions of the entire British coast, one on England and Wales (Steers, 1946a) and the second on Scotland (Steers, 1973). Perhaps it is because of the diversity of British coastal forms — as well as the long history of study — that British authors have contributed several key texts on coastal geomorphology to the literature at a variety of levels of technical complexity (e.g. Pethick, 1984; Carter, 1985, 1988; Hansom, 1988; Bird, 2000, Haslett, 2000).

There is considerable bias in the published literature, however. In geographical terms, the north and west of Britain are poorly represented; in topical terms, soft-rock coasts have had more attention than hard-rock, and low coasts have had far more than cliffs. Coasts that change form more rapidly have also received greater attention, whereas hard-rock cliffs, which seem to change very little in a lifetime, have received much less.

A computer-database bibliography of some 9000 items has been accumulated covering a large proportion of all papers and books published on the geomorphology of the British Isles since 1960, together with a selection of papers published before that date (based on Clayton 1964, together with *Geomorphological Abstracts, Geographical Abstracts* and *Geo Abstracts*). Of these, 1400 are classified under the heading 'Coasts'. (Table 1.1) gives a breakdown by date (the list is not comprehensive until after 1960, so the two columns are not comparable, but the fall-off in rate of publication of coastal papers since 1989 seems quite remarkable, and presumably is matched by a growth in other geomorphological topics, no doubt Quaternary geomorphology in particular). (Table 1.2) gives the number of published papers and books indexed under particular keywords (the categories are not exclusive), and gives a good idea of the relative cumulative interest in various aspects of coastal geomorphology. (Figure 1.1) is a map that displays the number of items in the bibliography dealing with coasts, allocated to the 100 km squares of the National Grid to which they refer.

(Table 1.1) Number of items in the computerized bibliography of geomorphology of Britain that are classified as 'Coasts' (total 1400), by year of publication.

Year	Items
1830–1859	5
1860–1899	15
1900–1909	1
1910–1919	10
1920–1929	24
1930–1939	36
1940–1949	28
1950–1954	68
1955–1959	73
1960–1964	102
1965–1969	86
1970–1974	121
1975–1979	197
1980–1984	229
1985–1989	209
1990–1994	68
1995–1999	102

(Table 1.2) Number of items under selected keywords (some items appear more than once as several keywords are allocated to each).

Beach	284
Erosion	267
Sea level	186
Cliffs	126
Saltmarsh	104
Sand dunes	90
Gravel/Shingle	86
Littoral/Longshore drift	79
Coastal protection	74
Spit	66
Coastal platform	42
Accretion	27
Sediment cell	3

As (Figure 1.1) shows, the geographical distribution of published coastal research is very uneven, with a clear bias to the south and east. The largest numbers are for TF (Lincolnshire, The Wash and North Norfolk) and SS (north and southern shores of the Bristol Channel).

(Table 1.3) Geographical analysis of the British coastal literature, using selected grid squares only.

Grid square	Estimated length of coastline	Number of publications	Coastline length per number of publications
SY (Dorset)	110 km	97	1.13 km
TM (Suffollc/Essex)	120 km	95	1.26 km
SD (Lancashire/S. Cumbria)	150 km	82	1.83 km
SN (Fishguard to Aberdovey)	95 km	35	2.71 km
NJ (south side of Moray Firth)	100 km	22	4.55 km
NZ (Durham/North Yorkshire)	130 km	18	7.22 km
NC (Sutherland)	150 km	9	16.67 km

Of course the length of coastline within a grid square varies considerably, but if we take the following examples of grid squares that have a generally linear coast without long indentations, we find the pattern set out in (Table 1.3). Clearly in this analysis, such coasts as Dorset, Suffolk/Essex and Lancashire/south Cumbria are among the most studied, whereas Sutherland is among the least. Therefore, (Figure 1.1) helps to highlight those areas of the British coast that are better understood geomorphologically, and, perhaps, identifies those areas where further study may help us to gain a more complete understanding of the coastal geomorphology of Britain.

The geological background

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The pattern of geological outcrops along the British coast (Figure 1.2) has a fundamental control on the nature of the coastline. This is for several reasons, outlined below

- Coastal topography: Underlying geology has influenced the topography of the land, and the detailed outline of the coast in large part reflects the relief of the littoral zone. Rocks that are susceptible to erosion tend to form bays and inlets, whereas erosion-resistant rocks form headlands. Local differences in the level to which outcrops adjacent to the coast have been lowered by subaerial erosion — and the impact of such differences on the coastal form — are seen best along the English Channel coast, such as along the coast of Dorset, or demonstrated in such contrasting situations as Beachy Head and the adjoining Pevensey Levels.
- Dissection in rocks of different strengths: Where relatively erosion-resistant rocks have been deeply dissected by erosion, the coastal outline is complex, such as in western Scotland. Where weaker rocks have been dissected, former headlands and bays may have been truncated by marine erosion, such as the Seven Sisters in Sussex.
- Geological control on cliff profile: Rocks of all strengths can be cut back by erosion to form cliffs, but weaker rocks generally fail more readily and so form sloping cliffs with angles from 20° to 40°, whereas erosion-resistant rocks are more likely to form near-vertical cliffs, such as at Duncansby, Caithness. In the more resistant rocks, the details of bedding and jointing commonly influence cliff form, both in plan and profile; thus seaward-dipping rocks are likely to suffer slide failure as basal erosion persists, leading to gentler slopes than on horizontal or landward-dipping strata.
- Lithological control of landsliding: Where weak rocks underlie stronger ones, landslides are likely to occur; good examples are Folkestone Warren, now largely controlled by drainage and 'toe loading', and Ventnor–Shanklin on the Isle of Wight, where seaward-dipping Cretaceous strata are still mobile. Where weaker rocks overlie more resistant strata, 'slope-over-wall cliffs' occur (see Chapter 2); examples include the south-west England peninsula (where the upper cliff retains a periglacial facet) and the till-capped Jurassic cliffs of North Yorkshire.
- Control by interfluve level: Rock resistance influences the general level of interfluves, and as cliffs cut back farther inland by wave action, cliff-height may increase as progressively higher interfluves are encountered; maximum cliff height would be attained at the point where the cliffline crosses the crest of the highest interfluves. However, in many areas cliffs are appreciably lower than this potential maximum, suggesting that the rocks are resistant enough to have prevented the landward movement necessary to attain the maximum potential cliff height (or perhaps that the period of stability since sea level reached its present position at that site has been insufficient to achieve much cliff recession).

Locations of the coastal geomorphology GCR sites [from (Figure 1.2)]

Hard-rock cliffs (Chapter 3)

1 St Kilda Archipelago, Western Isles

2 Villians of Hamnavoe, Shetland

3 Papa Stour, Shetland

4 Foula, Shetland

5 West Coast of Orkney

6 Duncansby to Skirza Head, Caithness

7 Tarbat Ness, Easter Ross

8 Loch Maddy–Sound of Harris coastline, Western Isles

9 Northern Islay, Argyll and Bute

10 Buffers of Buchan, Aberdeenshire

11 Dunbar, East Lothian

12 St Abb's Head, Berwickshire

13 Tintagel, Cornwall

14 South Pembroke Cliffs, Pembrokeshire

15 Hartland Quay, Devon

16 Solfach, Pembrokeshire

Soft-rock cliffs (Chapter 4)

17 Ladram Bay, Devon

18 Robin Hood's Bay, Yorkshire

19 Blue Anchor–Watchet–Lilstock, Somerset

20 Nash Point, Glamorgan

21 Lyme Regis to Golden Cap, Dorset

22 South-west Isle of Wight

23 Kingsdown to Dover, Kent

24 Beachy Head to Seaford Head, East Sussex

25 Ballard Down, Dorset

26 Flamborough Head, Yorkshire

27 Joss Bay (GCR Name: Foreness Point), Kent

28 Porth Neigwl, Caemarfonshire

29 Holderness, Yorkshire

Gravel and 'shingle' beaches (Chapter 6)

30 Westward Ho! Cobble Beach, Devon

31 Loe Bar, Cornwall

32 Slapton Sands, Devon

33 Hallsands, Devon

34 Budleigh Salterton Beach, Devon

35 Chesil Beach, Dorset

36 Porlock, Somerset

37 Hurst Castle Spit, Hampshire

38 Pagham Harbour, West Sussex

39 The Ayres of Swinister, Shetland

40 Whiteness Head, Nairnshire

41 Spey Bay, Morayshire

42 West Coast of Jura

43 Benacre Ness, Suffolk

44 Orfordness and Shingle Street, Suffolk

45 Rye Harbour, East Sussex

46 Dungeness, Kent

Sandy beaches and dunes (Chapter 7)

47 Marsden Bay, County Durham

48 South Haven Peninsula, Dorset

49 Upton and Gwithian Iowans, Cornwall

50 Braunton Burrows, Devon

51 Oxwich Bay, Glamorgan

52 Tywyn Aberffraw, Angelsey

53 Hinsdale, Lancashire

54 Luce Sands, Dumfries and Galloway

55 Sandwood Bay, Sutherland

56 Torrisdale Bay and Invernaver, Sutherland

57 Dunnet Bay, Caithness

58 Balta Island, Shetland

59 Strathbeg, Aberdeenshire

60 Forvie, Aberdeenshire

61 Barry Links, Angus

62 Tentsmuir, Fifc

Sand spits and tombolos (Chapter 8)

63 Pwll-ddu, Glamorgan

64 Ynyslas, Ceredigion

65 East Head, West Sussex

66 Spurn Head, Yorkshire

67 Dawlish Warren, Devon

68 Gibraltar Point, Lincolnshire

69 Walney Island, Lancashire

70 Winterton Ness, Norfolk

71 Morfa Harlech, Gwynedd

72 Morfa Dyifryn, Gwynedd

73 St Ninian's Tombolo, Shetland

74 Isles of Scilly

75 Central Sanday, Orkney

Machair (Chapter 9)

76 Machir Bay, Islay

77 Eoligarry, Barra, Western Isles

78 Ardivacher to Stoneybridge, South Uist, Western Isles

79 Homish and Lingay Strands (Machairs Robach and Newton), North Uist, Western Isles

80 Pabbay, Harris, Western Isles

81 Luskentyre and Corran Seilebost, Harris, Western Isles

82 Mangersta, Lewis, Western Isles

83 Tràigh na Berie, Lewis, Western Isles

84 Balnakeil, Sutherland

Saltmarshes (Chapter 10)

85 St Osyth Marsh, Essex

86 Dengie Marsh, Essex

87 Keyhaven Marsh, Hurst Castle, Hampshire

88 Solway Firth (north shore), Dumfries and Galloway

89 Solway Firth: Upper Solway flats and marshes (south shore)

90 Solway Firth: Cree Estuary, Dumfries and Galloway

91 Loch Gruinart, Islay, Argyll and Bute

Coastal assemblages (Chapter 11)

92 Culbin, Moray

93 Morrich More, Ross and Cromarty

94 Carmarthen Bay, Carmarthenshire

95 Newborough Warren, Anglesey

96 Morfa Dinlle, Gwynedd

97 Holy Island, Northumberland

98 North Norfolk Coast

99 The Dorset Coast: Peveril Point to Furzy Cliff

It is clear from the foregoing that development of a map of relative rock resistance to erosion (Figure 1.3) is particularly useful for interpreting coastal form. Whereas geological maps stress rock age and differentiation by lithology within the major age groups, coastal form reflects markedly — in both planform and elevation contrasts in rock strength, and it is the local contrasts that lead to the detail and diversity of our coasts. The outcrop pattern is intimately linked to rock strength (compare (Figure 1.2) and (Figure 1.3); see also (Table 2.1)).

By studying the relative elevation and dissection of rocks in Britain (using a database for the kilometre squares of the Ordnance Survey National Grid) a relative order of resistance to erosion was established for the 71 most common (outcrops >500 km^2) rocks in Britain (Clayton and Shamoon, 1998). While an exact fit to the resistance of rocks to erosion-rates measured at the coast is unlikely to be achieved, the general order of resistance is likely to be similar, and this may aid comparison between sites in future investigations. With six categories, the pattern shown in (Table 1.4) emerges.

(Table 1.4) General order of resistance to erosion of British rock types (from Clayton and Shamoon, 1998).

Very Resistant: Precambrian metamorphosed sediments, Cambrian quartzite and sandstone, Ordovician tuff.
Resistant: Old Red Sandstone, Lower Palaeozoic slates, Palaeozoic basalt and andesite.
High Average: Skiddaw slate, Millstone Grit, Carboniferous limestone, Yoredale series.
Low Average: Palaeozoic shale, Coal Measures, Devonian greywackes, Tertiary basalts.
Weak: Magnesian (Permian) limestone, Jurassic limestone, Hastings Beds, Chalk.
Very Weak: Mesozoic and Cainozoic mudrocks, Thanet sand.

Therefore, geological maps of Britain are important documents in understanding coastal geomorphology. Although (Figure 1.2) is at a small scale, broad connections between outcrop pattern and the outline of the coast can be traced; larger-scale maps, showing more detailed outcrop patterns, emphasize the geological control of coastal form at local levels still further. Thus while there are differences between the older and generally far more resistant rocks of northern and western Britain and the younger and weaker rocks found in east and southern England, within each of these zones local contrasts dominate the coastal geomorphology. From Flamborough Head in Yorkshire southwards and westwards to the Exe estuary in Devon, the Chalk and sandstones that form the cuestas of the scarpland and vale landscape also form the major coastal headlands (Flamborough Head, North Foreland in Kent, Beachy Head in Sussex, and the Needles on the Isle of Wight, for example, all on Chalk) and between them on the intervening clays or on till-covered littoral plateaux, wide bays, locally fronted by saltmarshes and sand dunes, alternate with low cliffs cut into the low till-capped plateaux of Holderness, Norfolk and Suffolk.

Geological influence on sediment supply into the coastal system

A further influence of geology on coastal geomorphology is in the provision of sediment that can be incorporated into beaches. Beaches around Britain vary considerably in their texture (from fine-grained sand to boulders) and in their lithology (from shelly sands to flint cobbles) and reflect the local supply of material of appropriate dimensions. Some coarse sediments are still brought to the coast by rivers, especially in Scotland and Wales, where gradients are steep and coarse-grained material is readily transported by Roods. In contrast, very little sediment other than mud (clay and silt) is now brought down the rivers of lowland Britain to the coast. Thus, especially in areas with more gentle inland relief it is the delivery of sediment from offshore as well as from retreating cliffs that has provided most of the material for the local beaches. Boulders and coarse gravel are derived from erosion of resistant rocks in areas such as Scotland and parts of the Welsh coast, their initial size depending on rock-joint spacing. Locally along the English coast, quartzites are the source of coarse gravel (e.g. at Budleigh Salterton); flints form the commonest pebbles and cobbles on beaches in the south of England.

Many 'shingle' (gravel) beaches (such as Slapton Sands in Devon, Chesil Beach in Dorset and Blakeney Point in Norfolk) have been built from offshore gravels, swept ashore as sea level rose during the Holocene marine transgression, and former sea-floor sediment has contributed to many beaches elsewhere (see (Figure 6.2)). In places, flints are derived from erosion of the Chalk in which they occur. Indeed, Chalk cliffs are generally associated with flint beaches because eroded Chalk debris is quickly broken down by wave action so that Chalk cobbles form a minor part of the beach material. Most flint in English beaches is secondarily derived from quite a wide range of intermediate sources. These include the Pebble Beds of the Tertiary succession of south-east England, where the 'Pebbles' are either derived directly from local erosion, or through their incorporation into river gravels, such as the sequence of Early Pleistocene river terraces — attributed in part to the River Thames — cropping out in Essex, Suffolk and Norfolk. Thus at Dunwich, the cliff contributes flints from gravels at the top of the exposure that were deposited by the ancient River Thames. In contrast, with no local landward source, the flints that dominate Slapton Sands must have been brought ashore from an offshore source. The former river concerned flowed down the English Channel, no doubt fed by such tributaries as the present-day Seine, Rhine and Thames at a time when much of the present-day area of the North Sea was occupied by an ice sheet.

Farther north in England, while we cannot rule out such offshore sources, a large proportion of the gravel has been eroded from glacial gravels and till cropping out along the coast or offshore. In Briton's Lane Pit, within the Cromer Ridge of north Norfolk, a 30 m-thick sequence of coarse flint gravels demonstrates the power of the ice and its associated meltwater in eroding nearby Chalk (for there are few quartzites or other erratics in this section) and so incorporating flints into its deposits. Normally, glacial gravels and tills include a range of erosion-resistant lithologies alongside flint, notably quartzites (which in part at least have been derived from Triassic strata) and metamorphic rocks high in quartz content, as well as well-cemented sandstones perhaps of Carboniferous or Jurassic age. Less chemically stable rocks, such as granites and limestones, are uncommon as clasts and may be absent. Thus it is this glacial assemblage of resistant gravel and (quartz) sand that dominates beaches along most of the coast north of the former glacial limit. Indeed flints are relatively common even on the Irish Sea coasts, for Chalk crops out on the floor of the Irish Sea, as well as lying beneath the lavas of Antrim.

In Scotland and Wales, by far the greatest source of gravel and sediment has been derived from glaciogenic sources, deposited both inland and on the adjacent shelf by either glaciers or glacial meltwater. As a result, the sediments are as varied as the rocks that were originally eroded by ice.

In the north and west of Scotland, erosion of Torridonian sandstones has yielded even older gravels onto beaches, which also commonly contain quartzite, metamorphic schist and gneiss clasts in addition to sandstones. In the northern and western isles a wide, nearshore shelf is the source of biogenic shell sand that has been swept onto beaches, locally reaching almost 100% of the beach materials (e.g. the 'Coral' beaches at Dunvegan, Skye). In the east of Scotland, igneous- and Old Red Sandstone-derived gravels dominate the extensive beaches sourced both from steep-fast flowing rivers and from offshore deposits over much of the Holocene Epoch. In south-east Scotland, Old Red Sandstone and Carboniferous sandstones and shales form the bulk of the beach material and produce beaches with a high proportion of quartz sand.

In Wales, sediment and gravel, other than that of glaciogenic origin, have predominantly been derived from Lower Palaeozoic and Precambrian shales and slates in the north and west, and mainly Carboniferous limestones in the south.

The coastal marine environment: tides, waves, surges and currents

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In global terms, the British Isles have unusually high tides and unusually stormy conditions; thus they have a very dynamic coast, one of the reasons why British coastal research has made such an important contribution to the world literature. However, each of these influences also varies greatly around Great Britain. Tidal range is highest at the head of inlets such as the Bristol Channel, and lowest on the English Channel coast between Start Point and Portsmouth, on the East Anglian coast within the North Sea, Cardigan Bay in Wales, and in Shetland in Scotland (Figure 1.4). Wave energy is highest on coasts exposed to the strong winds of western Britain and the North Atlantic swell; it is lower in such relatively sheltered areas as the Irish Sea and the North Sea. Given its western exposure to the Atlantic Ocean, the English Channel coast tends to fall into an intermediate category (Figure 1.5).

Both tidal movements and the advance of waves into shallow water create currents and these move sediment in the nearshore zone, shaping sandbanks, which in turn can affect the local conditions, for example, by forcing larger waves to break and so lose energy as they touch bottom on submerged banks, or even to break against them at low tide. In constricted bedrock channels, perhaps the best example is the Pentland Firth, the tides create extremely strong currents, and where they are channelled between sandbanks as in the Thames estuary or off Great Yarmouth, the patterns of ebb and flow (often dominating different channels) run much faster than in the open sea.

Tidal range has an effect on coastal landforms. Barrier beaches, behind which saltmarshes form, tend to be restricted to areas with relatively low tidal range, such as the north Norfolk coast. Such areas also have spits, which in some cases grow to many kilometres in length, for example, Blakeney Point and Orfordness. This is because wave processes are more efficiently focused on a narrow vertical range and so waves and wave-generated currents assume greater relative importance in shaping coastal form in these areas than tides.

High tidal-ranges can occur towards the head of estuaries (or Firths in Scotland), and here saltmarshes also develop, though compared with areas of low tidal range they are generally steeper and show much stronger zonation of vegetation, such as in the Bristol Channel—Severn estuary. Seawards of the vegetated marsh, wide tidal flats of sand or mud occur. At such sites, not only are tidal streams more important in determining coastal form, but the relative shelter of the estuary also reduces the impact of waves and wave-induced currents in the shaping of marsh terraces and creek systems. At intermediate tidal ranges, features resulting from both extremes can be found, in places the pattern reflecting local exposure to waves or local protection, so changing the wave energy—tidal range balance from one place to another.

It seems unlikely that tidal range can affect cliff evolution, because coastal cliff form is mainly controlled by the basal removal of material during storms, especially those coinciding with spring tides. However, the height range and perhaps also the slope of shore platforms fronting Jiffs will vary with tidal range. Where wave action is spread over a greater vertical range it will be less effective at every level than where the tidal range is very small. Thus we would expect wide, and almost level, shore platforms where there is a very small tidal range, and more steeply sloping platforms where the tidal range is high (Trenhaile, 1997).

In partly enclosed seas, strong winds and accompanying changes in atmospheric pressure can produce unusually low or unusually high sea levels, known respectively as 'negative surges' and 'surges'. Negative surges can be dangerous for large ships that might run aground or lose steering control over sandbanks, but seems to have little morphological effect. Surges can cause serious coastal flooding, and also have the effect of allowing waves to break with greater force and at higher elevations at the beach or cliff often producing the effect of several years of 'normal' cliff recession in a single tide. They can also lead to considerable changes along low coasts by cutting back dunes, removing sediment from beaches and producing washover fans where the outer coastal barrier is overtopped. Considerable changes followed the surge in the North Sea of 31 January–1 February, 1953, and severe tidal flooding was caused by an Irish Sea surge at Towyn on the North Wales coast in 1990. On coasts facing the Atlantic Ocean 'extreme waves' have been reported (e.g. those crossing Loe Bar early in the 20th century) and these may result from tsunamis generated far away by submarine earthquakes and by the interaction of large storm waves with local bathymetry (Hansom, 2001). High-level sand layers on the east coast of Scotland have been attributed to tsunamis triggered by the Storegga slides in the Norwegian Trough, some 7000 years ago (Long *et al.,* 1989).

The waves reaching the coast are mainly generated by winds offshore. In the case of the semi-enclosed seas of the Irish Sea and the North Sea, most waves are generated by winds blowing across relatively restricted fetches, and so have a short wave-length, short period, and are relatively steep. Thus along the coasts of these seas, the varying pattern of length of fetch is an important control over wave energies from all directions offshore as well as the frequency with which winds blow from any one direction. Wave height is proportional to the square root of the length of fetch, so that in the North Sea waves from a northerly direction are generally the largest, with a secondary maximum in East Anglia for waves from the south-east. In the Irish Sea, a west-facing beach like Blackpool, Lancashire, gets its largest waves from a westerly direction, but these are always short-period waves and so put rather small volumes of water onto the beach as they break. As a result, the wide, sandy beach at Blackpool generally consists of a series of ridges and intervening runnels; the seaward slopes of the ridges may be in equilibrium with the short-period waves. Locally on the North Sea coast, ridge-and-runnel beaches are found in the shelter of a headland, limiting waves reaching the beach to those from the east or south-east; an example is in Bridlington Bay, which is protected from the larger northerly waves by Flamborough Head, Yorkshire.

On those parts of coast exposed to North Atlantic storm and swell waves, energies are much higher and the long-period waves put large volumes of water onto the beach as they break. Thus (as well as providing excellent surfing), such wave conditions often produce very wide beaches with a gentle slope, for example Rhossili in South Wales, the beaches of the Western Isles and in some of the more exposed Cornish bays. Where strong regional winds build large waves, energies are very high, but it is also possible for long-period swell generated far offshore, even in the South Atlantic, to reach the western beaches. Such swell loses height as it moves across the ocean, but it can be distinguished by its typically long period. Beaches exposed to the Atlantic Ocean tend to be dominated by the high energies associated with long-period waves, even where the exposure is indirect and the waves reach the coast after refraction. But they are also exposed to local storm waves with much shorter wave-lengths and period, though often steep and rather destructive. In such locations, considerable changes in the beaches can occur from one storm to another or from storm to calmer conditions dominated by swell.

High wave-energies can cause considerable erosion even of resistant rocks, and will exploit structural weaknesses such as faults, joints and bedding planes. Narrow inlets, caves, stacks and natural arches are found along our higher-energy coasts even in the most resistant rocks. Good examples of such forms, eroded into resistant lithologies, are found almost everywhere on the islands of the St Kilda group and in the Shetland Islands, such as Foula and Papa Stour. They can also be found in weaker rocks where wave energies are lower, for example, the Chalk cliffs of Thanet, Kent. Waves are also responsible for the longshore drift of sediment along the coast and this is described in the following section.

Coastal sediment supply and sediment cells

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Some comments on the geological sources of the coarser beach sediments have already been made above. In many places beach sediments are derived updrift from cliffs undergoing erosion (the so-called 'feeder bluffs'). In some cases the only possible source of beach sediment may lie offshore, whereas in upland areas a large part of the coastal sediment supply is eroded inland and delivered down the main rivers. Finally, some lengths of coarse-grained beach sediment (storm beaches) such as Chesil Beach in Dorset, Slapton Sands in Devon, and Blakeney Point in Norfolk must have been brought landwards during the Holocene marine transgression and now represent relict accumulations which are no longer being added to. However, finer-grained sediment can still move onshore, for example, from shoals within Carmarthen Bay in Wales.

As Bird (1985) has noted in a global review, sediment loss from beaches during the last few decades, resulting in decreased width and increased slope, has been far more common than cases where sediment is accumulating and progradation occurring. The reasons for this remain uncertain, although a role is played by slowly rising sea level, reduction in offshore sediment supply and also by interference with eroding cliffs and longshore transport by coastal structures. The same pattern of beach sediment loss is documented on the English coast; for example, careful measurement from 1:10 000 maps between Flamborough Head and the Thames Estuary showed not only that the length of coast being eroded greatly exceeded that at standstill or prograding, but that along almost all of this coast the low-water mark (LWM) has receded more than high-water mark (HWM), which in turn has receded more than the coastline itself, i.e. the cliff top or the solid line often close to HWST (high-water spring tides) mapped by the Ordnance Survey. Thus the beaches along this part of the North Sea coast are steeper and far less wide than they were a century ago. However, the reasons for this are far from clear, though again sea-level rise, reduction of both offshore and fluvial supply and coastal engineering structures must all play an important part. Indeed, in England particularly, the widespread construction of groynes, revetments and walls has interfered with coastal sediment movement and the coastal sediment balance.

The alongshore transport of sediment (littoral or longshore drift) is achieved by waves and the currents they induce within the breaker zone. The direction is determined largely by the angle of wave approach, i.e. it is related to the dominant fetch. Thus the general direction of transport is southwards on the eastern coast of England, and eastwards on the Channel coast. In the northern North Sea, the pattern is westward movement along the Moray Firth and mainly southward movement along the Aberdeenshire and Angus coast. The pattern around the Irish Sea is a little more complicated since it is not open to the north as is the North Sea, and in general the same direction of transport is not maintained for such long distances as along the Channel and North Sea coasts (Figure 1.6). Locally where the coastal alignment changes, or shelter is provided by a major headland, the direction may be reversed. On some coasts the local direction of movement varies considerably from one month to another; this is generally where the fetch varies different directions (such as in the Irish Sea) and under these conditions the direction of longshore transport varies with the wind direction. But even if the pattern from one month to another is variable, such coasts generally show a consistent longterm pattern of movement, reflecting the dominant combination of frequency of wind direction and the length of fetch.

Beaches that are declining in sediment quantity, whether caused by sea-level rise, reduction of offshore and fluvial sources or anthropogenic interference, would normally revert to a dynamic equilibrium by allowing more rapid erosion of the coastal cliffs, thus improving sediment supply to the local beach system. That this is the natural pattern is suggested by the response to the southwards migration of ords (lengths of low beach volume) along the Holderness coast of

England, which is accompanied by a rapid rise in the local rate of cliff recession. However, increasingly, such cliffs have been protected by structures such as revetments and sea walls, so the sediment supply remains restricted, even though beaches are losing sediment downdrift and offshore. This is of course just one aspect of the struggle between a natural coastline that will move in position as an adjustment to, for example, sea-level rise, and the desire of coastal managers to stabilize the position of the coast.

Despite this general understanding of long-shore-transport patterns, the details of direction and rate of transport have only begun to be established over the last few decades. Part of the incentive has been the attempt to understand changing sediment volumes better, as the starting point for the improved management of the coast, whether through built structures or the feeding of sediment to beaches from offshore. Local studies of sediment transport include the use of radioactive tracers as at the southern tip of Orfordness and the adjacent Shingle Street beach, as well as various less successful attempts using dyed or fluorescent sand. More recently computer modelling has been used, involving the modelling of the offshore topography and the generation and refraction of waves based on offshore wind data iterated over several years. This has allowed estimates of potential long-shore transport, though at many locations this is not reached due to the shortage of sediment.

In several cases, such work has enabled a sediment budget to be quantified, involving the calculation of sediment input from cliffs (and its partition by size into mud, sand and gravel), the modelling of the rate of transport downdrift, the measurement of the volumes of prograded sediment in zones of accretion and on spits, and thus, as a balancing element, offshore removal, which has been generally very difficult to measure directly (see (Figure 5.5)). This was achieved relatively successfully (Clayton *et al.,* 1983) for the Norfolk cliffs and coast southwards to Great Yarmouth, and fairly consistent estimates have also been made for the Holderness cliffs, where the total volume eroded is higher, though a much greater proportion is mud.

More recently the drive to understand coastal sediment budgets and their inter-relationship with coastal management schemes has led to the adoption of littoral sediment cells and subcells as the basic units of coastal zone management in Great Britain (Figure 1.6). The primary cells are large scale and the dividing points are the headlands, such as Cairnbulg Point or Flamborough Head, around which almost no sediment can pass, or embayments that act as sediment sinks (e.g. the Wash). Within these cells are secondary subcells; some are short lengths where the coastal alignment reverses the direction of drfit for a limited distance, others are where renewed cliff supply restores the dwindling longshore drift and produces larger beach volumes. In terms of shoreline management plans, the sub-cells are the most important units, but maintaining the natural integrity of the primary cells is a consideration, based on the principle that any interference with longshore drift can disadvantage beaches — and coastal stability — downdrift. A difficulty in adopting this approach is that some cells are already severely disrupted by engineering works, either by coastal defence structures that have prevented coastal cliffs providing a continuing supply of sediment to maintain beaches, or schemes such as the reefs off of Sea Palling in Norfolk, which have obstructed the former southerly drift of coastal sediment.

Sea-level history

K.M. Clayton

We have a good general understanding of global sea-level history from the time of the last glacial maximum, some 18 000 years ago. The abstraction of water from the oceans to build the great land-based ice caps reduced global sea level to some 120–140 m below that of the present day. By the beginning of the Holocene Epoch, 10 000 years before present (BP), sea level was some 40 m below present, and as it continued to rise (the Holocene marine transgression) was within 10 m of its present stand at about 5000 years ago, and close to present level by 4000 years BP (Figure 1.7)a,b). However, the precise changes at any one site will depart from this pattern for many reasons, including crustal stability (tectonic changes, the effects of loading or removal of load by ice sheets and the oceans themselves, local sedimentation) and tidal changes as the coastal configuration has changed, as well as many other lesser effects that may lead to local departures from the general pattern of sea-level rise. For example, Carter (1982) has shown that the post-1950 fall of sea level at Belfast of about 1 mm a^{-1} is probably the result of land-claim around the estuary, rather than a genuine fall in sea level.

Thus local evidence of sea-level history is of great importance, but the complications involved mean that our knowledge is still very incomplete and not always well linked to our understanding of the likely causes. Further, we require both good stratigraphical evidence (including reliable relationship to the sea level of the time as well as accurate levelling to determine altitude) and good age determination (generally based on radiocarbon, converted to sidereal years) if the local evidence is to be useful; so prograding coasts generally have a better record of sea-level history than those undergoing erosion. Errors in age determination can result from inaccurate ^{14}C dates (e.g. the 'hard-water effect') or from compaction of sediments causing misjudgement of the postulated height of former sea-level markers.

An independent source of evidence for the last century or so is the trend of long-term tide-gauge records. The variability of short-term sea level with changes in the weather and the longer-term periodicity of spring and neap tides means that records of less than a few decades are unreliable, or frustrating where tide gauges have been discontinued (such as at Felixstowe) or recently established to help in the surge warning system, resulting in data which cannot yet give a statistically reliable long-term trend. Where gauges have remained in place for many decades, reliable data indicate that parts of northern Britain are still showing relative rise in land level (and thus relative sea-level fall), a result of continued recovery from the ice load of the last glaciation, while southern Britain generally shows relative sea-level rise, in places faster than the average annual rise of sea level (*c.* 1.5 to 2 mma^{-1}) around the coast, indicating at least local land submergence. The result is the widely accepted pattern of relative sea-level fall in the north-west and rise in the south, with relative stability along a line just south of the Scottish border (Figures 1.8) a,b). In Scotland, the pattern of relative sea-level rise is related to the distance from the isostatic uplift centre (see (Figure 1.8)b, with central Scotland undergoing uplift and subsidence characterizing the northern and Western Isles.

What is less clear is how far neotectonic movement, other than glacioisostatic recovery and the effects of water loading following sea-level rise, is of significance. The long-held view that Britain is tectonically stable has been challenged in recent years (Embleton, 1993) and several authors have reported evidence of relatively local neotectonic movements (e.g. Clayton and Shamoon, 1999; Ringrose *et al.,* 1991), but these have generally (though not universally) been inferred from evidence covering long periods since Mid- or Late Tertiary times. Thus the rates of coastal tectonic movement; while high enough to be detectable, are slow compared with both the known rates of postglacial isostatic recovery and submergence, and with the current rate of sea-level rise. Thus there is an 'inheritance effect' that has affected broad coastal (and near-coastal) form, but the direct effect of neotectonic movements on contemporary coastal change is likely to be small. Over time, further detail will emerge from comparison of local chronologies of Holocene sea-level change, adding to the significance of these studies.

Detailed local histories of sea-level change have been established in several locations where the stratigraphical record is good, including around Morecambe Bay, the Fens and the north Norfolk coast, and research continues to add further data to the sea-level history of these sites. From these records it appears that the general rise of sea level has not always persisted throughout the mid-late Holocene period, with a sequence of relative transgression succeeded by relative regression repeated several times. An example of this is the Fenland sea-level curve, which, while showing a general rise over the last 7000 years that slowly reduced in rate towards the present day, nevertheless includes at least four intervals of sea-level fall (Figure 1.7)b. Similar regressions are found in other records (e.g. the north Norfolk coast) though it is not always certain that they coincide in time. This is not necessarily to be expected, for the Fenland area shows an average rate of subsidence, when the sea-level curve is compared with the average of several North Sea records, of 0.91 m ka^{-1}, and there are hints that this has varied over time. Further, there is good evidence of a time-lag between sea-level tendency and local sedimentation in Fenland, so allowance is needed when comparisons are made with other areas. Thus the breaks in the general record of transgression may well result from a local combination of sea-level and land-level changes. Attempts have been made to separate these two influences, and in time we may expect greater success as the quality of local records improves. For the moment, it would be rash to suggest we have a reliable and detailed record of sea-level changes over the last few thousand years.

Currently, a better understanding is being acquired of the role of past sea-level change on prograding coasts such as The Wash–Fenland, north Norfolk and the Thames estuary, and this is concomitant with improvements in our understanding of coastal evolution. The contrasting history of many Scottish prograding coasts undergoing relative sea-level fall over the Holocene Epoch (and in places the delivery of relatively large volumes of sediment down rivers and from offshore) has yet to be compared to subsiding coasts farther south. Some Scottish coasts show progradation where large amounts of sediment arrived at a time coincident with a relative sea-level fall, such as in the Dornoch and Moray firths, but some coasts in the northern and western islands have undergone almost continuous relative sea-level rise. Our knowledge of the variation from place to place of relative sea-level rise has yet to be applied to the form and dimensions of shore platforms on coasts undergoing erosion, even though this seems likely to be a factor in the evolution of cuffed coasts.

Our understanding of climate change, including the evidence for a rise in mean world temperature over the past 150 years, is linked to the evidence of contemporary sea-level rise across the world oceans (and matched by the North Sea data) of 1.5 to 2 mm a^{-1}. Climate change models suggest that this rate of rise may increase to at least 4 mm a^{-1} and perhaps higher, with half of this rise coming from the expansion of the warming ocean. Nevertheless, future rates of sea-level rise may reach or exceed the highest rates experienced during the Holocene Epoch, so greater understanding of past changes must aid our management of such coasts in the future.

One aspect of future sea-level rise is that as the coastline is driven landwards (which will usually be the case except where sediment supply can keep pace with the tendency to such adjustment), the process causes what is currently termed 'coastal squeeze'. That is, the natural coastal landform areas from intertidal mudflats to saltmarshes, beaches and sand dunes will be reduced in width between the low-water mark and whatever man-made or natural slopes mark the inland penetration of the highest tides. Unless conditions allow these landward limits to move (e.g. by the abandonment of flood banks), the zone within which natural coastal landforms can develop will be reduced in width, and those forms will be less well developed and no doubt liable to still greater damage in future. The engineering adjustment to threatened coastal squeeze by the removal of artificial structures is termed 'managed re-alignment' or 'managed retreat' (Hansom *et al.*, 2001).

Coastal management and coastal engineering

K.M. Clayton

Over the last two centuries, the land near the coast has seen many changes in land use. The recreational use of the coast first led to fashionable seaside resorts, and with the development of the railway network many of these grew into major coastal towns devoted to sea bathing and leisure pursuits, with promenades and piers. At the same time, the industrial revolution led to the growth of ports and of seaside industry, while the increasing skill and resources of the coastal engineer, allowed ever-larger schemes of land-claim. Saltmarshes, once reclaimed on a small scale for grazing, were seen as ideal sites for large-scale industry looking for level land. That local docks could be developed for the import of raw materials and the export of heavy finished products was an added advantage. With the increased mobility offered by the motor car, seaside villages have expanded into commuting dormitory towns or retirement areas epitomized by Peacehaven east of Brighton.

The result of this combination of coastal urbanization and the confidence of coastal engineers has led to the profound modification of much of our coast (Figure 1.9). Few of the sites described in this volume, especially those in England, are entirely free of coastal structures, though care has been taken to select those that are least disturbed. Despite the caution of the Royal Commission on Coastal Erosion and Afforestation, which reported from 1907 to 1911 and noted that a balance would need to be struck between defended coasts and the supply of sediment from unprotected cliffs, much more of the coast has been modified throughout the 20th century. Events such as the serious flooding and loss of life of the 1953 surge on the North Sea coast of England encouraged further expenditure on coastal defences.

Conditions changed slightly after 1985 when all supervision of coastal engineering schemes at a national level in England and Wales was transferred to the then Ministry of Agriculture, Fisheries and Food (formerly the Department of the Environment had borne responsibility for upland coasts) and the same cost/benefit tests were applied to defences protecting upland coasts as to coastal flood defences, though to date few of the existing structures have been removed. However, many are now deteriorating rapidly, and where they protect undeveloped agricultural land it seems unlikely they will be replaced. In the same way, the modern advice that planning law should be used to prevent developments of land liable to flood, or of coasts liable to undergo erosion, will take many years to take effect, though if applied consistently a reduction in developed coasts should emerge.

Relatively little research has looked at the effects of engineering works on natural change at the coast. It seems likely that not only the production of sediment from cliffs undergoing erosion has been reduced (Clayton, 1989), but also the rate of transfer along the coast by long-shore drift has been modified by the large number of groynes along our shores. Indeed, these groynes may not only have reduced longshore transport, but in places seem likely to have allowed more beach sediment to be moved offshore and so be permanently lost to the coastal system. Sea walls increase wave reflection and often lead to sediment loss from the beaches fronting them. Land-claim of saltmarshes has reduced the volume of the tidal prism entering many estuaries and may have been a factor in the erosion of the remaining marshes in front of the sea banks (walls) protecting the areas that have been reclaimed. We lack full understanding of the reasons for the persistent erosion of many saltmarshes, although in places current schemes for the set back of the banks and re-establishment of saltmarsh may lead to a more general improvement in conditions.

The funding of coastal defence works in the UK has concentrated on the initial capital cost and not the cost of later repairs. This has made it difficult to finance beach nourishment as a method of coastal defence in the UK. Special arrangements were made to allow the early beach feeds, as at Portobello and Bournemouth, and the recycling of material as at Dungeness and on the eastern side of The Wash at Snettisham. It remains uncommon, although it is increasingly being utilized, for example along most of the Lincolnshire coast, and south of the artificial reefs on the Norfolk coast at Waxham and at Kingston-on-Spey in the Moray Firth.

The recognition that the British coast may be divided into a series of coastal sediment cells (some of which may have smaller subcells nested within them, see (Figure 1.6)) is now being applied to shoreline management. Under current arrangements, in England and Wales, a set of Shoreline Management Plans has been drawn up by Local Authorities, or groups of Local

Authorities (under the auspices of the Department of Environment, Food and Rural Affairs), for each coastal sector, the sectors being based mainly on the recognized coastal sediment cells. In Scotland, some Local Authorities have undertaken similar work for the coast under their jurisdictions, although it is not a formal requirement. The philosophy behind this approach is that it is through the understanding and management of coastal sediment volumes that the greatest stability may be achieved, and that within a cell, local areas may be allowed to undergo erosion in the knowledge that this will improve sediment supply, and thus stability, elsewhere. Where the solution of feeding sand (and/or gravel from offshore) is adopted, this can be seen to benefit the whole cell if the feed is in an updrift location, whereas in a few cases (such as at Dungeness and on the eastern side of the Wash), sediment is collected downdrift and recycled updrift to move again through the system on a cyclical basis.

In England and Wales, the development of Shoreline Management Plans involved a complex consultative process led by the Environment Agency and utilizing engineering consultants. Maritime local authorities and bodies such as the Countryside Council for Wales, English Nature, and the Countryside Agency were involved. These plans are updated at regular intervals; the result is a more organized and longer-term strategic assessment of needs than before, though inevitably the resulting plans tend to require considerable compromises between the widely varying views of the bodies involved. How far compromises can be made to work on the coast remains to be seen, but it may be that in future a choice between determination to hold the line, or a willingness to allow natural change in the future, would be better choices than some of the compromise proposals currently being adopted.

Certainly something of a change in attitude can be recognized at a national level. Proposals subject to cost/benefit assessment must now include the 'non-intervention' option, and, facing the inevitability of future sea-level rise, the advantages of 'managed re-alignment' are being canvassed. Insofar as these changes lead to no further encroachments on the length of natural coast remaining in Britain they will be welcomed by the geomorphologist.

One aspect of the coast that has received greater attention (especially since the surge of 1953) is coastal hazard, both the local threat of rapid cliff recession, but more widely the threat of coastal surges, both in the North Sea (e.g. 1953) and the Irish Sea (e.g. the flooding at Towyn in 1990). It is recognized that water levels can be raised during a surge by as much as 2.5 m, and with current and future sea-level rise, and perhaps an increase in storm frequency with climate change, the matter is taken seriously. Well-designed warning systems based on meteorological forecasting systems are now in place, and tidal barrages have been constructed, for example, on the Thames at Woolwich and at Hull and

Swansea. Education of the public at risk, however, is less developed.

Further reading

For further information on coastal geomorphology processes and influences, the reader is directed to *Coastal Systems* (Haslett, 2000) *Coastal Geomorphology: An Introduction* (Bird, 2000); An *Introduction to Coastal Geomorphology* (Pethick, 1984); *Coastal Environments: an Introduction to the Physical, Ecological and Cultural Systems of Coastlines* (Carter, 1988), and *Coasts* (Hansom, 1988). These titles give a comprehensive treatment of coastal evolution and dynamics, providing background for the study of coastal landforms and how and why they are changing, with worldwide coverage of examples, numerous illustrations and extensive references to the scientific literature. French (1997) provides useful discussion of managed re-alignment and coastal zone management and Mks and Spencer (1995) discuss coastal problems.

Steers provides descriptive texts on the coastlines of England and Wales (1964a) and Scotland (1973).

GCR site selection guidelines

V.J. May and N.Y. Ellis

The GCR site-selection exercise for coastal geomorphology followed four categories ('GCR Blocks'), one for each of England, Scotland and Wales and one for 'Saltmarsh Geomorphology'; although three of the 'Blocks' are country based, comparisons were made to ensure that certain types of site occurring in each were not over-represented in a Great Britain-wide context.

Before site assessment and selection began, the first stage in the project was to apply the ethos of the GCR — outlined below — in order to fine-tune GCR selection-criteria. The coastal geomorphological literature was reviewed to identify the most cited sites to assist in the compilation of lists of candidate GCR sites. The GCR site selection work also included a survey of the morphodynamics of the whole coastline, carried out in conjunction with the CORINE coastal erosion project (European Commission, 1998), which provided a means by which to judge the 'representativeness' (see below) of the short-listed sites.

Broad GCR site selection criteria

The general principles guiding GCR site selection are described in the introductory GCR volume (Ellis *et al.,* 1996), but can be encapsulated in three broad components:

- International geological or geomorphological importance (for example, Internationally renowned 'type' sites, but other sites that have informal, but widely held, international recognition are also selected).
- Presence of 'classic' or exceptional features that are scientifically important (for example, 'textbook' examples of particular features or exceptionally unusual or rare types of features are included).
- Presence of representative Earth science features that are essential in comprehensively portraying Britain's Earth history. Thus, a site may be selected for showing the most complete regional representation of phenomena that are otherwise quite widespread.

It should be assumed that an 'internationally' rated site will also be representative of an event or process and may include exceptional features.

In order to ensure true national importance in the selected representative sites, site selection was underpinned by the premise that the *minimum number* of sites should be selected. By choosing only those sites absolutely necessary to represent the most important aspects of Britain's

(Table 1.5) Morphosedimentological classification of the British coast (based on European Commission (1998 – the CORINE project érosion cotieré).

Morpho-sedimentological type	Active (km)	Protected* (km)	Total (km)
Hard-rock cliffs	7990	7	7997
Soft-rock cliffs	1401	221	1622
Shingle beaches	818	225	1043
Sand beaches	1274	302	1576
Heterogeneous beaches	415	126	541
Beaches for which no data available	59	0	59
Muddy and estuarine coasts	999	484	1483
Totals	12956	1365	14321
Anthropogenic coasts (including harbours, land-claim)			2096
Total			16417

* i.e. modified by coastal defence/protection works.

coastal geomorphology unnecessary duplication was avoided.

Where several choices of representative sites exist, a series of weightings was applied to the general guidelines to help to distinguish the best (or most suitable) site for the GCR. For example, preference was given to sites with the most extensive or best-preserved record of a certain feature, the most detailed geochronological evidence or a particularly long history of study. Sites that have contributed to our understanding of coastal geomorphology or have significant potential for future research were also preferred.

In some cases, 'representative' sites were selected for the GCR as part of a group of related sites. Such a group of sites may show different aspects of one type of phenomenon, which shows significant regional variations in its characteristics, for example, sites with similar land-forms have been selected from areas having different tidal ranges. Wave climates also vary greatly, the greatest contrast being between the North Sea and the Atlantic coastline. Within this, wave energies vary enormously, the highest being in the Outer Hebrides, west Orkney and Shetland. Thus suites of sites can be identified in the GCR that demonstrate the differences of wave climate and tidal range, as well as more local variations in wave and tidal conditions. In this case there may be 'core' sites, perhaps those showing the most extensive and best researched landform features, while other sites may demonstrate significant variations on the main theme. Nonetheless, it is the group of sites together that remains nationally important.

On an entirely practical level, all selected sites must be conservable, meaning in essence that development planning consents do not exist or that amendments can be negotiated.

Finally, extensive consultations were carried out with appropriate geomorphologists, and many sites were assessed carefully before the final listing was produced. The comments made by the specialists and the field observations were used to produce a modified site shortlist, and this was then slightly adjusted during preparation of the site descriptions for this volume.

GCR Networks

There are many problems inherent in producing a truly representative list of nationally important sites that merit conservation. In order to help provide a framework for selecting sites, the concept of GCR networks has been applied.

The geomorphology of the coastline is controlled by a complex interaction of factors — the dynamics of the coastal 'cell', geological controls (e.g. rock type and structures), the Pleistocene inheritance (isostatic and eustatic effects), sediment 'budget', tidal regimes as well as anthropogenic influence. It is the intention within the 'representativeness' rationale of the GCR to be able to demonstrate the interplay of these themes and their manifestations from the evidence present in the selected GCR sites. These themes can be thought of as providing a basis for individual *GCR Networks,* which link clusters of representative sites.

A broad categorization was devised for the European Commission CORINE project erosion cotiere (European Commission, 1998), and the classification scheme is shown in (Table 1.5). However, in order to establish a scheme of GCR networks for coastal geomorphology, a more detailed structure was required. Ultimately, some 26 networks (broadly following King, 1978) were identified for the GCR project. The themes were:

A. Cliffed coasts

1. Large-scale structural control: longitudinal and transverse coasts

2. Small-scale structural control: caves, arches, stacks, geos, zawns

3. Cliff forms and processes: plunging cliffs, slope-over-wall, hog's back, variety of rates of cliff retreat, differential erosion

4. Exhumed and emerged forms: cliffs, benches

5. Karstic development

B. Shore platforms (including both contemporary and emerged features)

6. Structurally controlled

7. Erosionally dominated

C. Beaches and intertidal sediments

8. Beach orientation: relation to wave direction, swell-dominated beaches

9. Beaches undergoing erosion

10. Prograding beaches

11. Beach phases

12. Pre-existing sediment sources, including pre-existing clasts

13. Emerged ('raised') beaches

14. Cliff-foot beaches

15. Dunes: rock-based, gravel-based, restricted sources, sand plains

16. Spits

17. Barrier beaches

18. Cuspate forelands and nesses

19. Tombolos and tied islands

20. Intertidal sediments

21. Mudflats, ridge and runnel forms

22. Saltmarsh morphology — creeks, saltpans, piping

23. Machair

D. Coastal valleys

24. Chines, truncated valleys, coastal waterfalls

E. Inlets and submerged coasts

25. Fjords, rias, estuaries

F. Semi-enclosed bays

26. Restricted sediment sources and transfers, submarine barriers, sediment sorting

In England and Wales alone, 186 sites were identified as candidates to represent these themes, each of which was visited and assessed before being reduced to a select 59 GCR sites. For Great Britain as a whole, 99 GCR sites were selected (see (Figure 1.2)).

Clearly, any one site may be helpful in elucidating several of these themes and therefore may contribute to more than one GCR Network (for example, Culbin, on the Moray Firth, provides information on sea-level change as well as gravel delivery data over the Holocene Epoch at a site characterized by well-developed dunes situated on top of spit structures; Carmarthen Bay demonstrates sea-level change and the geological controls in cliff development; see (Table 1.6)). Many sites demonstrate several themes, although some are dominated by a single key feature; this has been the basis for the arrangement of the chapters in this book. However, sites with particularly diverse assemblages of coastal features are grouped together in a final chapter.

The GCR sites described in this volume exclude major coastal landslides, such as Folkestone Warren; which are described in the *Mass Movements* volume of the GCR Series (Cooper, in prep.). Cross-reference to these sites, however, is made in Chapter 2 and the chapter on soft-rock cliffs (Chapter 4). Also, sites that are of interest for coastal features that are particularly important for elucidating the Pleistocene history of Britain are described in the Quaternary volumes of the GCR series (e.g. Campbell and Bowen, 1989, Gordon and Sutherland, 1993).

Similarly those sites on the coast that are important for their palaeontological, stratigraph-ical, petrological or mineralogical features are described elsewhere in the GCR series.

GCR site boundaries

Definition of the boundary of the sites was based primarily upon the extent of the landform suite, but on the more rapidly changing sites, the geographical area in which processes that produce and maintain the landform suite was included as far as possible. Therefore, on a dynamic coast with unconsolidated sediment, definition of boundaries was based initially upon the process-unit — the sediment-transport cell — where this can be recognized. However, technically this means that many coastal geomorphology GCR sites should extend seawards beyond the low-water mark (LWM), since the sediments and the processes are predominantly marine. However, a limitation is that areas below the LWM are not explicitly covered by the Site of Special Scientific Interest (SSSI) system by which GCR sites are conserved.

On hard-rock cliffs, the landward boundary is usually the level of spray action or of subaerial processes such as gullying, but on several sites it has been set back a few metres from the cliff-top edge. On cliffs undergoing rapid erosion, the boundary has been identified with a probable position no more than 10 years hence. In these cases, it will be necessary to adjust the boundary as cliff retreat continues. The inland boundary of dune systems is usually the edge of blown sand that has not been reclaimed for farming or forestry. Where dunes have been afforested, the zone over which coastline changes have been documented in the 20th century has been included.

Anthropogenic influences and the GCR

Prior to the GCR project, with the Coast Protection Act (1949) and the east coast floods of 153, considerable attention was given to the design of coastal structures and the maintenance of sea *defences.* The former Naturc Conservancy Council carried out a large number of surveys of beaches and dunes; sites such as Chesil Beach, Dawlish Warren and Orfordness became key field sites. In the 1950s, Gibraltar Point became established as a field site undergoing regular monitoring, as Scolt Head Island had since the 1920s.

(Table 1.6) Main features of each GCR Site, broadly following the classification of King, 1978, to show where different features are represented.

Table 1.6 Column headings

1. Large-scale structural control	14. Cliff-foot beaches
2. Small-scale structural control	15. Dunes, including sandplains
3. Cliff forms and processes	16. Spits
4. Exhumed forms: cliffs, benches	17. Barrier beaches
5. Karstic development	18. Cuspate forelands and nesses
6. Shore platforms — structural control	19. Tombolos and tied islands
7. Shore platforms — erosional control	20. Intertidal sediments
8. Beach orientation	21. Mudtlats, ridge and runnel forms
9. Beach undergoing erosion	22. Saltmarsh morphology
10. Prograding beach	23. Machair
11. Beach phases	24. Coastal valleys
12. Pre-existing clasts	25. Inlets and submerged coasts
13. Emerged ('raised') beaches	26. Semi-enclosed bay

	Chapter 3 Hard-rock cliffs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	St Kilda Archipelago	x	x	x	x																					x	
2	Villians of Hamnavoc, Shetland	x	x	x	x			x								.										x	
3	Papa Stour, Shetland	x	x	x	x			x							x											x	
4	Foula, Shetland	x	x	x	x		x	x							x											x	
5	West Coast of Orkney	x	x	x	x		x	x							x											x	
6	Duncansby to Skirza Head, Caithness	x	x	x	x		x	x						x	x											x	

7	Tarbat Ness, Easter Ross	x		x	x			x						x	x												
8	Loch Maddy-Sound of Harris coastline			x																						x	x
9	Northern Islay, Argyll and Bute	x			x			x						x	x												
10	Butlers of Buchan, Aberdeenshire		x	x	x			x							x												
11	Dunbar, East Lothian	x	x	x	x		x	x						x	x												
12	St Abb's Head, Berwickshire	x	x	x			x	x						x	x												
13	Tintagel, Cornwall	x		x			x								x												
14	South Pembroke Cliffs, Pembrokeshire		x	x	x	x																					
15	Hartland Quay, Devon	x	x	x			x	x																	x		
16	Solfach, Pembrokeshire			x				x													x				x	x	
	Chapter 4 Soft-rock cliffs																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
17	Ladram Bay, Devon		x	x			x								x												
18	Robin Hood's Bay, Yorkshire	x	x	x			x	x		x					x												
19	Blue Anchor—Watchet—Lilstock, Somerset		x	x			x	x																			

20	Nash Point, Glamorgan		x	x			x	x																			
21	Lyme Regis to Golden Cap, Dorset		x	x						x			x		x												
22	South-west Isle of Wight	x	x	x			x	x	x	x					x					x					x		
23	Kingsdown to Dover, Kent		x	x				x		x					x												
24	Beachy Head to Seaford Head, East Sussex	x	x	x			x	x	x	x					x										x		
25	Ballard Down, Dorset	x	x	x				x							x												
26	Flamborough Hcad, Yorkhsire	x	x	x			x	x							x												
27	Joss Bay (Forencss Point), Kent		x	x				x							x												
28	Porth Neigwl, Gwynedd			x					x	x					x												
29	Holdcmcss, Yorkshire		x	x					x	x					x												
	Chapter 6 Gravel and 'shingle' beaches																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
30	Westward Ho! Cobble Beach, Devon								x	x			x				x										

31	Loe Bar, Cornwall		x				x	x	x					x		x									
32	Slapton Sands, Devon							x	x					x		x									x
33	Hallsands, Devon	x	x	x			x		x				x												
34	Budleigh Salterton Beach, Devon		x					x	x	x		x													
35	Chesil Beach, Dorset		x				x	x	x		x	x							x						
36	Porlock, Somerset																								
37	Hurst Castle Spit, Hampshire							x	x	x						x				x	x	x			
38	Pagham Harbour, West Sussex						x	x		x						x			x						x
39	The Ayres of Swinister, Shetland							x								x	x		x	x					x
40	Whiteness Head, Moray							x	x	x			x		x	x				x		x			
41	Spey Bay, Moray							x	x	x	x	x	x		x	x				x		x			
42	The West Coast of Jura, Argyll and Butc		x			x	x					x	x	x											
43	Benacre Ness, Suffolk							x	x	x	x							x							
44	Orfordness and Shingle Street, Suffolk							x	x	x						x		x							

45	Rye Harbour, East Sussex								x	x	x					x	x	x									
46	Dungeness, Kent								x	x	x	x	x				x	x	x		x						
	Chapter 7 Sandy beaches and coastal dunes																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
47	Marsden Bay, County Durham		x	x				x	x			x			x												
48	South Haven Peninsula, Dorset				x				x	x	x					x											
49	Upton and Gwithian Towns, Cornwall		x	x	x					x					x	x											
50	Braunton Burrows, Devon		x	x	x			x	x	x	x			x		x	x				x						
51	Oxwich Bay, Glamorgan								x	x	x					x											
52	Tywyn Abcrffraw, Anglesey			x					x	x	x					x											
53	Ainsdale, Lancashire								x	x	x	x				x						x				x	
54	Luce Sands. Dumfries and Galloway								x		x	x		x		x					x	x	x				
55	Sandwood Bay, Sutherland								x	x				x		x					x			x			
56	Torrisdale Bay and Invernaver, Sutherland								x	x	x			x		x					x	x	x	x		x	x

57	Dunnet Bay, Caithness								x	x		x				x					x						
58	Balta Island, Shetland									x						x								x			
59	Stratlibeg, Aberdeenshire								x	x	x	x		x		x					x						
60	Forvic, Aberdeenshire								x	x	x			x		x	x				x						
61	Barry Links, Angus								x	x		x		x		x			x		x						
62	Tentsmuir, Fife								x	x	x	x				x	x				x	x					
	Chapter 8 Sand spas and tombolos																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
63	Pwll-ddu, Glamorgan			x					x		x					. x	x										
64	Ynyslas, Ccrcdigion								x	x	x					x	x				x		x				
65	East Head, West Sussex								x	x	x					x	x				x						
66	Spurn Head, Yorkshire								x	x	x					x	x				x						
67	Dawlish Warren, Devon		x						x	x						x	x				x						
68	Gibraltar Point, Lincolnshire								x		x	x				x	x				x	x	x				
69	Walney Island. Lancashire			x					x	x	x				x	x	x	x									
70	Winterton Ness, Norfolk								x	x						x			x								
71	Morfa Barka, Merioncth, Gwynedd								x	x	x					x	x				x	x	x				

72	Morfa Dyffryn, Merioneth, Gwynedd								x	x	x		x			x	x		x	x	x						
73	St Ninian's Tombolo, Shetland			x					x		x					x				x	x			x		x	
74	Isles of Scilly		x	x				x	x	x	x		x		x		x			x	x						
75	Central Sanday. Orkney								x	x	x	x				x	x			x	x	x		x		x	
	Chapter 9 Machair																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
76	Machir Bay, Islay, Argyll and Bute		.	.					x	x				x		x					x			x			
77	Eoligarry, Barra, Western Isles								x	x	x					x				x	x	x	x	x		x	
78	Ardivacher to Stoncybridge, South Uist								x	x						x					x			x		x	
79	Homish and Lingay Strands (GCR name: Machairs Robach and Newton), North Uist								x	x	x					x	x			x	x	x	x	x		x	
80	Pabbay, Harris, Western Isles									x	x					x					x			x		x	

81	Luskentyre and Corran Scilebost, Harris								x	x						x	x		x		x		x	x		x	
82	Mangestra, Lewis, Western Isles									x											x			x			
83	Traigh nit Berle, Lewis, Western Isles								x	x						x					x			x		x	
84	Balnakeil, Sutherland								x	x				x		x					x			x		x	

Chapter 10 Saltmarshes

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
85	Culbin, Moray								x	x	x	x	x	x		x	x	x			x	x	x				
86	Morrich More, Ross and Cromarty								x	x	x	x		x		x	x				x	x	x				
87	St Osyth Marsh, Essex								x	x	x	x	x				x				x	x	x				
88	Dengie Marsh, Essex								x	x	x	x	x				x				x	x	x				
89	Keyhaven Marsh, Hurst Castle, Hampshire												x				x				x	x	x			x	
90	Solway Firth (north shore), Dumfries and Galloway													x							x	x	x				

91	Solway Firth: Upper Solway flats and marshes (south shore), Cumbria													x							x	x	x			x	
92	Solway Firth: Crec Estuary (Outer Solway Firth), Dumfries and Galloway													x							x	x	x			x	
93	Loch Gruinart, Islay										x			x		x					x	x	x				

Chapter 11 Coastal assemblages

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Culbin, Moray — see site number 85																										
Morrich More, Ross and Cromarty — see site number 86																										

94	Carmarthen Bay (including GCR site Burry Inlet), Carmarthenshire	x	x	x	x		x	x	x	x	x	x	x	x							x	x	x		x	x	
95	Newborough Warren, Anglesey		x	x				x	x	x	x	x				x	x				x	x	x			x	
96	Morfa Dinlle, Gwynedd			x					x	x	x					x	x				x						
97	Holy Island (GCR name: Goswick—Holy Island—Budle Bay, Northumberland	x	x	x	x		x	x	x	x	x	x		x	x	x	x	x			x	x	x				
98	North Norfolk Coast			x				x	x	x	x	x			x	x	x	x			x	x	x				
99	The Dorset Coast: Peveril Point to Furzy Cliff	x	x	x			x	x	x	x			x		x												x

Since then, management of the coastline has been an important focus for some coastal geomorphologists, often in association with coastal ecologists, engineers and planners. In particular, between 1969 and 1981, Ritchie and colleagues in the University of Aberdeen produced for the then Countryside Commission of Scotland a detailed inventory of all the beaches, sand dunes and machair of Scotland, their geomorphology and the pressures to which they were subjected. This work has formed a useful benchmark for many of the Scottish GCR sites described and interpreted in this volume.

It is difficult to ascribe the geomorphological conservation value to sites that have been significantly affected by human activities. Very many coastal sites have been affected directly and indirectly by coast protection, tidal defences and reclamation projects, by mineral extraction, or by intensive recreational use. Some remote or otherwise undeveloped sites are used for activities that interfere with access, such as nuclear power stations or military training areas. Some GCR coastal geomorphology sites certainly include minor artificial structures, and it is not always possible to select GCR sites that are 'complete', 'natural' and 'unspoilt'. But, in general, sites where interference has been widespread have not been included in the GCR. There are two substantial exceptions: Spurn Head and Dungeness, both heavily modified major landforms. Such sites have been included in the GCR because the classic importance and long-history of study of the site argue for inclusion; indeed ongoing study of such sites will be important if we are to improve our understanding of how coasts react to changes brought about by human activity.

Legal protection of the GCR sites

V J. May and N.V Ellis

The list of GCR sites has been used as a basis for establishing Earth science Sites of Special Scientific Interest (SSSIs), protected under the Wildlife and Countryside Act 1981 (as amended) by the statutory nature conservation agencies (the Countryside Council for Wales, English Nature and Scottish Natural Heritage).

The SSSI designation is the main protection measure in the UK for sites of importance to conservation because of the wildlife they support, or because of the geological and geomorphological features that are found there. About 8% of the total land area of Britain is designated as SSSIs. Well over half of the SSSIs, by area, are internationally important for a particular conservation interest and are additionally protected through international designations and agreements.

About one third of the SSSIs have a geological/geomorphological component that constitutes at least part of the 'special interest'. Although some SSSIs are designated solely because of their importance to wildlife conservation, there are many others that have both such features and geological/geomorphological features of special interest. Furthermore, there are localities that, regardless of their importance to wildlife conservation, are conserved as SSSIs solely on account of their importance to geological or geomorphological studies.

Therefore, many SSSIs are composite, with site boundaries drawn from a 'mosaic' of one or more GCR sites and wildlife 'special interest' areas; such SSSIs may be heterogeneous in character, in that different constituent parts may be important for different features.

There are, therefore, coastal SSSIs not described in this volume that are important for saltmarsh, machair, dune and shingle features as habitat/wildlife sites, regardless of the underlying geomorphology. Although such habitat types are intrinsically linked to the geomorphology, these other sites were not deemed to achieve the GCR standard for their geomorphology alone, or they duplicated geomorphological features better seen at other sites (The 'minimum number' criterion of the GCR is an important factor here (see above)). Therefore, for example, although only 11 localities are described in this volume for 'saltmarsh morphology' there are many other SSSIs that have been designated because of the habitat/wildlfe value of their saltmarsh, which will also be of interest to the geomorphologist.

Conversely, many of the SSSIs that are designated solely because of their Earth science features have interesting wildife and habitat features, underlining the inextricable links between 'the environment' and the underlying geology and geomorphology.

It is clear from the discussion in previous sections that the conservation interest of the geomorphological features is likely to be affected by shoreline management activities outside the site itself, especially where the GCR sites lie within larger sediment transport cells. However, since SSSI notification of GCR sites presently extends to mean low-water mark in England and Wales, and mean low-water of spring tides in Scotland, there is no statutory protection of the shallow water sediments that may be the main sediment source for beaches.

International measures

Presently, there is no formal international conservation convention or designation for geological/geomorphological sites below the level of the 'World Heritage Convention' (the 'Convention concerning the Protection of the World Cultural and Natural Heritage'). World Heritage Sites are declared by the United Nations Educational, Scientific and Cultural Organisation (UNESCO). The objective of the World Heritage Convention is the protection of natural and cultural sites of global significance. Many of the British World Heritage sites are 'cultural' in aspect, but the Giant's Causeway in Northern Ireland and the Dorset and East Devon Coast are inscribed because of their importance to the Earth sciences as part of the 'natural heritage' — the Dorset and East Devon site is of particular relevance here insofaras it was the outstanding geology and coastal geomorphology that led to its inscription. The St Kilda World Heritage site certainly has an important geological component contributing to its status.

(Table 1.7) Coastal Annex I habitats occurring in the UK (from McLeod *et al.*, 2002.)

EU code	Habitat name	Lay name	Priority habitat/ UK special species responsibility	
1130	Estuaries	Estuaries		x
1140	Mudflats and sandflats not covered by seawater at low tide	Intertidal mudflats and sandflats		
1150	Coastal lagoons	Lagoons	x	x
1160	Large shallow inlets and bays	Shallow inlets and bays		x
1170	Reefs	Reefs		x
1210	Annual vegetation of drift lines	Annual vegetation of drift lines		
1220	Perennial vegetation of stony banks	Coastal shingle vegetation outside the reach of waves		x
1230	Vegetated sea cliffs of the Atlantic and Baltic coasts	Vegetated sea cliffs		x
1310	*Salicornia* and other annuals colonizing mud and sand	Glasswort and other annuals colonizing mud and sand		
1320	*Spartina* swards (*Spartinion maritimae*)	Cord-grass swards		
1330	Atlantic salt meadows (*Glauco- Puccinellietalia maritimae*)	Atlantic salt meadows		
1420	Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	Mediterranean saltmarsh scrub		
2110	Embryonic shifting dunes	Shifting dunes		
2120	Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	Shifting dunes with marram		
2130	Fixed dunes with herbaceous vegetation ('grey dunes')	Dune grassland	x	x
2140	Decalcified fixed dunes with *Empetrum nigrum*	Lime-deficient dune heathland with crowberry		
2150	Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)	Coastal dune heathland	x	
2160	Dunes with *Hippophae rhamnoides*	Dunes with sea-buckthorn		

2170	Dunes with *Salix repens* ssp. *argentea* (*Salicion arenariae*)	Dunes with creeping willow		
2190	Humid dune slacks	Humid dune slacks		x
21A0	Machairs	Machair		x
2250	Coastal dunes with *Juniperus* spp.	Dunes with juniper thickets	x	
8330	Submerged or partially submerged sea caves	Sea caves		x

In contrast to the Earth sciences, there are many other formal international conventions — particularly at a European level — concerning the conservation of wildlife and habitat. Of course, many sites that are formally recognized internationally for their contribution to wildlife conservation are underpinned by the geological/ geomorphological character, but this fact is implicit in such designations. Nevertheless, some of the sites described in the present volume are not only geomorphological SSSIs, but also *habitat* sites recognized as being internationally important. These areas are thus afforded further protection by international designations above the provisions of the SSSI system. Of especial relevance to the present volume are those coastal habitat types that are dependent on coastal geomorphology and are conserved as Special Areas of Conservation.

Special Areas of Conservation (SACs)

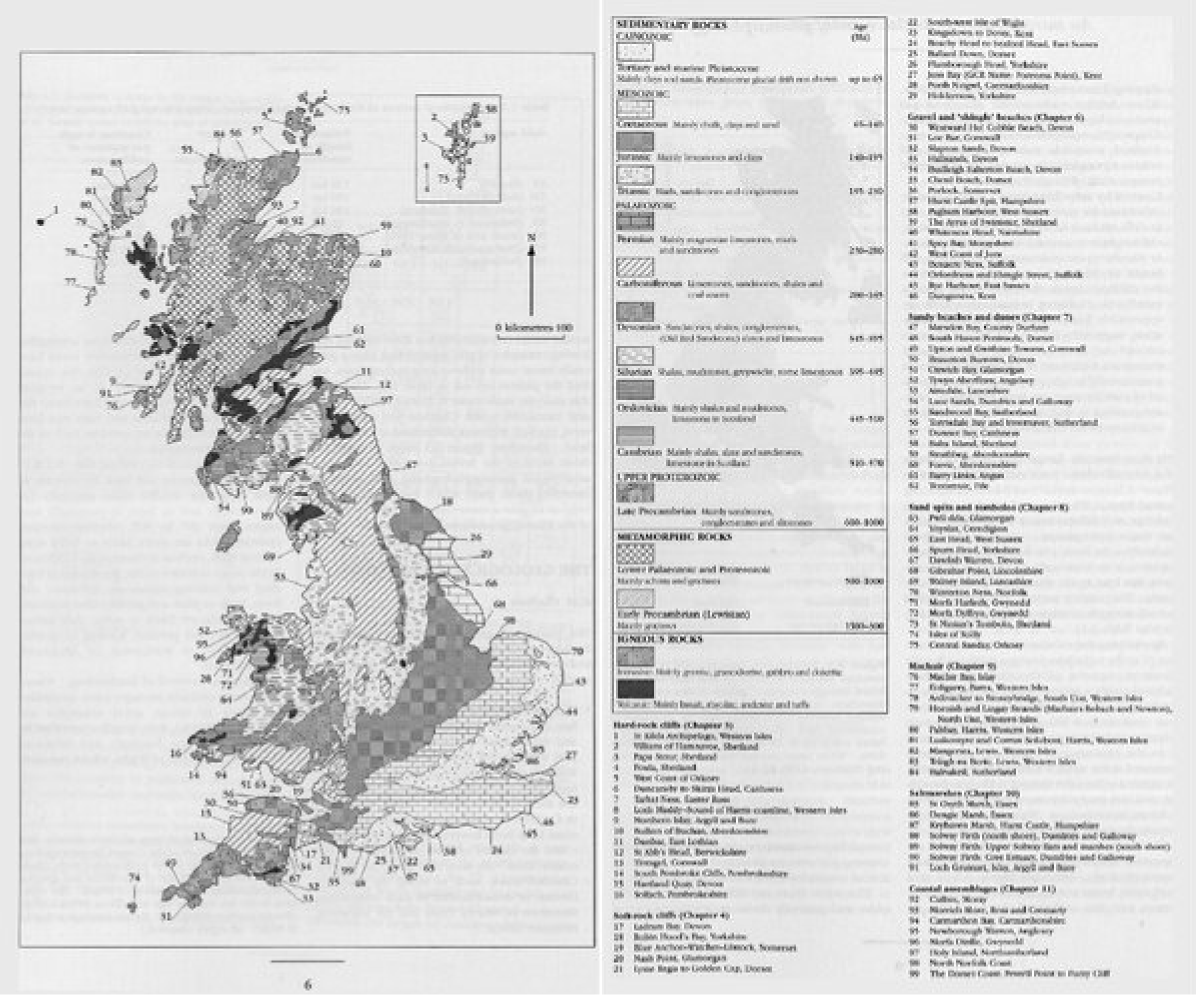
In 1992 the European Community adopted Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, commonly known as the 'Habitats Directive'. This is an important piece of supranational legislation for wildlife conservation under which a European network of sites Special Areas of Conservation (SACs) — is selected, designated and protected. The aim is to help conserve the 169 habitat types and 623 specks identified in Annexes I and II of the Directive.

Of the Annex I habitat types, 76 are believed to occur in the UK. The habitat types are very variable in the range of ecological variation they encompass. Some are very narrowly defined, comprising a single vegetation type; others are large units defined on a physiographic basis, such as Estuaries and Machairs, encompassing complex mosaics of habitats, and correspond approximately to the 'Broad Habitats' and/or 'Priority Habitats' of the UK Biodiversity Action Plan (Jackson, 2000). Although the habitats are identified for the conservation importance of their biological features, individually or collectively, many also represent geomorphological features, and this relationship is particularly clear in the list of coastal Annex I habitats (Table 1.7). Taken together, these cover virtually the full range of intertidal sediments, saltmarshes, dunes, shingle structures and sea-cliff habitats which occur in the UK.

Where habitats have qualified for selection, a process has been applied to ensure that the examples selected are of high quality and adequately represent the feature across its geographical and ecological range in the UK (McLeod *et al.,* 2002).

GCR site selection in conclusion

It is clear from the foregoing that many factors have been involved in selecting and protecting the sites proposed for conservation and described in this volume. Sites will rarely fall neatly into one category or another; normally they have assets and characteristics that satisfy a range of the guidelines and preferential weightings. A full appreciation of the reasons for the selection of individual sites cannot be gained from these few paragraphs. The full justification and arguments behind the selection of particular sites are only explained satisfactorily by the site accounts given in subsequent chapters of the present volume.



(Figure 1.2) Geological map of Great Britain, also showing the locations of the Coastal Geomorphology GCR Sites. The map shows sedimentary rocks classified according to their age of deposition and igneous rocks according to their mode of origin. The numbers in the key indicate age in millions of years (Ma). (Permit number IPR/26–45C British Geological Survey. (NERC. All rights reserved.)

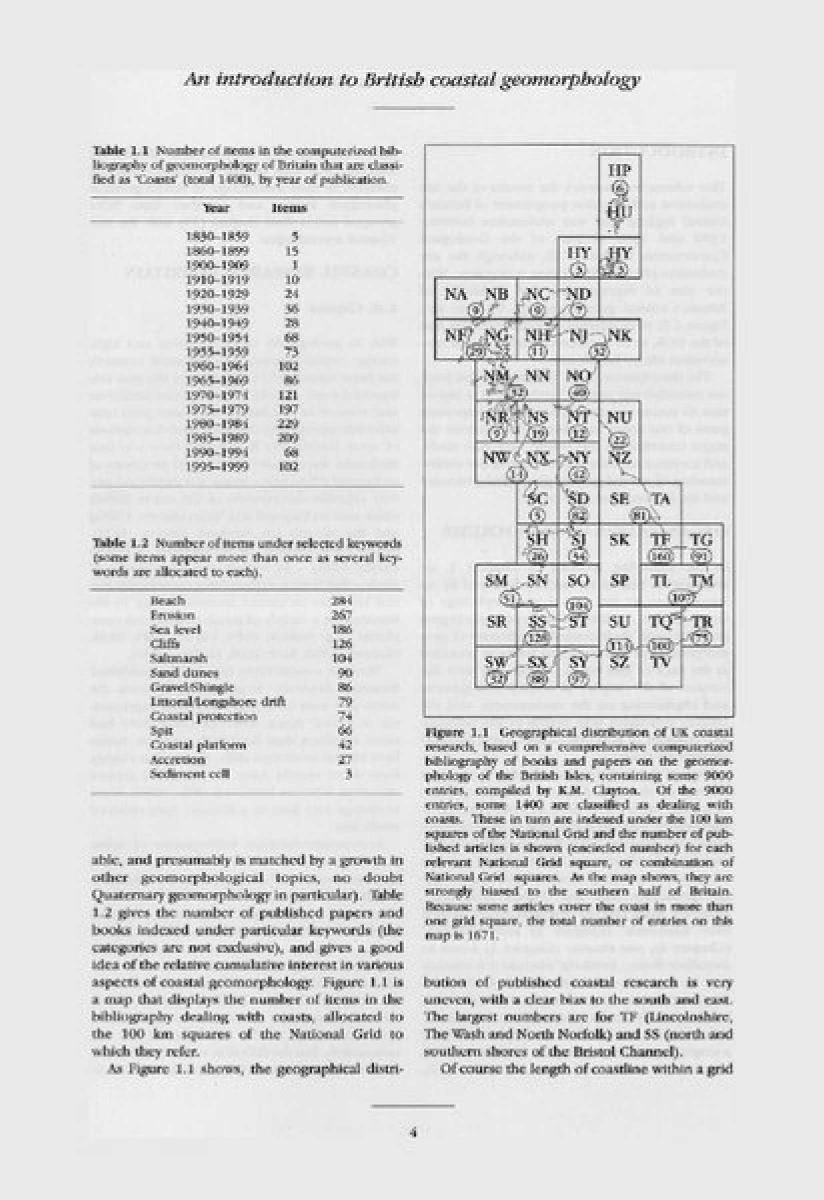


Table 1.1 Number of items in the computerized bibliography of geomorphology of Britain that are classified as 'Coasts' (total 1400), by year of publication.

Year	Items
1830–1859	5
1860–1899	15
1900–1909	1
1910–1919	10
1920–1929	24
1930–1939	36
1940–1949	28
1950–1954	68
1955–1959	73
1960–1964	102
1965–1969	86
1970–1974	121
1975–1979	197
1980–1984	229
1985–1989	209
1990–1994	68
1995–1999	102

Table 1.2 Number of items under selected keywords (some items appear more than once as several keywords are allocated to each).

Beach	284
Erosion	267
Sea level	186
Cliffs	126
Saltmarsh	104
Sand dunes	90
Gravel/Shingle	86
Littoral/Longshore drift	79
Coastal protection	74
Spit	66
Coastal platform	42
Accretion	27
Sediment cell	3

Figure 1.1 Geographical distribution of UK coastal research, based on a comprehensive computerized bibliography of books and papers on the geomorphology of the British Isles, containing some 9000 entries, compiled by K.M. Clayton. Of the 9000 entries, some 1400 are classified as dealing with coasts. These in turn are indexed under the 100 km squares of the National Grid and the number of published articles is shown (encircled number) for each relevant National Grid square, or combination of National Grid squares. As the map shows, they are strongly biased to the southern half of Britain. Because some articles cover the coast in more than one grid square, the total number of entries on this map is 1671.

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As Figure 1.1 shows, the geographical distribution of published coastal research is very uneven, with a clear bias to the south and east. The largest numbers are for TF (Lincolnshire, The Wash and North Norfolk) and SS (north and southern shores of the Bristol Channel).

Of course the length of coastline within a grid

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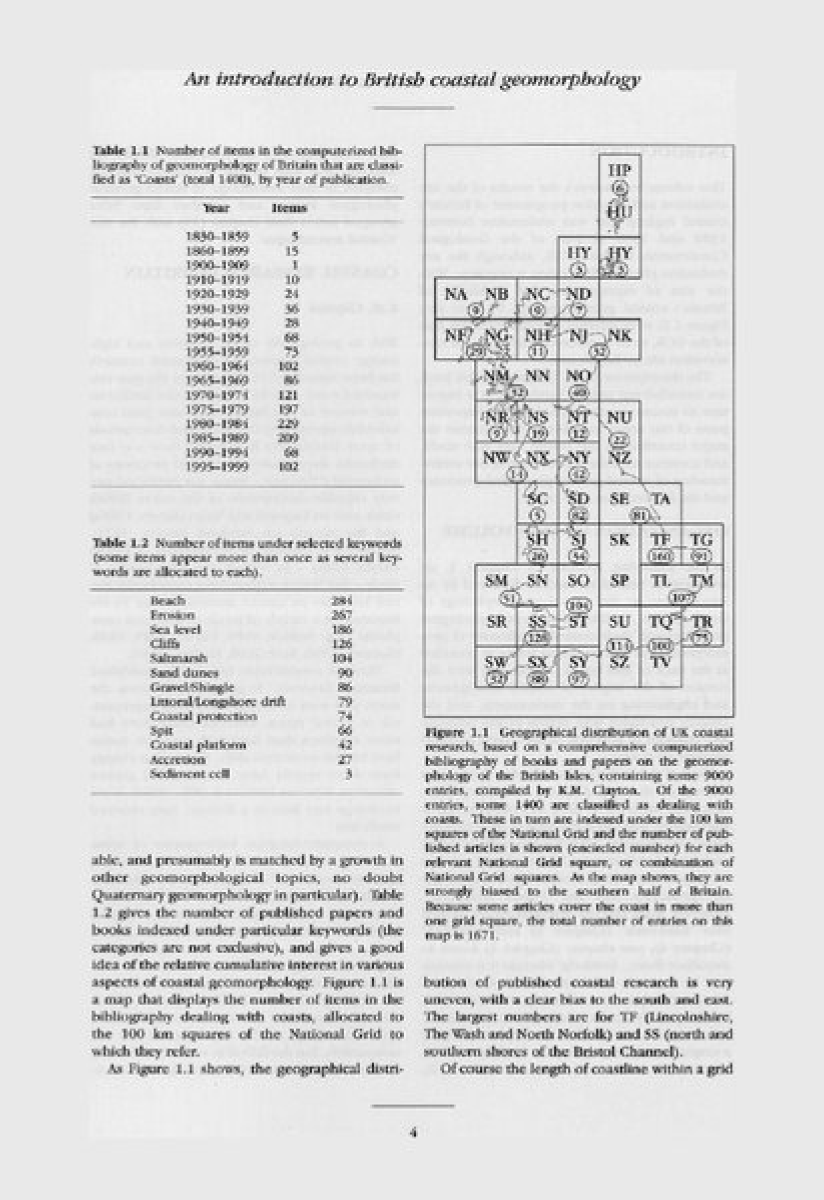

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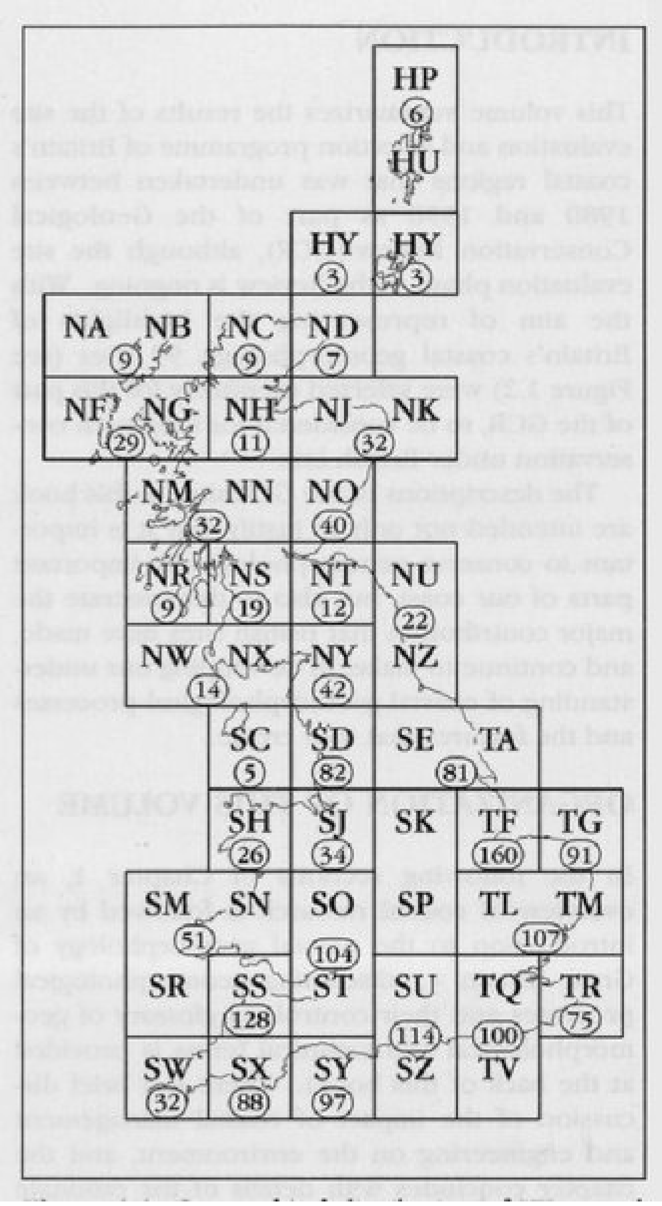

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Table 1.3 Geographical analysis of the British coastal literature, using selected grid squares only.

Grid square	Estimated length of coastline	Number of publications	Coastline length per number of publications
SY (Dorset)	110 km	97	1.13 km
TM (Suffolk/Essex)	120 km	95	1.26 km
SD (Lancashire/S. Cumbria)	150 km	82	1.83 km
SN (Fishguard to Aberdovey)	95 km	35	2.71 km
NJ (south side of Moray Firth)	100 km	22	4.55 km
NZ (Durham/North Yorkshire)	130 km	18	7.22 km
NC (Sutherland)	150 km	9	16.67 km

square varies considerably, but if we take the following examples of grid squares that have a generally linear coast without long indentations, we find the pattern set out in Table 1.3. Clearly in this analysis, such coasts as Dorset, Suffolk/Essex and Lancashire/south Cumbria are among the most studied, whereas Sutherland is among the least. Therefore, Figure 1.1 helps to highlight those areas of the British coast that are better understood geomorphologically, and, perhaps, identifies those areas where further study may help us to gain a more complete understanding of the coastal geomorphology of Britain.

THE GEOLOGICAL BACKGROUND

K.M. Clayton

The pattern of geological outcrops along the British coast (Figure 1.2) has a fundamental control on the nature of the coastline. This is for several reasons, outlined below.

- **Coastal topography**: Underlying geology has influenced the topography of the land, and the detailed outline of the coast in large part reflects the relief of the littoral zone. Rocks that are susceptible to erosion tend to form bays and inlets, whereas erosion-resistant rocks form headlands. Local differences in the level to which outcrops adjacent to the coast have been lowered by subaerial erosion – and the impact of such differences on the coastal form – are seen best along the English Channel coast, such as along the coast of Dorset, or demonstrated in such contrasting situations as Beachy Head and the adjoining Pevensey Levels.
- **Dissection in rocks of different strengths**: Where relatively erosion-resistant rocks have been deeply dissected by erosion, the coastal outline is complex, such as in western Scotland. Where weaker rocks have been dissected, former headlands and bays may have been truncated by marine erosion, such as the Seven Sisters in Sussex.
- **Geological control on cliff profile**: Rocks of all strengths can be cut back by erosion to form cliffs, but weaker rocks generally fail more readily and so form sloping cliffs with angles from 20° to 40°, whereas erosion-resistant rocks are more likely to form near-vertical cliffs, such as at Duncansby, Caithness. In the more resistant rocks, the details of bedding and jointing commonly influence cliff form, both in plan and profile; thus seaward-dipping rocks are likely to suffer slide failure as basal erosion persists, leading to gentler slopes than on horizontal or landward-dipping strata.
- **Lithological control of landsliding**: Where weak rocks underlie stronger ones, landslides are likely to occur; good examples are Folkestone Warren, now largely controlled by drainage and 'toe loading', and Ventnor–Shanklin on the Isle of Wight, where seaward-

Overleaf:
Figure 1.2 Geological map of Great Britain, also showing the locations of the Coastal Geomorphology GCR Sites. The map shows sedimentary rocks classified according to their age of deposition and igneous rocks according to their mode of origin. The numbers in the key indicate age in millions of years (Ma). (Permit number IPR/26-45C British Geological Survey © NERC. All rights reserved.)

(Table 1.3) Geographical analysis of the British coastal literature, using selected grid squares only.

(Figure 1.3) Relative rock resistance for 71 different outcrops (divided by lithology and age) was established through computer analysis of data on altitude, dissection, and geology for a grid of kilometre squares covering Great Britain and the surrounding continental shelf. Six consistent classes were established using up to 19 variables in various combinations. White areas are unclassified. (From Clayton and Shamoon, 1998, fig. 1).

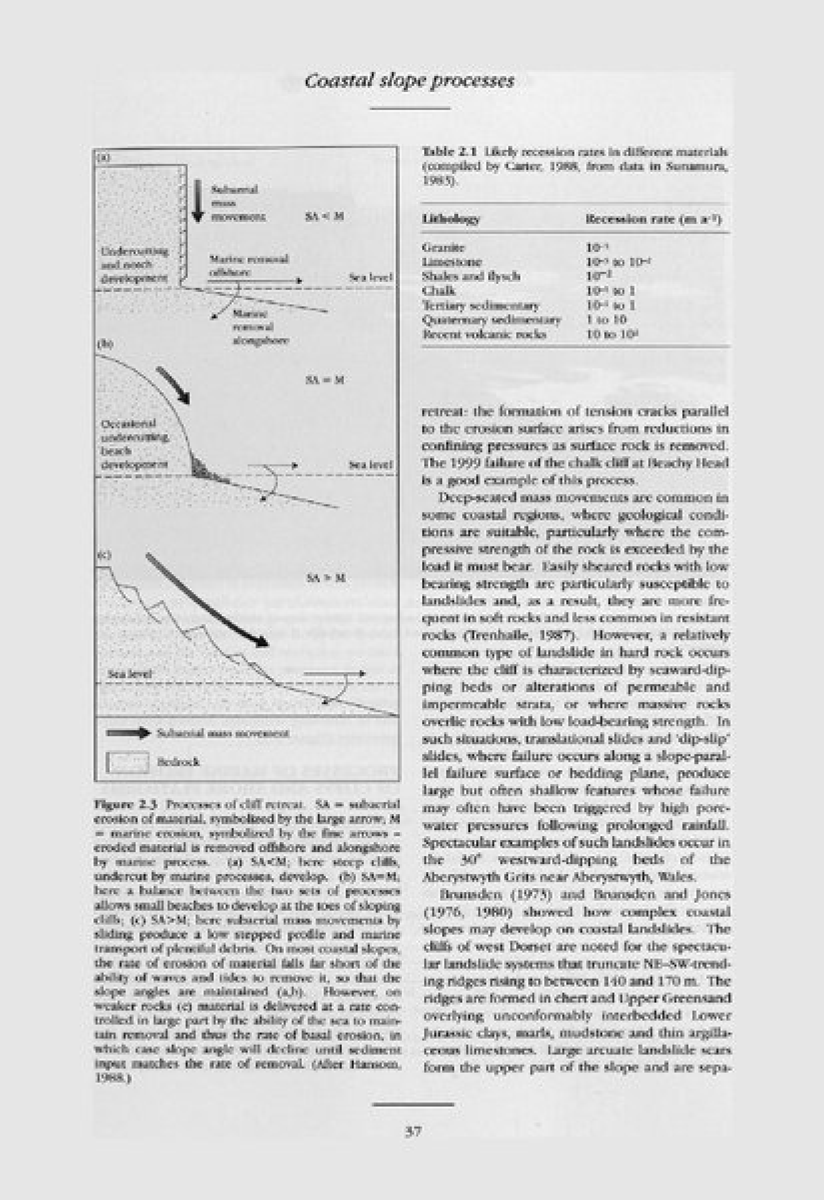


Figure 2.3 Processes of cliff retreat. SA = subaerial erosion of material, symbolized by the large arrow; *M* = marine erosion, symbolized by the fine arrows = eroded material is removed offshore and alongshore by marine process. (a) SA<M; here steep cliffs, undercut by marine processes, develop. (b) SA=M; here a balance between the two sets of processes allows small beaches to develop at the toes of sloping cliffs; (c) SA>M; here subaerial mass movements by sliding produce a low stepped profile and marine transport of plentiful debris. On most coastal slopes, the rate of erosion of material falls far short of the ability of waves and tides to remove it, so that the slope angles are maintained (a,b). However, on weaker rocks (c) material is delivered at a rate controlled in large part by the ability of the sea to maintain removal and thus the rate of basal erosion, in which case slope angle will decline until sediment input matches the rate of removal. (After Hansom, 1988.)

Table 2.1 Likely recession rates in different materials (compiled by Carter, 1988, from data in Sunamura, 1983).

Lithology	Recession rate (m a^{-1})
Granite	10^{-3}
Limestone	10^{-3} to 10^{-2}
Shales and flysch	10^{-2}
Chalk	10^{-2} to 1
Tertiary sedimentary	10^{-1} to 1
Quaternary sedimentary	1 to 10
Recent volcanic rocks	10 to 10^{2}

retreat: the formation of tension cracks parallel to the erosion surface arises from reductions in confining pressures as surface rock is removed. The 1999 failure of the chalk cliff at Beachy Head is a good example of this process.

Deep-seated mass movements are common in some coastal regions, where geological conditions are suitable, particularly where the compressive strength of the rock is exceeded by the load it must bear. Easily sheared rocks with low bearing strength are particularly susceptible to landslides and, as a result, they are more frequent in soft rocks and less common in resistant rocks (Trenhaile, 1987). However, a relatively common type of landslide in hard rock occurs where the cliff is characterized by seaward-dipping beds or alterations of permeable and impermeable strata, or where massive rocks overlie rocks with low load-bearing strength. In such situations, translational slides and 'dip-slip' slides, where failure occurs along a slope-parallel failure surface or bedding plane, produce large but often shallow features whose failure may often have been triggered by high pore-water pressures following prolonged rainfall. Spectacular examples of such landslides occur in the 30° westward-dipping beds of the Aberystwyth Grits near Aberystwyth, Wales.

Brunsden (1973) and Brunsden and Jones (1976, 1980) showed how complex coastal slopes may develop on coastal landslides. The cliffs of west Dorset are noted for the spectacular landslide systems that truncate NE–SW-trending ridges rising to between 140 and 170 m. The ridges are formed in chert and Upper Greensand overlying unconformably interbedded Lower Jurassic clays, marls, mudstone and thin argillaceous limestones. Large arcuate landslide scars form the upper part of the slope and are sepa-

(Table 2.1) Likely recession rates in different materials (compiled by Carter, 1988, from data in Sunamura, 1983).

Table 1.4 General order of resistance to erosion of British rock types (from Clayton and Shamoon, 1998).

Very Resistant: Precambrian metamorphosed sediments, Cambrian quartzite and sandstone, Ordovician tuff.
Resistant: Old Red Sandstone, Lower Palaeozoic slates, Palaeozoic basalt and andesite.
High Average: Skiddaw slate, Millstone Grit, Carboniferous limestone, Yoredale series.
Low Average: Palaeozoic shale, Coal Measures, Devonian greywackes, Tertiary basalts.
Weak: Magnesian (Permian) limestone, Jurassic limestone, Hastings Beds, Chalk.
Very Weak: Mesozoic and Cainozoic mudrocks, Thanet sand.

northern and western Britain and the younger and weaker rocks found in east and southern England, within each of these zones local contrasts dominate the coastal geomorphology. From Flamborough Head in Yorkshire southwards and westwards to the Exe estuary in Devon, the Chalk and sandstones that form the cuestas of the scarpland and vale landscape also form the major coastal headlands (Flamborough Head, North Foreland in Kent, Beachy Head in Sussex, and the Needles on the Isle of Wight, for example, all on Chalk) and between them on the intervening clays or on till-covered littoral plateaux, wide bays, locally fronted by saltmarshes and sand dunes, alternate with low cliffs cut into the low till-capped plateaux of Holderness, Norfolk and Suffolk.

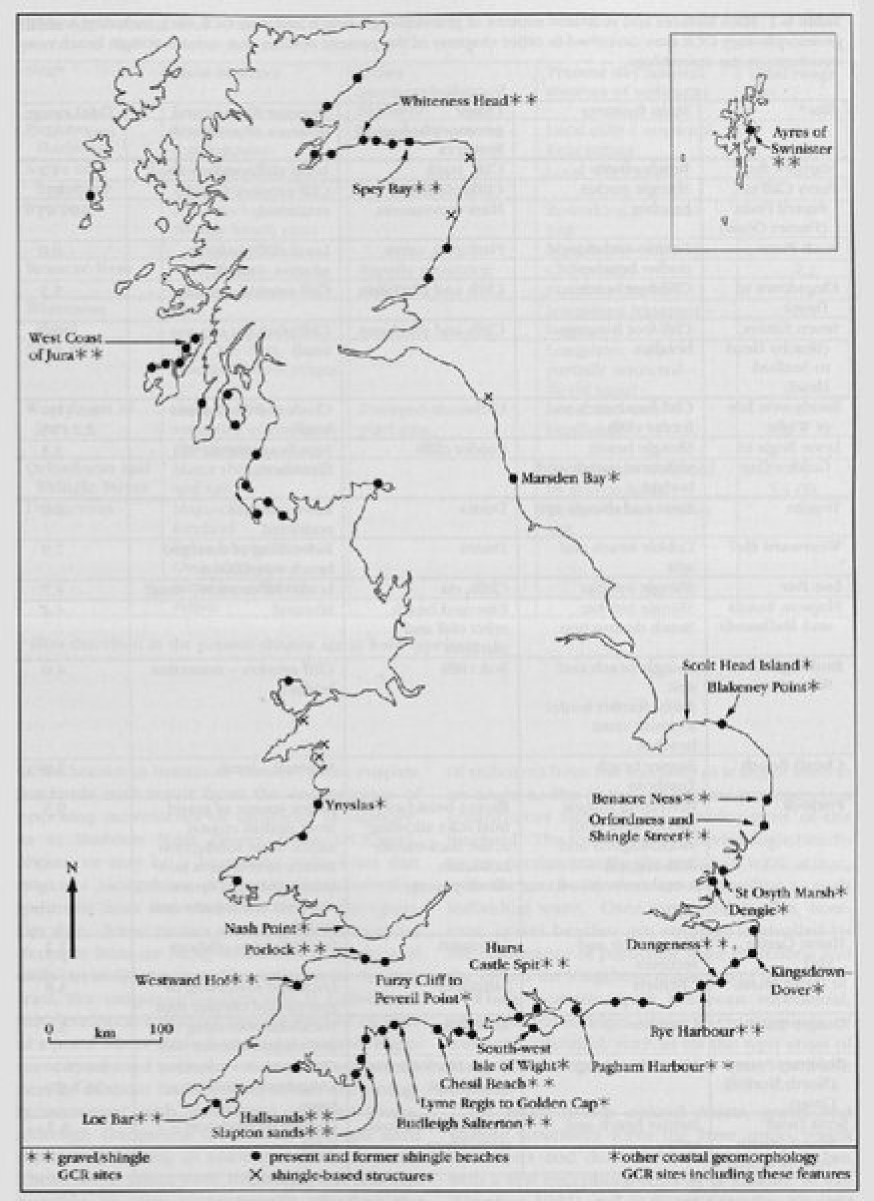
Geological influence on sediment supply into the coastal system

A further influence of geology on coastal geomorphology is in the provision of sediment that can be incorporated into beaches. Beaches around Britain vary considerably in their texture (from fine-grained sand to boulders) and in their lithology (from shelly sands to flint cobbles) and reflect the local supply of material of appropriate dimensions. Some coarse sediments are still brought to the coast by rivers, especially in Scotland and Wales, where gradients are steep and coarse-grained material is readily transported by floods. In contrast, very little sediment other than mud (clay and silt) is now brought down the rivers of lowland Britain to the coast. Thus, especially in areas with more gentle inland relief, it is the delivery of sediment from offshore as well as from retreating cliffs that has provided most of the material for the local beaches. Boulders and coarse gravel are derived from erosion of resistant rocks in areas such as Scotland and parts of the Welsh coast, their initial size depending on rock-joint spacing. Locally along the English coast, quartzites are the source of coarse gravel (e.g. at Budleigh Salterton); flints form the commonest pebbles and cobbles on beaches in the south of England.

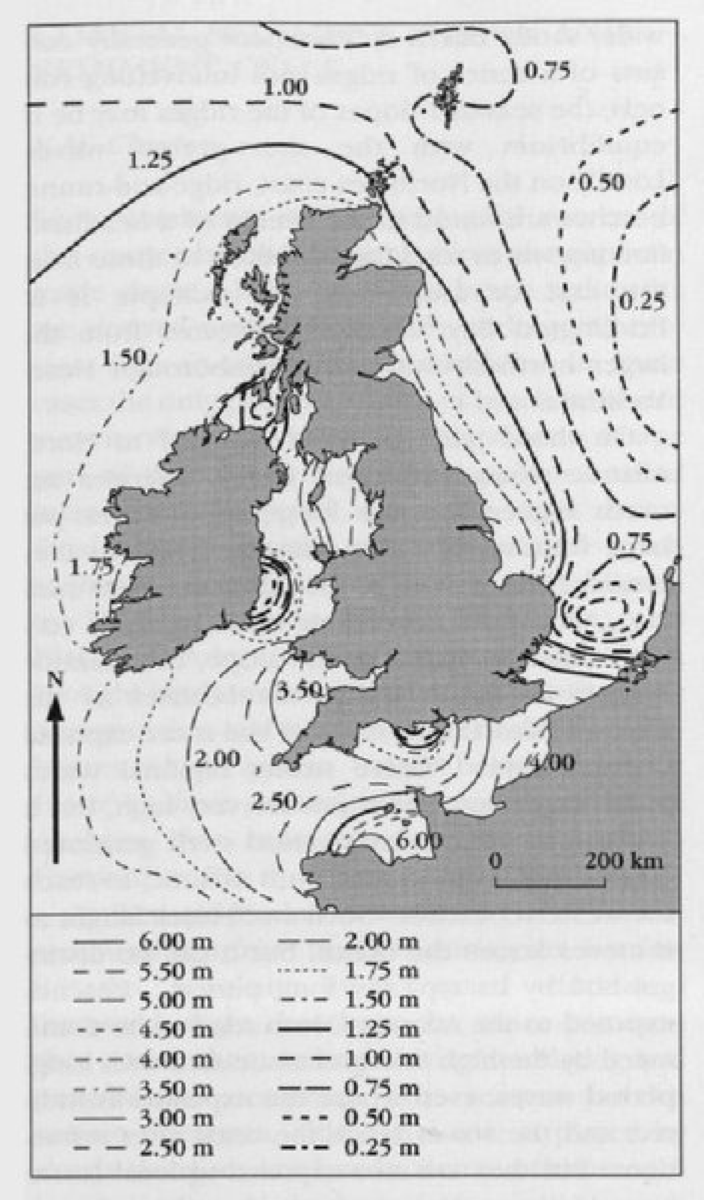
Many 'shingle' (gravel) beaches (such as Slapton Sands in Devon, Chesil Beach in Dorset and Blakeney Point in Norfolk) have been built from offshore gravels, swept ashore as sea level rose during the Holocene marine transgression, and former sea-floor sediment has contributed to many beaches elsewhere (see Figure 6.2). In places, flints are derived from erosion of the Chalk in which they occur. Indeed, Chalk cliffs are generally associated with flint beaches because eroded Chalk debris is quickly broken down by wave action so that Chalk cobbles form a minor part of the beach material. Most flint in English beaches is secondarily derived from quite a wide range of intermediate sources. These include the Pebble Beds of the Tertiary succession of south-east England, where the 'Pebbles' are either derived directly from local erosion, or through their incorporation into river gravels, such as the sequence of Early Pleistocene river terraces – attributed in part to the River Thames – cropping out in Essex, Suffolk and Norfolk. Thus at Dunwich, the cliff contributes flints from gravels at the top of the exposure that were deposited by the ancient River Thames. In contrast, with no local landward source, the flints that dominate Slapton Sands must have been brought ashore from an offshore source. The former river concerned flowed down the English Channel, no doubt fed by such tributaries as the present-day Seine, Rhine and Thames at a time when much of the present-day area of the North Sea was occupied by an ice sheet.

Farther north in England, while we cannot rule out such offshore sources, a large proportion of the gravel has been eroded from glacial gravels and till cropping out along the coast or

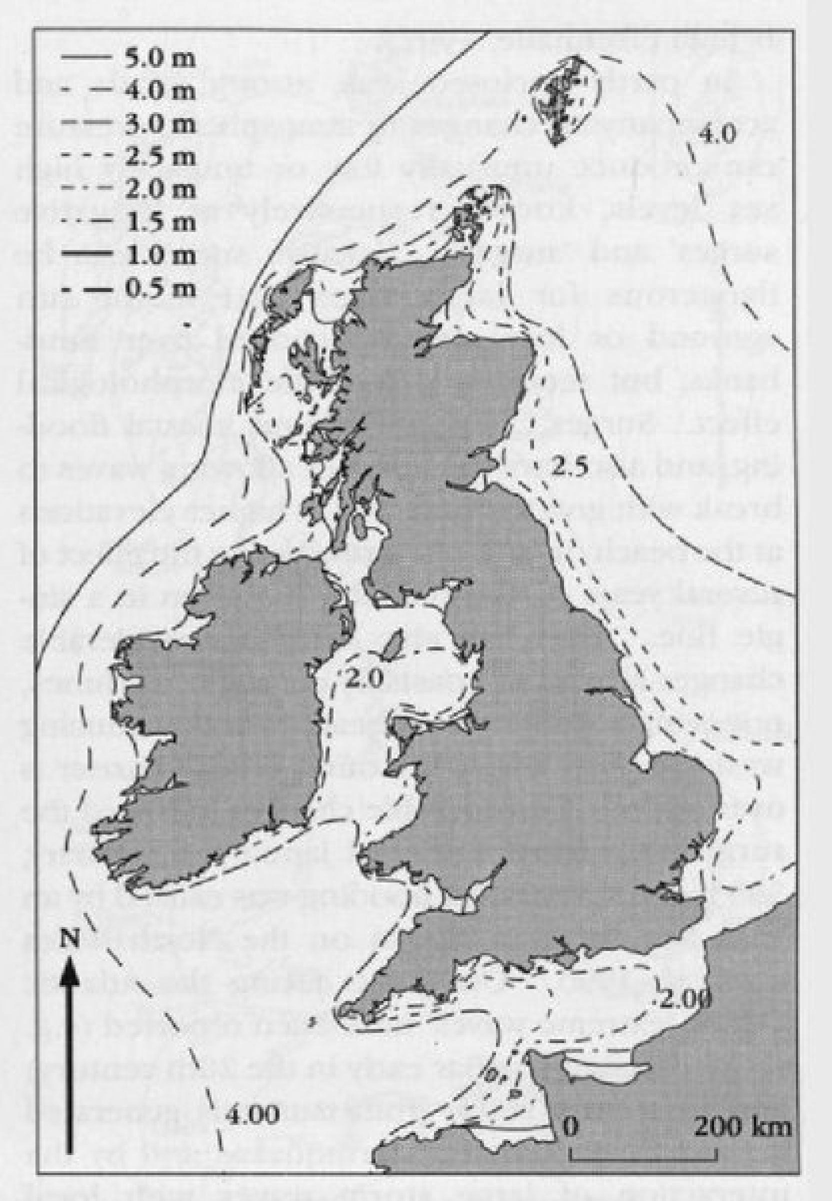
(Table 1.4) General order of resistance to erosion of British rock types (from Clayton and Shamoon, 1998).



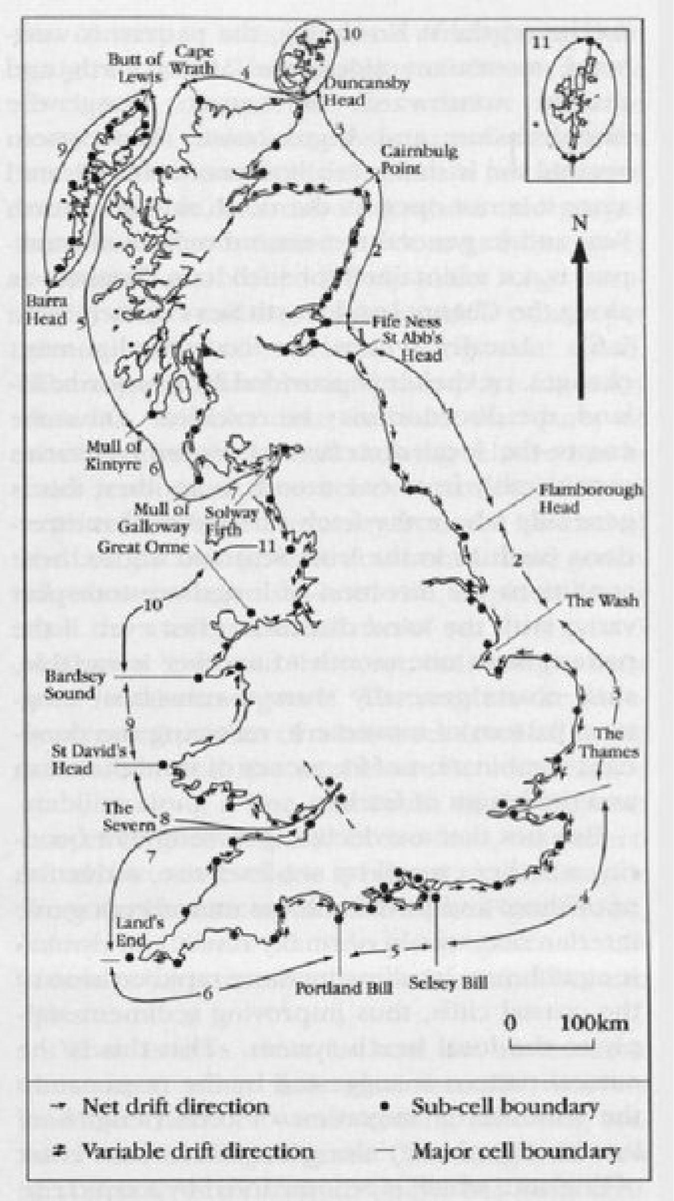
(Figure 6.2) Coastal shingle and gravel structures around Britain, showing the location of the sites selected for the GCR specifically for gravel/shingle coast features, and some of the other larger gravel structures.



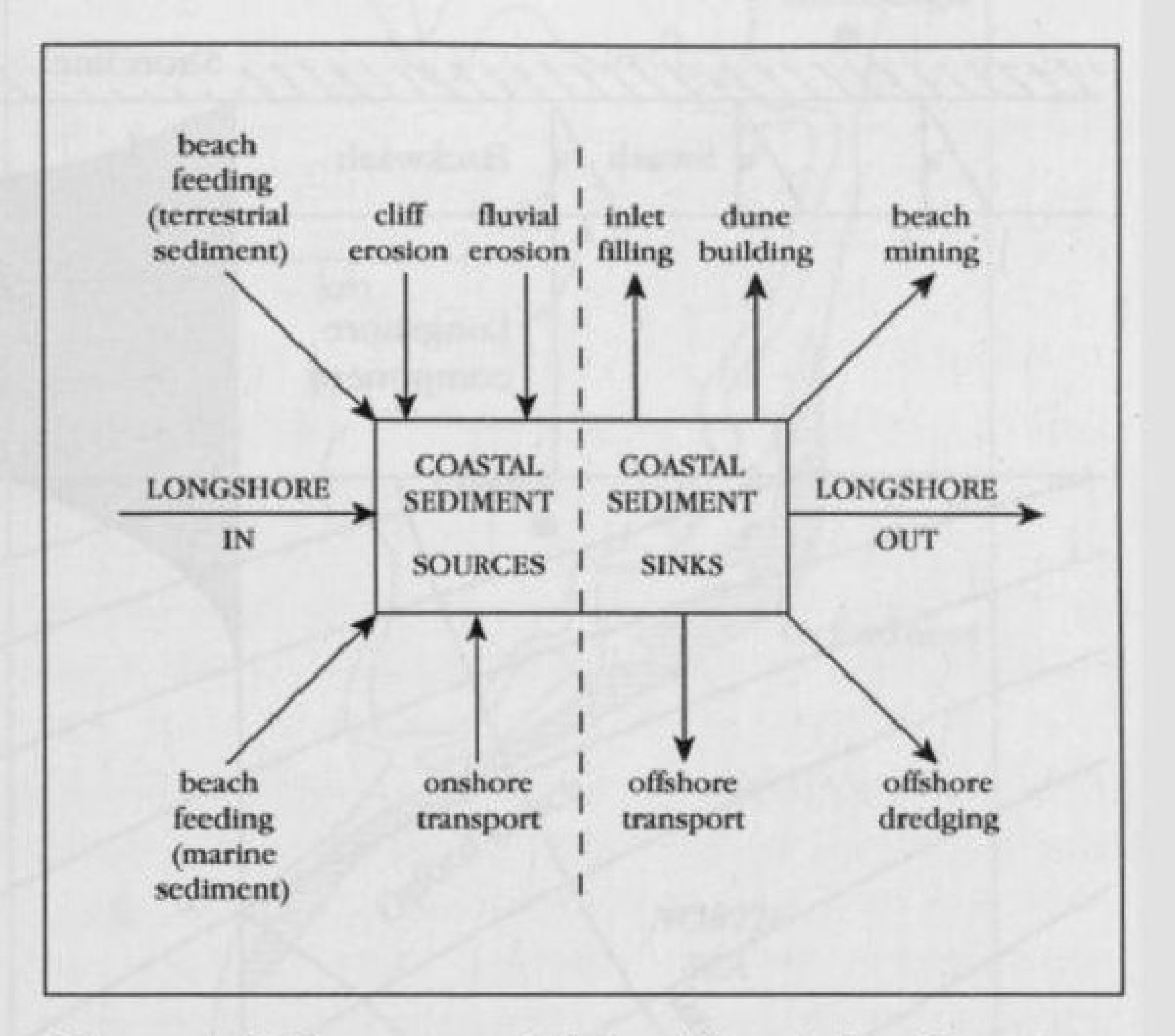
(Figure 1.4) Spring tidal amplitude (measured in metres) around the British coast. Elevations should be doubled to give spring tidal range. (UKDMAP 1998, NERC.)



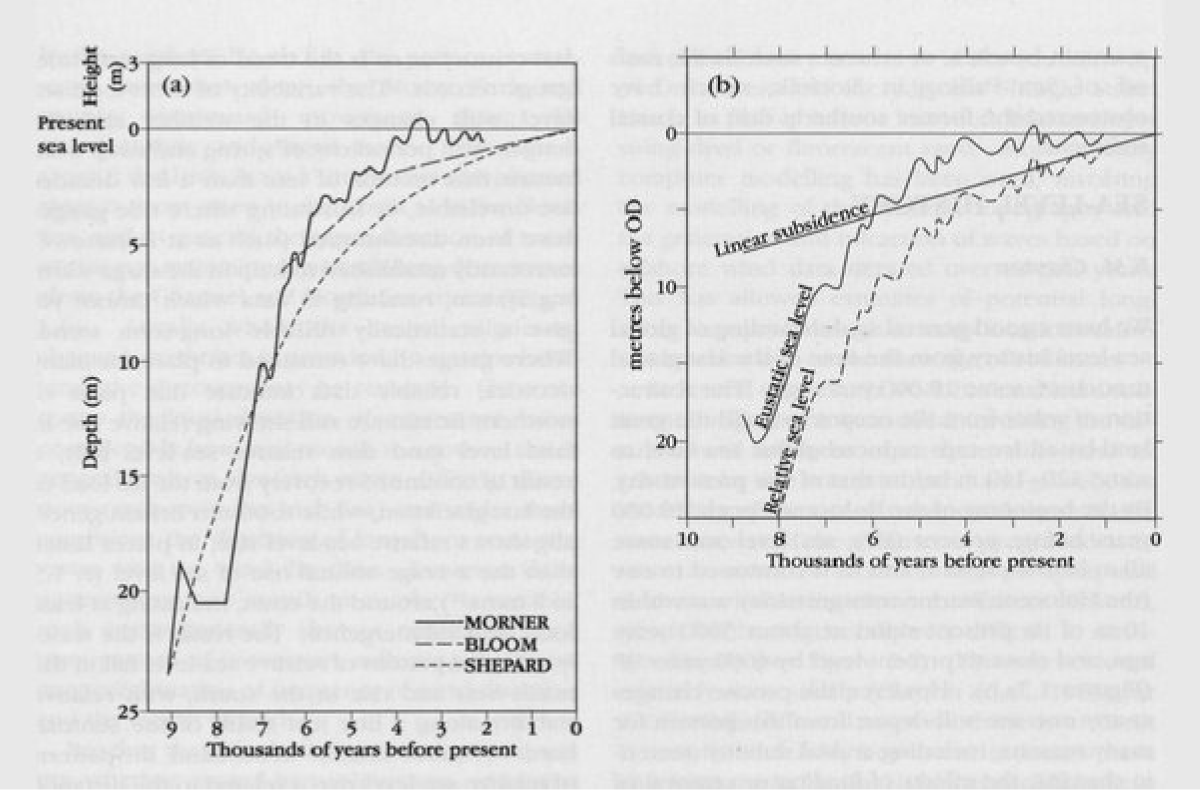
(Figure 1.5) Significant wave height exceeded for 10% of the year (significant wave height is the mean value of the highest 1/3 of all waves). Wave height is one of the manifestations of the quantity of wave energy. (UKDMAP 1998 NERC.)



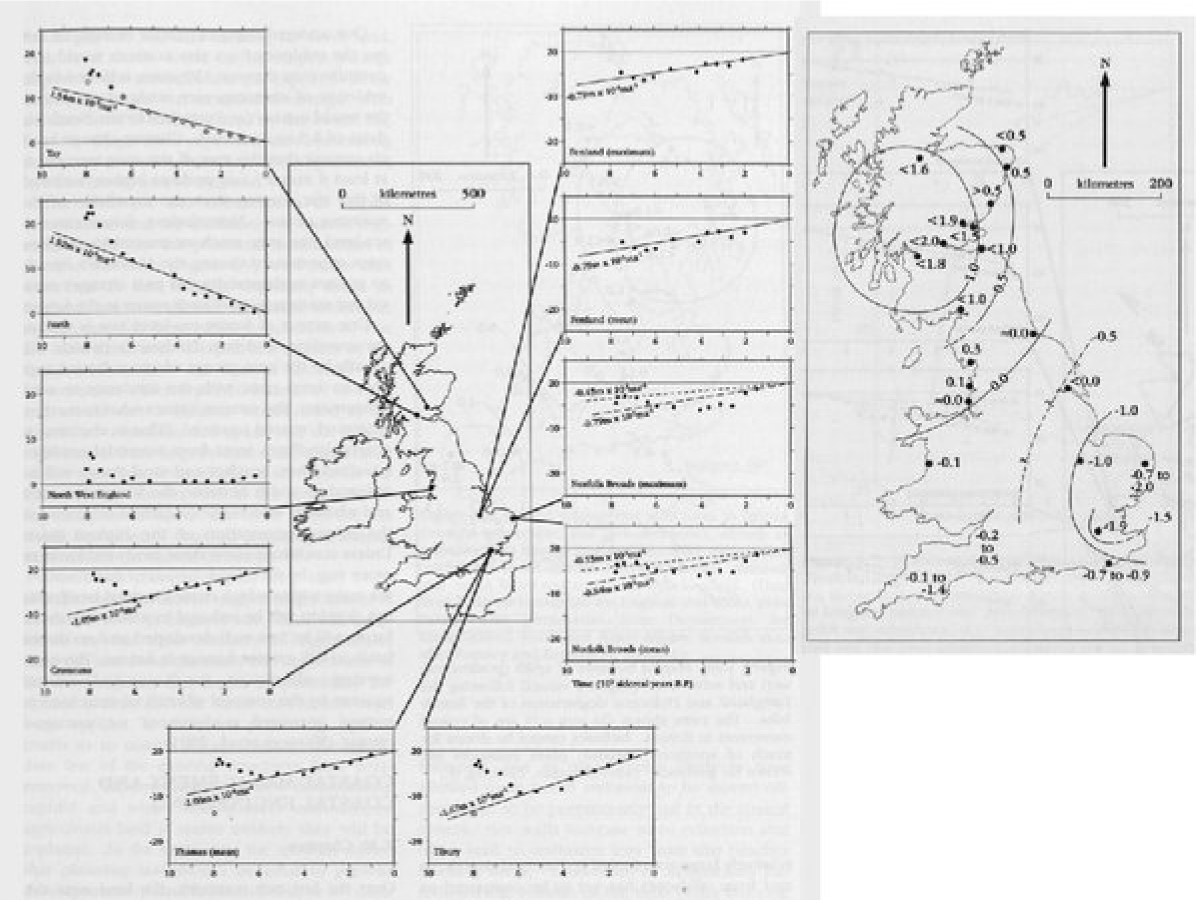
(Figure 1.6) Littoral sediment cells and subcells and direction of littoral drift. After Motyka and Brampton, 1993 and HR Wallingford, 1997. Cells are numbered 1 to 7 anticlockwise from St. Abb's Head for Scotland and there are three subcells within the Orcadian cell and two within the Shetland cell (shown in the inset); clockwise from St Abb's Head, cells are numbered 1–11 for England and Wales.



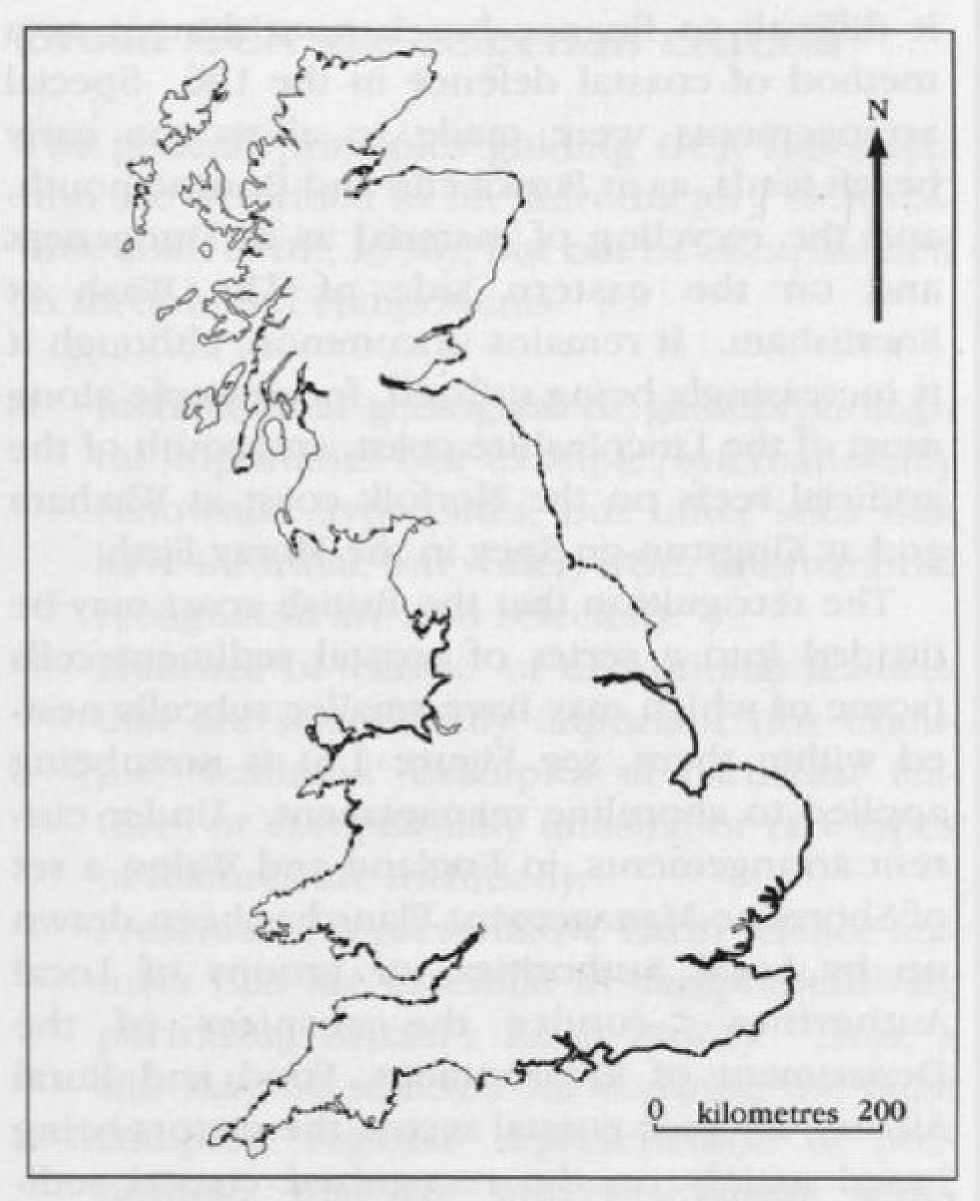
(Figure 5.5) Sources and sinks of coastal sediment can be quantified to produce a sediment budget. Note the human element in the coastal sediment budget. (After Davies, 1980.)



(Figure 1.7) Holocene sea-level history: (a) global view; (b) sea-level history in the area around The Wash (Norfolk/Lincolnshire). Three views of the global change in sea level over the last 10 000 years are shown in (a); the smooth curves combine data from different areas, a reconstruction based on a smaller region will show an irregular pattern over time (Shepard, 1963; Bloom, 1978; Monier, 1972). Because of the local effects of uplift and subsidence, it is increasingly recognized that such global sea-level curves have the potential to mislead and that local relative sea-level curves are generally more secure. The sea-level curve in (b) for the area around The Wash is based on an accreting sedimentary sequence preserved in an area that is subsiding at an average rate of 0.9 m ka^{-1}. If this subsidence has been at a steady rate, then the local relative sea-level curve (the pecked line) can be converted to a eustatic curve (the solid line) by subtracting the effect of subsidence. (Based on Chorley et al., 1984, and Tooley and Shennan, 1987.)



(Figure 1.8) a. Uplift and subsidence, based on trends in sea level around the coast of Britain. These trends are established by comparing local sea-level curves with the eustatic trend shown in Figure 1.7b. Open circles indicate that the data were obtained by the author by extrapolation. The vertical scale on the graphs is in metres OD, the horizontal scale is in 10^3 sidereal years before present. (After Tooley and Shennan, 1987, p.136, fig. 4.9.) b. Map of isobases of uplift (positive values) and subsidence (negative values) following the Lateglacial and Holocene deglaciation of the British Isles. The rates shown (in mm a^{-1}) are of crustal movement in Britain. Isobases cannot be drawn for much of southern England; point estimates are shown for guidance. (After Sherman, 1989, fig. 9.)



(Figure 1.9) Coastal engineering structures in Britain ('coastal protection' and 'sea defences'), shown as coastline with heavier line weight. Note the concentration on south-eastern England, Bristol channel, and north Wales and north-west England. (Data from Halcrow Group Ltd for England and Wales, published with permission from Department for Environment, Food and Rural Affairs; Scottish data after Ramsey and Brampton, 2000a-f.)

cussion of managed re-alignment and coastal zone management and Viles and Spencer (1995) discuss coastal problems.

Steers provides descriptive texts on the coastlines of England and Wales (1964a) and Scotland (1973).

GCR SITE SELECTION GUIDELINES

V.J. May and N.V. Ellis

The GCR site-selection exercise for coastal geomorphology followed four categories ('GCR Blocks'), one for each of England, Scotland and Wales and one for 'Saltmarsh Geomorphology'; although three of the 'Blocks' are country based, comparisons were made to ensure that certain types of site occurring in each were not over-represented in a Great Britain-wide context.

Before site assessment and selection began, the first stage in the project was to apply the ethos of the GCR – outlined below – in order to fine-tune GCR selection-criteria. The coastal geomorphological literature was reviewed to identify the most cited sites to assist in the compilation of lists of candidate GCR sites. The GCR site selection work also included a survey of the morphodynamics of the whole coastline, carried out in conjunction with the CORINE coastal erosion project (European Commission, 1998), which provided a means by which to judge the 'representativeness' (see below) of the short-listed sites.

Broad GCR site selection criteria

The general principles guiding GCR site selection are described in the introductory GCR volume (Ellis *et al.*, 1996), but can be encapsulated in three broad components:

- International geological or geomorphological importance (for example, internationally renowned 'type' sites, but other sites that have informal, but widely held, international recognition are also selected).
- Presence of 'classic' or exceptional features that are scientifically important (for example, 'textbook' examples of particular features or exceptionally unusual or rare types of features are included).
- Presence of representative Earth science features that are essential in comprehensively portraying Britain's Earth history. Thus, a site may be selected for showing the most complete regional representation of phenomena that are otherwise quite widespread.

It should be assumed that an 'internationally' rated site will also be representative of an event or process and may include exceptional features.

In order to ensure true national importance in the selected representative sites, site selection was underpinned by the premise that the *minimum number* of sites should be selected. By choosing only those sites absolutely necessary to represent the most important aspects of Britain's

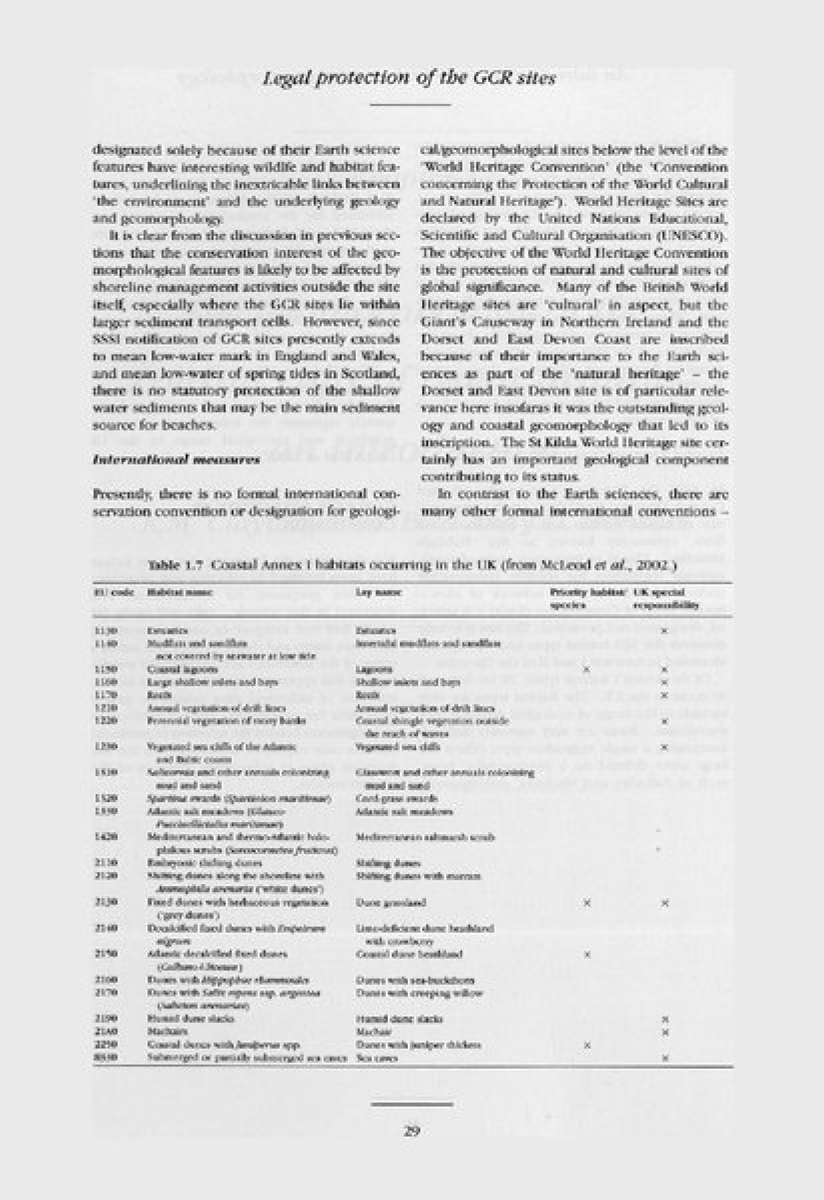
Table 1.5 Morphosedimentological classification of the British coast (based on European Commission (1998 – the CORINE project érosion cotière).

Morpho-sedimentological type	Active (km)	Protected* (km)	Total (km)
Hard-rock cliffs	7990	7	7997
Soft-rock cliffs	1401	221	1622
Shingle beaches	818	225	1043
Sand beaches	1274	302	1576
Heterogeneous beaches	415	126	541
Beaches for which no data available	59	0	59
Muddy and estuarine coasts	999	484	1483
Totals	12956	1365	14321
Anthropogenic coasts (including harbours, land-claim)			2096
Total			16417

* i.e. modified by coastal defence/protection works.

(Table 1.5) Morphosedimentological classification of the British coast (based on European Commission (1998 – the CORINE project érosion cotieré).

(Table 1.6) Main features of each GCR Site, broadly following the classification of King, 1978, to show where different features are represented.



designated solely because of their Earth science features have interesting wildlife and habitat features, underlining the inextricable links between 'the environment' and the underlying geology and geomorphology.

It is clear from the discussion in previous sections that the conservation interest of the geomorphological features is likely to be affected by shoreline management activities outside the site itself, especially where the GCR sites lie within larger sediment transport cells. However, since SSSI notification of GCR sites presently extends to mean low-water mark in England and Wales, and mean low-water of spring tides in Scotland, there is no statutory protection of the shallow water sediments that may be the main sediment source for beaches.

International measures

Presently, there is no formal international conservation convention or designation for geological/geomorphological sites below the level of the 'World Heritage Convention' (the 'Convention concerning the Protection of the World Cultural and Natural Heritage'). World Heritage Sites are declared by the United Nations Educational, Scientific and Cultural Organisation (UNESCO). The objective of the World Heritage Convention is the protection of natural and cultural sites of global significance. Many of the British World Heritage sites are 'cultural' in aspect, but the Giant's Causeway in Northern Ireland and the Dorset and East Devon Coast are inscribed because of their importance to the Earth sciences as part of the 'natural heritage' – the Dorset and East Devon site is of particular relevance here insofaras it was the outstanding geology and coastal geomorphology that led to its inscription. The St Kilda World Heritage site certainly has an important geological component contributing to its status.

In contrast to the Earth sciences, there are many other formal international conventions –

Table 1.7 Coastal Annex I habitats occurring in the UK (from McLeod *et al.*, 2002.)

EU code	Habitat name	Lay name	Priority habitat/ species	UK special responsibility
1130	Estuaries	Estuaries		×
1140	Mudflats and sandflats not covered by seawater at low tide	Intertidal mudflats and sandflats		
1150	Coastal lagoons	Lagoons	×	×
1160	Large shallow inlets and bays	Shallow inlets and bays		×
1170	Reefs	Reefs		×
1210	Annual vegetation of drift lines	Annual vegetation of drift lines		
1220	Perennial vegetation of stony banks	Coastal shingle vegetation outside the reach of waves		×
1230	Vegetated sea cliffs of the Atlantic and Baltic coasts	Vegetated sea cliffs		×
1310	*Salicornia* and other annuals colonising mud and sand	Glasswort and other annuals colonising mud and sand		
1320	*Spartina* swards (*Spartinion maritimae*)	Cord-grass swards		
1330	Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	Atlantic salt meadows		
1420	Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	Mediterranean saltmarsh scrub		
2110	Embryonic shifting dunes	Shifting dunes		
2120	Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	Shifting dunes with marram		
2130	Fixed dunes with herbaceous vegetation ('grey dunes')	Dune grassland	×	×
2140	Decalcified fixed dunes with *Empetrum nigrum*	Lime-deficient dune heathland with crowberry		
2150	Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)	Coastal dune heathland	×	
2160	Dunes with *Hippophae rhamnoides*	Dunes with sea-buckthorn		
2170	Dunes with *Salix repens* ssp. *argentea* (*Salicion arenariae*)	Dunes with creeping willow		
2190	Humid dune slacks	Humid dune slacks		×
21A0	Machairs	Machair		×
2250	Coastal dunes with *Juniperus* spp.	Dunes with juniper thickets	×	
8330	Submerged or partially submerged sea caves	Sea caves		×

(Table 1.7) Coastal Annex I habitats occurring in the UK (from McLeod et al., 2002.)