Coastal Geomorphology of Great Britain

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Chapter 11

Coastal assemblage GCR sites

INTRODUCTION

V.J. May

There are several lengths of the British coast in which, in addition to outstanding specific features such as well-developed saltmarshes or gravel beaches, the total assemblage of individual features is also outstanding. There are seven sections of coast in Britain selected for the GCR that each contain a wide diversity of individual coastal forms that together form an integrated coastal system or 'coastal assemblage' (see Figure 1.2 for locations and Table 11.1, below, for an outline of the principal features). The sites are Morrich More in the Dornoch Firth, Ross and Cromarty, and Culbin in the Moray Firth in Scotland; Holy Island, Northumberland, the North Norfolk Coast, and The Dorset Coast in England; and Carmarthen Bay and Newborough Warren and Morfa Dinlle at the western end of the Menai Strait in Wales. The origins and dynamics of each site have been the subject of considerable debate. Each of the sites falls within a different part of the British coast and is affected by different tidal and wave conditions, sediment supply and sea-level histories. Carmarthen Bay is the only member of this group of sites that is predominantly macrotidal and faces the high-energy Atlantic wave environment; there are few other sites on the European coast that combine these features with a distinctive record of sea-level change. In contrast, the north Norfolk coast is dominated by large depositional structures mainly in sand and shingle but also sheltering important saltmarshes. The links between the longshore transport regime and the development of the structures has been a focus of debate. Both Carmarthen Bay and the north Norfolk coast include a wide range of predominantly depositional features in which cliff erosion plays a limited role in the sediment budget, and reworking of the existing beaches and shallow-water sediments is more important. Both lie in situations where glaciation has played a role in the development of the coast, either in providing sources of sediments or in producing a cliffed coastline within which the sediments have been deposited and reworked.

In contrast, the coast of south-eastern Dorset

Table 11.1 Main geomorphological features of the 'Coastal Assemblage' GCR sites.

Site	Main geomorphological features	Tidal range (m)
Culbin	Extensive dune system with dunes up to 30m high; parabolic dunes; emerged gravel strandplain and spits; sandy spits; gravel spits; extensive intertidal sandflats and saltmarshes; westerly shift.	3.6
Morrich More	Emerged sandy coastal strandplain with interdigitated saltmarsh and sandy beaches on either flank; offshore sandy islands and spit; large parabolic dune system; 1 km width intertidal sandflats in Dornoch Firth.	3.4
Carmarthen Bay	Major dunes; sand-spits and barrier beaches; hard-rock and easily eroded cliffs; rias; emerged beaches; extensive intertidal sandflats; and saltmarshes.	8.0
Newborough Warren and Morfa Dinlle	Major dunes (linear and parabolic); Holocene dunes; gravel spits; hard-rock and easily eroded cliffs; extensive intertidal sandflats; estuary; saltmarshes.	4.2
Holy Island	Barrier beaches; spits; emerged beach; longshore and offshore sediment sources (Huddart and Glasser, 2002)	4.1
North Norfolk Coast	Scolt Head Island, a major barrier island; Blakeney Point, a large shingle spit; intertidal flats; beaches; dunes; saltmarshes; cliffs. One of the few areas on the coastline of England and Wales where saltmarsh morphology, including saltpans, has been examined in detail.	6.4 (west) to 4.7 (east)
The Dorset Coast: Peveril Point to Furzy Cliff	Differential erosion to a longitudinal coastline; includes such classic landforms as Lulworth Cove. Hard-rock and soft-rock cliffs; platforms; landslides; pocket beaches; chines; submerged rock barriers.	1.7 (east) to 2.0 (west)

is cliffed and affected by sea-level change, but one where coastal alignment and forms owe much to geological structure and lithology. Erosion has produced an unrivalled variety of cliffs, bays and beaches. Beaches are formed mainly in flint and chert but, even though the chalk cliffs are undergoing erosion, many of the beaches are not supplied with significant quantities from such sources today. Changes in sea level and in the position of the coastline have left a legacy of hanging and deeply incised valleys, in contrast to Carmarthen Bay where sediment-rich, drowned estuaries and rias feature strongly.

The origins of the Purbeck coast are not well understood, even though parts have been very well described (e.g. Brunsden and Goudie, 1981), especially the geology (Damon, 1884; Strahan, 1898; Arkell, 1947; House, 1993). The sole evidence on this coast of higher sea levels is at Portland Bill, and although the coast east of St Alban's Head may preserve relict features, there is no other direct evidence of higher sea levels here. The effects of differential erosion are well known here. Unlike the other sites, this coast has increasingly been investigated underwater and so the nature of rocky seabed geomorphology can be used to further the interpretation of the features.

Although individual features such as Lulworth Cove and Stair Hole, Dorset, or Scolt Head Island, Norfolk, are outstanding in their own right, their importance is significantly increased by their association with other features of the adjacent coast. Such localities could be included within previous chapters of the present volume, but despite their individual importance, these features are best described within the wider regional context and in association with each other. Three of the sites (Carmarthen Bay, North Norfolk Coast and Dorset Coast) are highly segmented in terms of their morpho-sedimentology, with between 31 and 35 segments each, and averaging 1.7 km in length, based on the form and dynamics of the shoreline (Table 11.2). The coast of Caernarfon Bay includes seven of the CORINE categories (see p. 21, Chapter 1), a smaller number of segments and a similar mean segment length to Carmarthen Bay. This reflects the higher proportion of long sandy beaches. This variety reflects the impact of changing relative sea levels, the resistance of materials, and large-scale deposition.

Large-scale deposition is also a strong theme at Culbin, Morrich More and Holy Island where plentiful sediment has been available for beach building during much of the Holocene Epoch, aided by a falling relative sea level. All three sites combine internationally important features within complexes of gravel features, sand beaches, spits, dunes and saltmarshes. At Culbin, in the Moray Firth, a large gravel strandplain composed of gravel ridges and spits has become elevated over the Holocene Epoch and subsequently buried by large quantities of wind-blown sand. Much of the present-day coast is dominated by

Table 11.2 CORINE categories, data for the Carmarthen Bay, North Norfolk Coast, Purbeck (Dorset Coast) and Newborough Warren/Morfa Dinlle GCR sites; measurements are in km.

CORINE categories		Carmarthen Bay	North Norfolk	Purbeck	Newborough Warren and Morfa Dinlle
(A)	Hard-rock cliffs (with fringing beaches)	10	0	7	4
(B)	Soft rock cliffs (with fringing beaches)	1(1)	2(1)	21(4)	1
(C)	Pocket beaches	1	0	3	0
(D)	Coarse clastic beaches	2	3	0	1
(E)	Sandy beaches	9	13	0	5
(G)	Foreshores: fine sediments	4	11	11	1
(H)	Estuary	2	1	1	1
(J)	Port/harbour zone	3	0	0	0
(L)	Embankment	0	1	1	1
(X)	Mixed beaches	0	2	2	0
Mean segment length (km)		2.25	1.47	1.42	2.30
Total segments		32	35	31	14

sandy beaches and spits, which move westwards, some of the source sand eroded from sand dunes that have been blown eastwards, opposite to the direction of longshore drift. Most of the past and present gravels have migrated west and downdrift at rates of 15 m a^{-1} to form an impressive spit complex composed of largely unvegetated recurved ridges that now enclose extensive areas of sandy saltmarshes behind. In contrast to the longshore dominated system at Culbin, the Morrich More in the Dornoch Firth is essentially an emerged sandy strandplain composed entirely of a staircase of dune-capped sandy beach ridges whose orientation matches that of the approaching wave crests from the north-east (i.e. swash-aligned). Flanked by inlets on either side, the inter-ridge hollows have allowed tidal access and the development of saltmarsh so that the sandy beach ridges and saltmarsh hollows interdigitate. Since the coast is emerging, there is a close age association between the beaches and the saltmarsh with the youngest saltmarshes occurring towards the flanking inlets and the outer coast.

The south-western end of the Menai Strait brings together two sites of international importance in their own right, Newborough Warren and Morfa Dinlle. In both sites, the development of dunes plays a role, although this is the dominant interest at Newborough Warren. The spits and gravel ridges of the Abermenai spit and at Morfa Dinlle combine to provide evidence of the Holocene development of the shoreline of a major tidal estuary in which there has been little anthropogenic interference.

The present chapter describes sections of the British coastline that have been least affected by human interference. They show extraordinarily well the ways in which coasts of different geological materials and structures respond to marine and subaerial processes over a wide range of time and spatial scales. The Scottish site descriptions are followed by those for Wales and lastly for England.

CULBIN, MORAY (NH 980 615)

J.D. Hansom

Introduction

Culbin, located on the southern shore of the Moray Firth (see Figure 10.1 for general location), is a site of exceptional international interest for the scale, complexity and diversity of its coastal geomorphology. The site comprises an emerged sand and gravel strandplain covering over 30 km^2 containing numerous westward-trending spits and ridges, and is backed to landward by a prominent emerged cliff. An extensive and formerly mobile sand-dune system has developed on top of the gravel basement (Mackie, 1897; Steers, 1937; Ovington, 1950; Comber 1993). At one time it was the largest area of open sand dune in Britain, but most of the area was stabilized by conifer afforestation between 1922 and 1963. The active-process environments and landforms of Culbin are no less impressive than their emerged predecessors. A wide intertidal zone extends from Findhorn in the east to Nairn in the west, and displays several well-developed spit and bar features. Overall the Culbin foreland in the east is erosional whereas accretion occurs towards the west at the spit at Buckie Loch. Farther west still, the proximal (eastern) part of The Bar is erosional whereas its distal (western) end is extending (Comber *et al.*, 1994). Landwards of these constructive spit and barrier features, and also within Findhorn Bay, a series of extensive sandflats and sandy saltmarsh has developed in the low-energy, sheltered environment (Comber *et al.*, 1994).

Description

The Culbin coastline extends over *c.* 12 km from the mouth of the River Findhorn in the east to Nairn Links in the west (Figure 11.1). Culbin plays an integral part in understanding the physiographic evolution of the coast of the Moray Firth and should be viewed not in isolation but as part of a similar beach and dune coast that stretches from Spey Bay in the east to Whiteness Head Spit in the west (see site report in Chapter 6). The dominant westerly drift along the southern shore of the Moray Firth (Ramsay and Brampton, 2000c) is integral to the understanding of both contemporary and Holocene landform evolution in this area.

The Holocene gravel ridges that lie beneath the dunes of Culbin Forest provide an exceptional assemblage of emerged features related to higher relative sea levels over the last 6500 years. Radiocarbon dates from peat deposits found on top of the gravels but beneath the dunes show

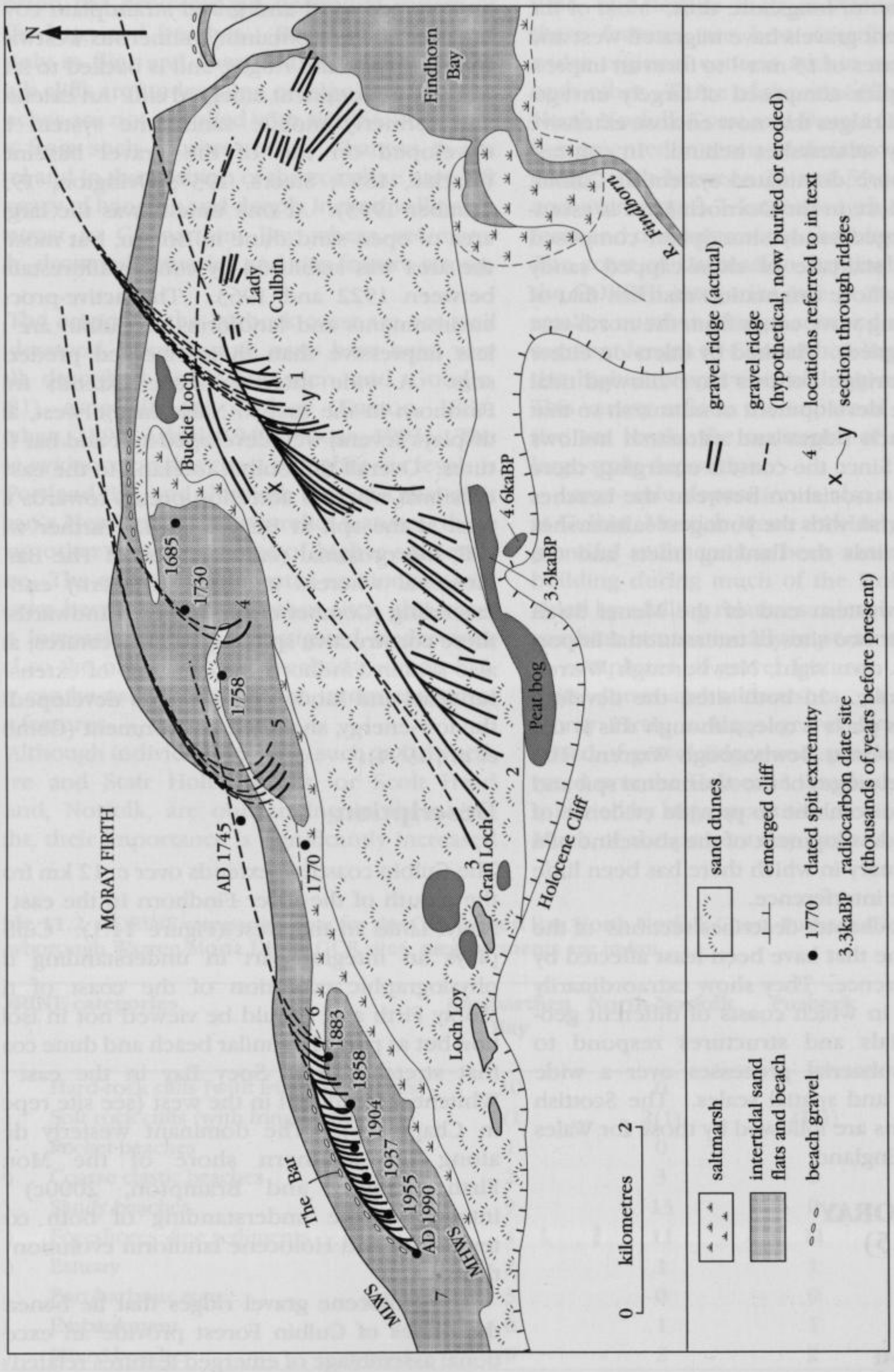


Figure 11.1 The GCR site of Culbin is a large and complex gravel strandplain composed of suites of partially visible emerged ridges capped by large sand dunes. The pattern of the underlying gravels can be reconstructed into a series of westward-extending gravel spits; the updrift erosion of the earlier spits fed the downdrift extension of the more recent ones that have been dated using historical maps and aerial photographs. Extensive sandflats and saltmarshes have developed in the shelter of the westward-extending spits. See Figure 11.2 for the section X–Y. (After Hansom, 1999.)

that sea level has fallen in this area during the past 6500 years (Comber, 1993). This isostatically driven fall in relative sea level in the Culbin area is reflected everywhere on the coast of the Moray Firth, and followed an earlier period of rapid sea-level rise (Smith, 1997). Given the altitudes and spatial locations of the emerged gravel ridges of Culbin, it is clear that they were emplaced during this phase of falling sea level (Comber, 1993, 1995).

Superimposed on these emerged gravels a major inland dune-system has developed, creating what was formerly the largest area of bare sand in Britain, prior to afforestation. The emerged marine beach deposits, which underlie the entire area of Culbin, are backed by an extensive abandoned cliff whose base lies at *c.* 9 m OD. The cliff can be traced around much of the Moray Firth (Hansom, 1988) and is the counterpart of the cliff at Spey Bay to the east (see GCR site report in Chapter 6). In the Culbin area the 5–7 m-high cliff is cut mainly into Late Devensian glaciogenic and glaciofluvial deposits and forms a divide between older (late Devensian) deposits to landward, and younger (Holocene) deposits to seaward (Firth, 1989).

The most striking landforms preserved within the Culbin dunes are the emerged gravel storm-ridges, found at altitudes of up to 10.9 m OD (Comber, 1993). Owing to the cover of dune sand, the gravel ridges are discontinuously exposed in the field, but can be traced on the ground and in aerial photography in an arcuate form, spanning approximately 5 km of sporadic exposure. These ridges represent abandoned upper beach deposits thrown up under high-energy storm events, and are composed of gravel clasts 30–50 mm in diameter. A narrow belt of ridges extends westwards across the north-eastern flank of Culbin, before splaying out southwards into a 'fan' at NH 997 630 (Figure 11.1, location 1). Landwards of this point, the approximately parallel ridges begin to splay out markedly into at least two distinct groups, which extend towards the south-west (Figure 11.1, locations 2 and 3). At the main apex of this 'fan' structure the landward ridges are truncated by the ridges to seaward, indicating erosion of the earlier features (Comber, 1995). Transects levelled across the entire sequence of ridges from the emerged cliff to the present-day beach display declining altitudes to the seaward from a maximum of 10.9 m OD to a minimum of 3.7 m OD. However, between some groups of ridges there is a marked ridge-crest fall of almost 3 m (Figure 11.2).

The Culbin dune system covers an area of approximately 13 km² and displays a range of forms unparalleled in any UK dune system. The orientation of the axes of most of the dunes is south-west to north-east, with blowthrough patterns preserved on account of their artificial fix-

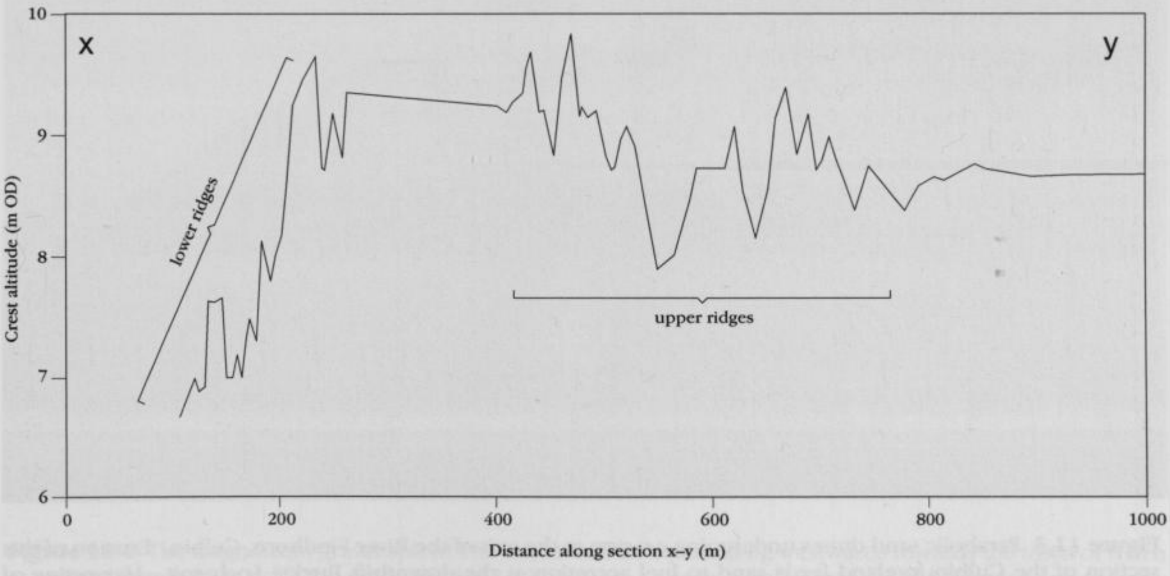


Figure 11.2 The gravel ridges over a 1000 m transect from x–y (see Figure 11.1) show two groups of emerged ridges, the most seaward of which decline rapidly in height towards the north-west. (After Comber, 1995.)

ing by afforestation. Three main dune types occur at Culbin: parabolic dunes; formerly transgressive dunes; and butte dunes. The parabolic dunes of Maviston, near Loch Loy in the west of the site (Figure 11.2), attain a maximum height of 15 m, with flanks up to 400 m long and a maximum width of *c.* 400 m, making these among the largest of their kind in Europe (Comber *et al.*, 1994). Prior to stabilization by planting, Ogilvie (1923) recorded the maximum height of the active Maviston dunes as 16.5 m, but the crests have since settled. Formation of the dunes progressed as a classic parabolic blowthrough sequence from an initial straight dune crest trending parallel to the coast. Destabilization of the central zone of the crest through the destruction of the vegetated surface produced an area of crestal instability, allowing sand to be blown downwind and allowing the dune crest to migrate and inundate the surfaces behind. Erosion of the lateral slopes of the widening blowthroughs accelerated the process, as did funnelling of the incident wind towards the unstable zone. While the central section of the dune continued to extend downwind, the flanks of the dune remained vegetated and thus stable, creating the distinctive parabolic dune forms found today. The exceptional size of the dunes at Maviston has meant that rates of movement were relatively low, retaining the essential form of the features since at least 1923 until stabilization by forestry (Ogilvie, 1923; Steers, 1937; Edlin, 1976).

Not all of the Culbin dunes display the effects of blowthrough activity, and examples of high dunes, reaching altitudes of up to 30 m, with the smoothed and rounded forms of previously unvegetated transgressive dunes are found, particularly in the west central area of the forest in the vicinity of the underlying gravel 'fan'. A good example of such a dune is Lady Culbin, located at NJ 013 640 (Figure 11.1). Ovington (1950) noted that the Lady Culbin dune moved at an average rate of 6.5 cm per day over a six-

Figure 11.3 Parabolic sand dunes undergoing erosion at the exit of the River Findhorn, Culbin. Erosion of this section of the Culbin foreland feeds sand to fuel accretion at the downdrift Buckie Loch spit. Harvesting of timber over a 20–30 m-wide dune edge zone is part of a management regime designed to reduce erosion caused by disruption of the dune surface by toppling, and to allow mechanical harvesting to be carried out in safety. (Photo: J.D. Hansom.)

week period. Butte dunes are the eroded remnants of formerly vegetated and stabilized surfaces that have subsequently suffered erosion on all sides to leave a residual flat-topped stump flanked by steep, often unvegetated, slopes of sand. Good examples of butte dunes occur in the north-east of Culbin.

The contemporary coastal geomorphology of Culbin can be considered in terms of five landform assemblages: the Culbin foreland to the east of Buckie Loch; the Buckie Loch spit; The Bar (locations 6 and 7, Figure 11.1), and the extensive intertidal northern sandflats and saltmarshes in the shelter of the spits and barriers (Figure 11.1).

The Culbin foreland extends west from the Findhorn estuary to the Buckie Loch. The foreshore beach is composed mainly of sands, although gravel occurs on the foreshore at the mouth of the Findhorn. Much of this foreland coast is subject to severe erosion, which has resulted in the cutting of the backing sand dunes into prominent bare-sand cliffs up to 8 m high (Figure 11.3). Frontal erosion of these old dunes is recorded to be occurring at rates of up to 1 m a^{-1} (Ritchie *et al.*, 1978; Comber, 1993; Comber *et al.*, 1994). Dune erosion occurs despite the occurrence of relatively wide sandy beaches (up to *c.* 200 m) along the foreland. At the westward extremity of the former Buckie Loch a spectacular recurved spit (the Buckie Loch spit) extends westwards. The spit is presently *c.* 3 km long and up to 130 m wide in its central section, becoming narrower westwards. The spit foreshore is predominantly sandy but the upper foreshore sediment coarsens westwards so that a small gravel ridge has developed on its distal end. The rear of the spit is dominated by several suites of stabilized dune ridges, with actively accreting dunes occurring at both proximal and distal ends of the spit. Erosion of the updrift part of Buckie Loch Spit is resulting in occasional washover of low parts of the frontal dune and gradual infill of the Buckie

Figure 11.4 The magnificent gravel spit of The Bar at Culbin is extending westwards towards the town of Nairn at approximately 15 m a^{-1}. The sandy Buckie Loch spit can be seen in the upper middle distance and the narrow erosional neck at the eastern end of The Bar. This updrift erosion has truncated earlier ridges and is now encroaching into the area of saltmarsh that has developed behind the bar and may ultimately threaten the larger area of saltmarsh that lies in the right foreground. (Photo: P. and A. Macdonald/SNH.)

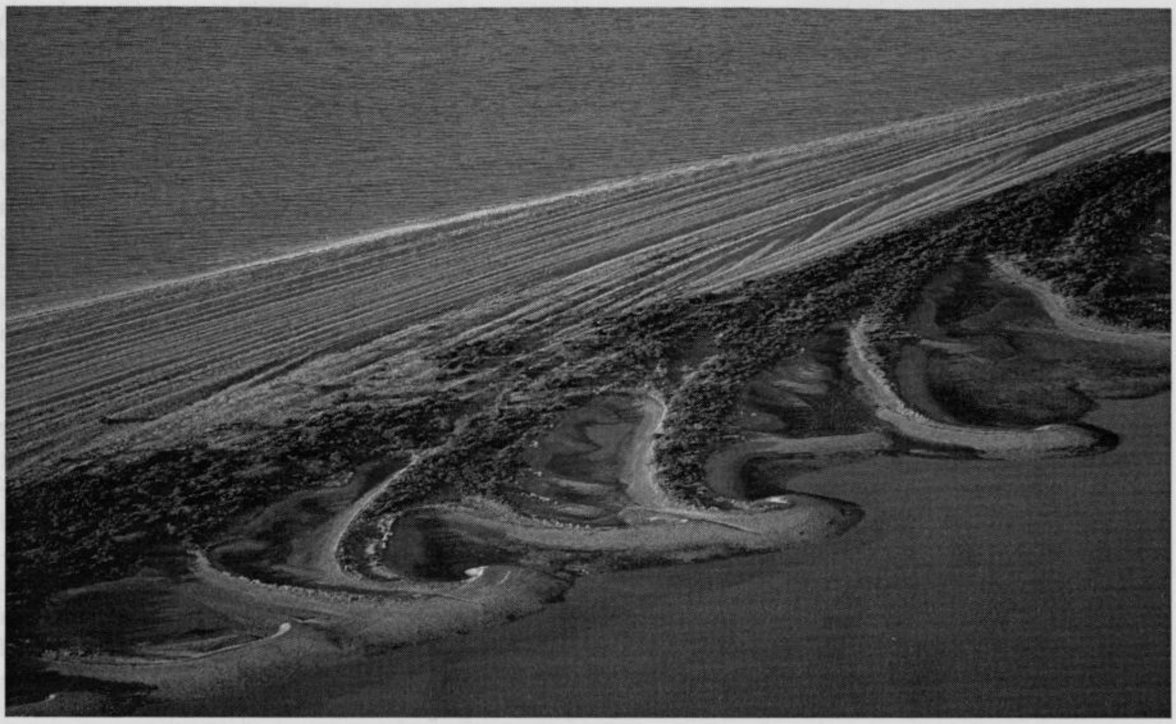


Figure 11.5 Spectacular recurves extend from the active outer beach ridges at The Bar at Culbin into the sheltered area behind. The inner recurved parts of the gravel ridges support small areas of heather, gorse, broom and pine whereas the intertidal flats between the gravel ridges support small areas of saltmarsh (see Figure 11.4). (Photo: P. and A. Macdonald/SNH.)

Figure 11.6 An extensive area of saltpans and linear creeks characterize the area of saltmarsh that has developed at the heads of the two intertidal lagoons that lie either side of the area where The Bar at Culbin is attached to the mainland (see Figure 11.4). (Photo: J.D. Hansom.)

Loch, which is now infilled.

The Bar at Culbin forms the most distinctive coastal feature on the southern shore of the Moray Firth and is a fine example of a 'flying barrier', with tidal lagoons and saltmarsh behind (Figure 11.4). The feature represents an attached gravel barrier orientated north-east–south-west and extending over a distance of 7.3 km. It is now attached to the mainland by a low neck of saltmarsh fronted by a gravel beach. At its narrowest the width of the saltmarsh behind the beach is only 250 m, the seaward edge being subject to burial by washover of gravels during storms. Recession of the beach over the saltmarsh has exposed peat on the foreshore. The eastern part of the Bar is mainly sandy, and is adorned with prominent sand dune ridges that sit on top of southward-trending gravel recurves that extend into the intertidal lagoon. The western end comprises the main part of the 'flying barrier' and displays a series of multiple gravel storm ridges backing an active gravel beach (Figure 11.5). Up to 13 major recurving gravel ridges occur landwards of the active ridge and represent recently abandoned shoreline features that have been dated (Figure 11.1, locations 4–7).

An extensive intertidal sandflat with multiple sand-bars occurs seawards of both the Buckie Loch spit and The Bar. These sandflats also extend into the channels and the intertidal zone on the landward side behind the Buckie Loch spit and The Bar, where the shelter afforded has allowed saltmarshes to develop (Figures 11.4 and 11.5). The marshes commonly have a small undercut edge of *c.* 0.2 m in height (Ritchie *et al.*, 1978); although some edges grade smoothly from sandflat to saltmarsh. The saltmarshes range from low developmental marsh surfaces characterized by intermittent stands of common saltmarsh-grass *Puccinellia* and samphire *Salicornia* (Figure 11.6) to substantial areas of high marsh supporting a full vegetation cover merging landwards to freshwater marsh species. The two largest areas are identified as the marsh surface landward of the central section of The Bar and the area landward of Buckie Loch spit. The marsh landward of The Bar is adorned with numerous saltpans and linear creeks (Figure 11.6). The area of saltmarsh landward of Buckie Loch spit is expanding rapidly as distal extension of the spit continues to provide a lower-energy environment in which progradation can occur. Buckie Loch itself was probably a former saltmarsh, abandoned by westward migration of the active marsh, and subsequently dominated by freshwater species before infilling occurred through washover, sand blow and colonization by trees.

Interpretation

The geomorphology of Culbin was central to Ogilvie's (1923) interpretation of the Holocene development of the Moray Firth. Ogilvie (1923) first described and mapped the emerged gravel features and relict cliff along the southern Moray Firth coast, linking the development of these features to a higher relative sea level and the reworking of vast quantities of glaciofluvial and glacial deposits from the Moray Firth coastal plain and the inner continental shelf as sea level adjusted following deglaciation. Ogilvie's account together with Steer's (1937) work on Culbin emphasized the importance of the westward direction of longshore drift along the southern shore of the Moray Firth to landform development throughout the Holocene Epoch. The excellent groundwork and elegant theories of coastal development provided by these early workers were pursued by Comber (1993, 1995), Hansom and Comber (1994), Comber *et al.* (1994) and Hansom (1999), who provide the most recent interpretation of the evolution of Culbin, and indeed the southern shore of the Moray Firth.

At the peak of the Holocene transgression (*c.* 6500 years BP) the high-stand of relative sea level at *c.* 9 m OD in the Culbin area impinged upon and re-trimmed a pre-existing cliff that probably had been cut initially during the Lateglacial period. During this time of higher relative sea level a marine corridor existed to the east of Culbin, south of the high ground of Burghead–Lossiemouth, which was then an offshore island (Ogilvie, 1923; Comber, 1993). Under conditions of net westerly drift, sediment from the River Spey is thought to have moved freely through this corridor and into a proto-Burghead Bay to be augmented by sediment from the River Findhorn. Combined with the net onshore movement of sediment under a rising sea level, a strongly positive sediment budget was created at the present-day location of Culbin (Hansom, 1999). The shoreline response to such rapid sediment input was to prograde seawards, and progradation at Culbin occurred in a similar fashion to many other gravel-dominated foreshore systems (e.g. Carter *et al.*, 1987) by developing a suite of multiple sub-parallel ridges. Transects across the gravel ridge 'fan' (Figure 11.1) demonstrate the trend in falling sea level that occurred after the peak of the Holocene transgression (Figure 11.2). The highest set of ridges in the 'fan' were deposited at the peak of the transgression, while most of the ridges landwards and eastwards occur at lower altitudes and were deposited as sea level fell and so are younger (Comber, 1993). The falling sea level reduced water depths in the marine corridor to the east of Culbin and it became blocked with westward-drifting sediment from the Spey. At Culbin, the loss of this sediment feed from the east was to dramatically reduce the amount of sediment available for storm ridge sedimentation. The sedimentary record of this decline in sediment supply at Culbin is represented by fewer gravel ridges deposited over time, creating a net steepening of the ridge suite to seaward and the beginning of erosion of the updrift gravels in the eastern part of Culbin itself.

The above interpretation suggests that the locus of gravel accumulation has shifted through time from the east of Culbin to the west, where it is now represented by The Bar. The attached gravel barrier has been migrating alongshore in a westerly direction towards the town of Nairn since least 1685 AD as documented by Ross (1992; Figure 11.1). This process of updrift erosion fuelling downdrift accretion has been a feature of the coastal development of the southern Moray Firth throughout the Holocene Epoch (Comber, 1995). Figure 11.1 shows a hypothesized development sequence, running numerically from 1–7, of Culbin Sands and The Bar proposed by Hansom and Comber (1994), Comber (1995) and Hansom (1999). The reworking of sediment from updrift to fuel downdrift accumulation can be seen to account for the truncated emerged gravel ridge sequences in the 'fan' (Figure 11.1, locations 1, 2 and 3). Radiocarbon dating of peat taken from depressions at the foot of the emerged cliff suggests that abandonment of gravel spit 3 occurred between 4600 and 3300 years BP when the River Findhorn abandoned a westerly course at Cran Loch to breach northwards through the gravel beach close to the present exit of the river (Comber, 1993). The process of spit destruction is suggested to have been repeated several times in the similar, though much younger, features that form The Bar and its predecessors. Hansom (1999) indicates the mode of emplacement of the gravel storm-ridges has remained the same since at least the mid-Holocene and represents a predictable response of sediment recycling within conditions of restricted sediment supply. In conditions of deficit, sediment within specific coastal cells is re-organized by erosion of some parts and re-deposition in others (Carter, 1988). Figure 11.1 also demonstrates the tendency over time of the Culbin foreshore to rotate clockwise to face north-east in an attempt to align itself normal to incident wave approach, evolving from a drift towards a swash alignment of the coast (Davies, 1980).

The entire length of The Bar at Culbin is subject to reworking as proximal erosion in the east fuels distal accretion in the west (Comber *et al.*, 1994). Where both contemporary and recently abandoned ridges have been truncated in the deeper water of the distal end, wave refraction has carried gravel around the tip (Figure 11.5). This results in recurves forming behind the sequential positions of the former distal ends of The Bar, some of the truncated remnants of which are now found in seemingly anomalous locations (for example Figure 11.1, locations 4 and 5). Between 1976 and 1989 The Bar continued to extend westwards at a mean rate of 14.6 m a^{-1} (Comber, 1993), demonstrating that the processes that created this section of the Scottish coastline over the Holocene Epoch still operate. Today's Bar is a direct descendant of many previous barriers and spits on this coast.

The Culbin dune system has been described extensively (e.g. Ogilvie, 1923; Steers, 1937; Ovington, 1950; Edlin, 1976). Several well-developed palaeosols are found at various sites throughout Culbin Forest and contain important information concerning the development of the dunes (Comber *et al.*, 1994). The palaeosol profiles are particularly mature, a feature unusual in dune systems of this size given their propensity to become remobilized under combined natural and anthropogenic pressure. The earliest documented reference to the mobile dune belt at Culbin was by Boethius in 1097 AD (in Craig, 1888), who referred to the inundation of parts of Moray by sand thrown up during storms in the North Sea, but several earlier periods are known including a major period of sand dune instability at *c*. 4500 years BP (Hickey, 1991). The most recent period of dune activity at Culbin coincides with the end of the most recent phase of wide-scale dune re-activation. This phase began in the 13th century and ended during the mid–late 17th century with the stormiest period of the 'Little Ice Age' (Hickey, 1991). The maturity of the Culbin palaeosol profiles suggests that some of the dunes remained stable for the early part of this dune mobilization phase (Comber *et al.*, 1994), supporting a full vegetation cover that prevented sand-blow. The dunes seem to have become re-activated relatively late in the sequence of dune activity. The documented story of the destruction of the Culbin estate by blown sand reports that the estate was overwhelmed over the course of a single storm in 1694 AD (Steers, 1937). However, it is more likely that the dunes were subject to an extended period of destabilization, with the final inundation occurring during the 1694 event. Destabilization was probably aided by the removal of the closed vegetation cover and, in particular, the removal of marram *Ammophila arenaria* for thatch (Comber *et al.*, 1994). In response to the loss of the important agricultural estate of Culbin, an Act of the Scottish Parliament was passed in 1695 to prevent pulling of 'bent' (marram) from sand dunes (Ross, 1992).

As demonstrated by Comber (1993) the contemporary coastal development of the Culbin foreshore can be directly linked to the Holocene evolution of the entire landform assemblage. The diverse process environment of the Culbin foreshore provides an excellent site for the study of a wide range of coastal processes and landforms. Erosion of the dunes west of the River Findhorn and on the updrift section of the Buckie Loch spit fuels downdrift accretion of the spit, which has been extending in a westerly direction at a mean rate of 22.3 m a^{-1} over the period 1870–1988 (Comber *et al.*, 1994). As erosion proceeds at the eastern extremity of the Buckie Loch spit, storm washover and marine incursion into the Buckie Loch occurs. A shallow lake in the late 19th century, the Buckie Loch is now a low, intermittently flooded area of grassland and deciduous trees fronted by a low dune-ridge. It is likely that westerly accretion will progressively seal the upper part of the Buckie Loch spit marsh, creating a new Buckie Loch farther to the west of the original (Comber *et al.*, 1994). By that time the present-day site of the Buckie Loch will have been all but removed, as erosion proceeds at the eastern end. Such change in both the Buckie Loch and The Bar has implications for the extensive saltmarshes that have accreted in the shelter afforded by the two major spits. Migration of the protecting structures and erosion of their updrift ends forces commensurate change in the sheltered environments behind and exposes the backing saltmarsh to erosion. Such activity is presently most severe at the neck, midway along The Bar, where saltmarsh peat is exposed on the intertidal zone as the foreshore transgresses landwards (Figure 11.4).

Conclusions

Culbin is an exceptional site for coastal geomorphology. Within Europe, no comparable suite of emerged gravel ridges and spits with capping sand dunes matches the scale, complexity and preservation of the features at Culbin. The gravel ridges record the fall of sea level from its mid-Holocene high at about 6500 years BP to its present-day level. In addition, a reduction in sediment supply forced a switch from widespread gravel accretion to a period of reworking of pre-existing gravel spit structures. Such internal reorganization of sediment has resulted in the sequential development of migrating spits, the most recent of which can be seen in the present-day Bar (Hansom, 1999). Resting on top of the ridges, the Culbin dunes once formed one of the largest areas of blown sand in Britain and although subsequently, and very successfully, stabilized by forestry, they are rated internationally as a geomorphologically important site for sand dune development. Culbin is also a key regional site for the interpretation of the history of Holocene landform evolution in the Moray Firth.

No less impressive are the active process environments of Culbin, with a dynamic migrating sand spit whose extension has led to the infill of a small lake and its imminent erosion. Culbin also has a spectacular example of a 'flying barrier', a spit whose eastern section is a dune-adorned sandy feature and whose western end is a superb rapidly extending gravel spit backed by numerous recurved gravel ridges (Figure 11.5). Both of these features are associated with the development of wide intertidal sandflats on both seaward and landward sides, the latter providing a sheltered environment for the development of saltmarshes. Culbin is a unique mix of spectacular Holocene emerged features together with equally impressive contemporary coastal processes and forms.

MORRICH MORE, ROSS AND CROMARTY (NH 803 835–NH 892 830)

J.D. Hansom

Introduction

Morrich More is a large coastal strandplain on the southern shore of the Dornoch Firth (see Figure 10.1 for general location) between Tain and Inver. Its development is related to a shallow offshore zone and the presence of abundant sandy material, which has been brought onshore and deposited in a series of sequential beach ridges under conditions of a falling relative sea level. The stratigraphical and morphological record contained within Morrich More is central to the understanding and reconstruction of the Holocene coastal development of the Dornoch Firth and wider Moray Firth (Hansom and Leafe, 1990; Hansom, 1991, 1999, 2001; Smith *et al.*, 1992; Firth *et al.*, 1995). Access to Morrich More is restricted on account of its use as a Royal Air Force weapons range.

Morrich More contains a diverse variety of constructional coastal landforms including an emerged strandplain, attached sandy barriers and spits, stabilized dunes including parabolic dunes, embryo and foredune succession, saltmarshes and sandflats. The importance of Morrich More, both within the British Isles and internationally, lies in the extent, scale and diversity of its geomorphology together with the fact that the transitional zones between accretionary landforms are well developed and preserved.

In view of the quantities of sediment involved, it is likely that the mid-Late Holocene seaward growth of Morrich More was the most rapid of any coastal feature in Great Britain.

The continuity between the Holocene and contemporary landforms of Morrich More make it an invaluable site for the reconstruction of past process environments as well as for study of the interaction of modern process-form relationships.

Description

The Morrich More strandplain consists of an alternating sequence of low dune-capped sand ridges separated by lower and wetter areas and saltmarsh. The entire landform covers an area of *c.* 34 km², of which *c.* 29 km² lies within the GCR site. The southern limit of the low-lying area of emerged sands is the *c.* 8–10 m OD base of a prominent slope that marks the line of an emerged cliff. Seawards of the cliff, a strandplain with 50 or so emerged sandy ridges extend *c.* 8 km to the north-east into the Dornoch Firth. The main ridges are marked on Figure 11.7. The majority of these features are aligned north-west–south-east and decline in altitude from 8.6 m OD close to the base of the cliff to 1.4 m OD at the present-day coastline. The emerged marine ridges of Morrich More are composed entirely of medium- to fine-grained sand, capped with dune sand and can be split into four distinct altitudinal groupings (Hansom, 1991). In the south of the site, the highest group of ridges are typically 1–1.5 m high, occur at 6.0 to 8.6 m OD and are spaced about 100 m apart. At 6.4 m OD beneath one of these higher ridges, a layer of woody peat yielded a radiocarbon age of 6445 years BP (Hansom and Leafe, 1990). A second set of ridges at heights of between 4.4 and 5.5 m OD occur to the seawards of the higher ridges and occupy the central section of Morrich More. Farther north and seawards, the lowest sets of sand ridges occur at altitudes of 2.5 to 4.0 m OD and 1.4 to 2.4 m OD. The latter group occur at the same altitude as the modern beach ridge. These lower ridges are more widely spaced than those to landward (Figure 11.8) and are adorned with windblown sand, taking their height to 4–5 m OD. As a result, the most recently deposited ridges on the outer coast, those of Patterson Island and Innis Mhór, are the largest and most prominent of any of the Morrich ridges.

In summary, as the emerged strandplain falls in altitude from over 8 m OD at the base of the cliff to 1.4 m OD at its seaward margin, there is a corresponding fall in the number of beach ridges, an increase in their spacing and a general increase in their prominence towards the open coast (Figure 11.7). Although many of the emerged ridges are covered in a thin veneer of blown sand, their form is obscured in three areas by extensive dune development, in the west, in the east and on the outer coast at Patterson Island and Innis Mhór. A feature of many of the emerged sand ridges is that they display truncated westward trending recurves at their northern ends, comparable to the modern features of the contemporary coast.

In the nearshore and intertidal zone, active sand-bars move onshore to produce a

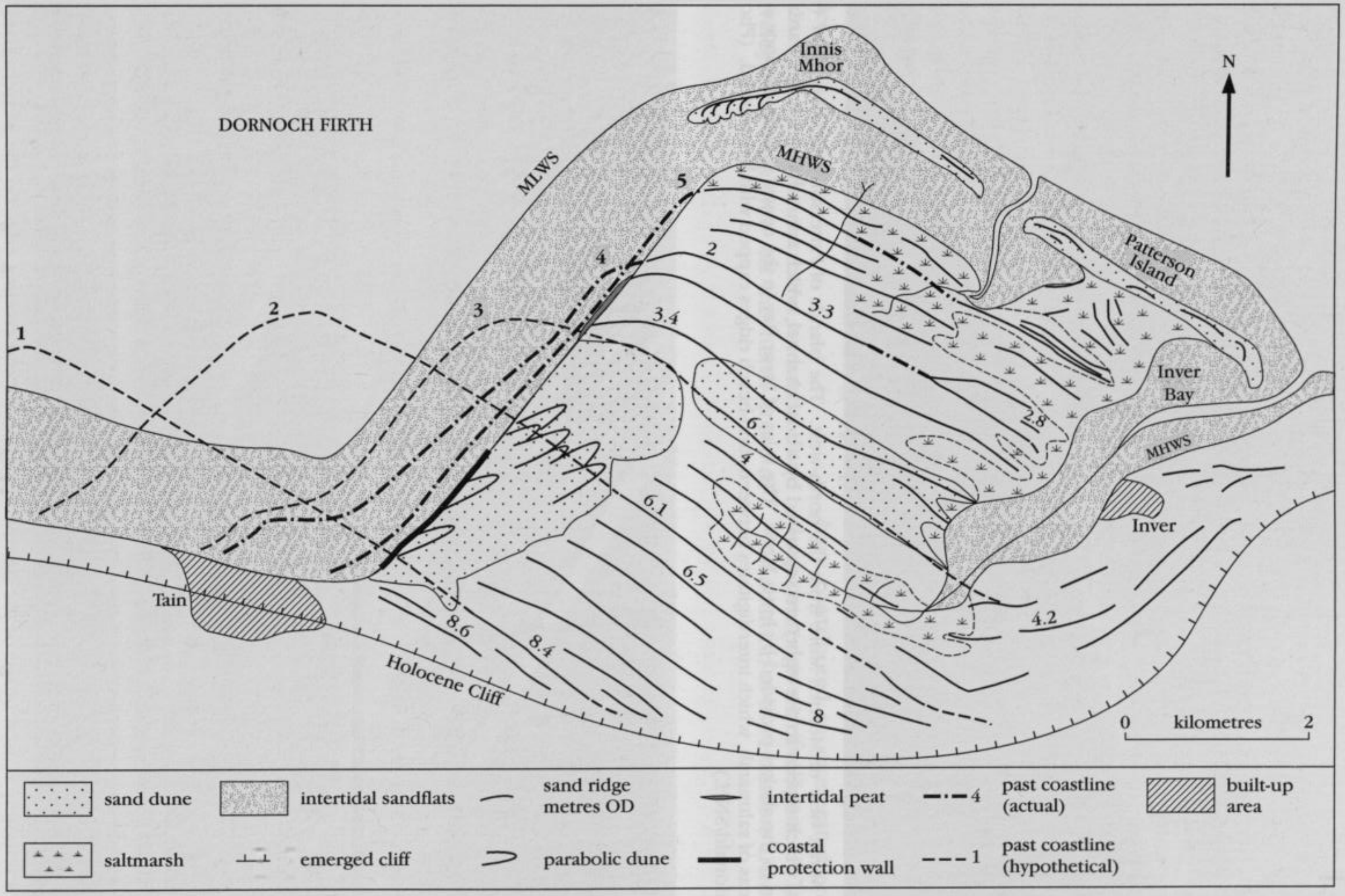


Figure 11.7 Morrich More is a series of emerged sand beach ridges adorned with sand dunes, which together form a progradational strand-plain jutting out into the Dornoch Firth. Saltmarsh interdigitates between the sand ridges in the north and east of the structure. The numbered coastlines correspond to the approximate locations of reconstructed and actual coastal positions. Heights of the sand ridges are given in metres above OD. (After Hansom, 1999.)

Figure 11.8 Aerial view of Morrich More from the north-west. The islands of Patterson and Innis Mhór (the eastern end of which is seen to the right) are separated by a tidal channel, which connects with a large area of sand accretion in the shelter provided by Innis Mhór. The inlet of Inver Bay in the centre middle distance supports large areas of saltmarsh, which interdigitates between sand-beach ridges capped with blown sand. (Photo: P. and A. Macdonald/SNH.)

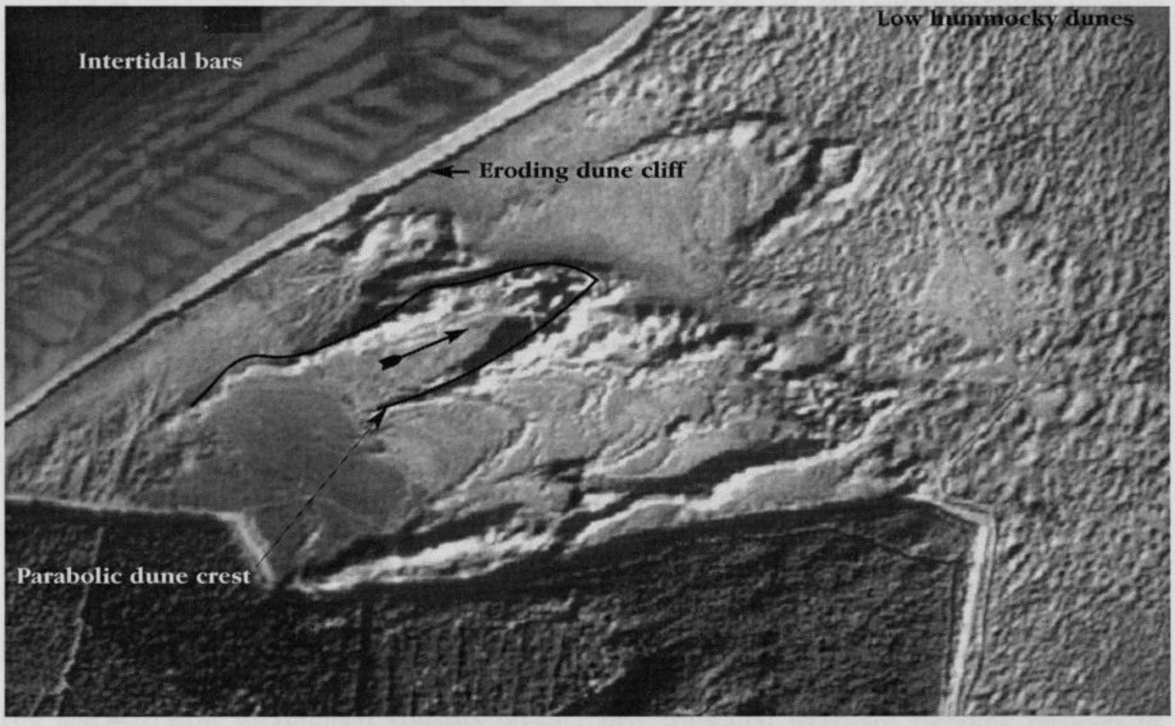


Figure 11.9 A remotely sensed image of the narrow upper beach and eroding edge on the western flank of Morrich More showing the large fixed parabolic dunes and the area of low dunes downwind. Intertidal bars are well-developed on the 1 km-wide intertidal flats on the Dornoch Firth side of Morrich More, and may indicate the direction of sediment movement under the flood tide (onshore) and ebb tide (alongshore to the north-east). North is at the top of the image. The arrow indicates direction of migration of the parabolic dunes. (After Hansom and Leafe, 1990.)

prominent sandy barrier (Hansom and Leafe, 1990). This barrier comprises two dune-capped high-tide 'islands' of Innis Mhór in the west and Patterson Island in the east, punctuated by a tidal channel in the middle (Figure 11.8). The fronting beach is shallow and sandy and is mainly backed by accreting sand dunes. Both extremities of the barrier islands are characterized by recurving sand spits. At the entrance to Inver Bay in the east, a simple low sand spit is deflected southwards into the bay. At the entrance to the Dornoch Firth in the west, a section of Innis Mhór characterized by erosion is connected to a *c.* 2 km-long westerly trending sandy spit that extends into the Firth. This spit is weakly recurved and is composed of several ridges that are now capped with dunes. The two dune-clad islands of Innis Mhór and Patterson Island are now connected to the main body of the strandplain by sandflat and saltmarsh, which is inundated to a depth of 1 m at high spring tides.

In contrast to the accretion and new dune development displayed on the north coast of Morrich More, the side that faces west to the Dornoch Firth is backed by an eroding dune edge whose base lies at MHWS and is fronted by a steep and narrow sandy beach (Figure 11.9). The height of the cliff undergoing erosion varies depending on the height of the sand dune behind, being usually about 2 m but reaching 14 m in the afforested dunes in the south-west, where mature trees topple onto the foreshore. In places along this shore, outcrops of peat are exposed on the intertidal beach. Extending from the foot of the beach, a prominent low-gradient, intertidal sandflat reaches 1 km in width before the low-tide channel of the Dornoch Firth is reached to the north-west. Low sand-bars exist on the sandflat surface (Figure 11.9). In response to erosion of the western flank of Morrich More, a series of low boulder revetments have been constructed over a 2 km stretch north-east from Tain. These have been effective in reducing erosion locally, but have contributed to accelerated erosion of the dune coast down-drift (Figure 11.7).

In addition to the extensive areas of intertidal

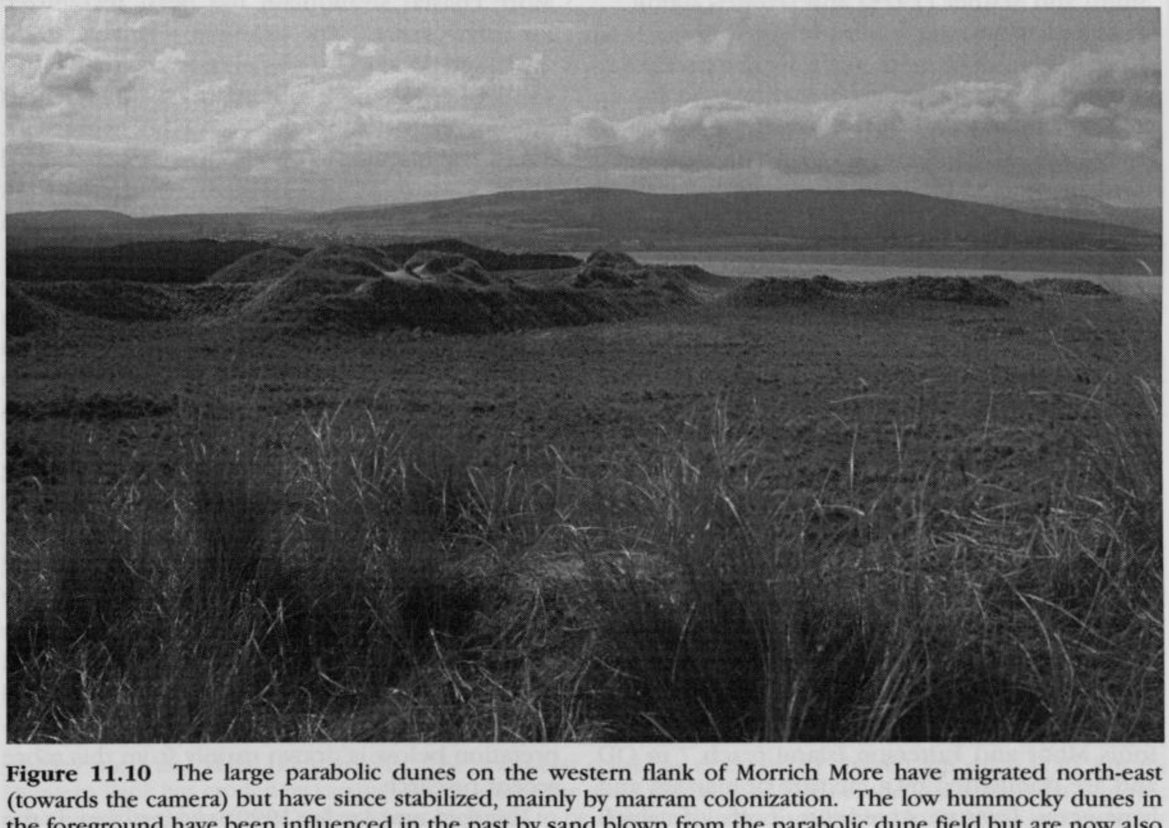


Figure 11.10 The large parabolic dunes on the western flank of Morrich More have migrated north-east (towards the camera) but have since stabilized, mainly by marram colonization. The low hummocky dunes in the foreground have been influenced in the past by sand blown from the parabolic dune field but are now also stable and covered mainly with marram and smaller areas of heather. (Photo: J.D. Hansom.)

sandflat on the western flank of Morrich More, similar areas also exist in the shelter provided by the barriers of Innis Mhór and Patterson Island and within Inver Bay. On the more-elevated sections of sandflat, tidal inundation is of lower frequency and duration, thus allowing saltmarsh vegetation to colonize. The 260 ha of saltmarsh on Morrich More represents 5% of the remaining natural saltmarsh in Scotland and it is a distinctive system in its own right on account of its relationship with the beach ridges (Hansom and Leafe, 1990). The saltmarshes are drained by linear creek systems, which extend into Morrich More along the axes of the inter-ridge swales or hollows (Figure 11.7). Thus, saltmarsh and emerged beach ridges interdigitate, and the extremities of the beach ridges become progressively buried. The complex vegetation pattern of Morrich More is dominated by this pattern of interdigititated ridges and slacks (Smith and Mather, 1973) and the strandplain carries a rich flora of over 200 flowering species, ranging from intertidal sandflat species to Juniper–*Calluna* heath on the oldest landward ridges (Stapleton and Pethick, 1996). The vegetation succession of Morrich More is discussed in further detail in Smith and Mather (1973) and Dargie (2000).

The most striking feature of the western sand dune margin of Morrich More are the exceptionally high parabolic dunes, which extend for up to 1 km inland and have a relief amplitude in excess of 14 m (Figure 11.9). The dunes are fixed by vegetation, mainly marram *Ammophila arenaria* and heather *Calluna vulgaris*, although the southern part is now artificially stabilized by afforestation. The highest dunes occur at the northern tip of the forested area and reach 20 m OD in a series of large parabolic dunes. These dunes exhibit exceptionally steep and often knife-edged slopes in excess of 30°. The alignment of the ridges and deflation hollows (250°) indicates a north-eastwards migration, sub-parallel to the western edge of Morrich More (Figure 11.10). Within the deflation hollows the water table is visible, and the sides reveal buried palaeosols. Only a small part of the most easterly of these dunes remain mobile with sand faces spilling forward, and the majority of the system has been stabilized by vegetation. The dunes of the outer coast islands of Innis Mhór and Patterson Island reach 7 m OD and are dominated by a mixture of marram and lyme-grass *Leymus arenarius*, both of which grow vigorously in the active aeolian depositional conditions on the outer coast.

Grass-covered low dune surfaces are confined to the western shore and its landward environments. A low undulating dune plain is truncated along the western edge by backshore erosion producing a scarp of about 1 m high and enabling the limited beach sand available to be blown up onto the dune surface behind. The dune surface carries browntop bent–sheep's fescue (*Agrostis tenuis-Festuca ovina)* and white clover *Trifolium repens* and locally is being stripped by wind-scour. A number of erosional scarps dissect the surface, taking the form of small linear cuts orientated east and north-east. The sand scarps often have small areas of sand accumulation at their downwind ends, which are progressively being colonized by marram.

Interpretation

Morrich More forms part of a network of sites used to infer the complex interaction between sea level, sediment supply and coastal evolution of the Dornoch Firth over the Holocene Epoch (Hansom, 1991, 2001; Firth *et al*., 1995). The scientific importance of the immense Morrich More coastal strandplain has been recognized for many years. For example, Ogilvie (1923) described Morrich More as 'a wave-built sandy strandplain ... built out gradually throughout the uprising of the coast'. Further work (e.g. Smith and Mather, 1973; Smith, 1983) described Morrich More as an emerged strandplain built up during a succession of changing land–sea relationships during the Holocene Epoch. Smith (1986) goes further, suggesting that the entire Morrich More system is genetically a coastal strandplain created by *c*. 6500 years of shoreline accretion in the form of swash-bars thrown up by wave activity. However, perhaps as a result of the size and complexity of Morrich More, there was a lack of any detailed geomorphological studies until the work of Hansom and Leafe (1990). This work led to the reconstruction of the Holocene evolution of the Dornoch Firth (Hansom, 1991; Firth *et al*., 1995) and emphasized the role that contemporary processes play in the continued development of Morrich More (Stapleton and Pethick, 1996; Hansom, 1999, 2001). The interpretation below is drawn mainly from this more recent research.

Hansom and Leafe (1990) suggest that at the peak of the Holocene transgression, in a situation of plentiful sediment supply, large amounts of sand were transported onshore and beach ridges began to develop rapidly close to the Holocene cliff. A radiocarbon date of 6450 years BP from peat found in a section at 6.4 m OD beneath one of these ridges (Hansom and Leafe, 1990) indicates that the ridge formed soon after this date. The age and altitude of the suite of sand ridges, at altitudes of 6.0 to 8.6 m OD, suggests development at the culmination of the Main Postglacial Transgression (Firth *et al.*, 1995). The progressive eastward progradation of the Morrich More shoreline was probably produced by onshore movement and vertical accretion of nearshore bars fed from offshore sediments, the narrow spacing and number of the landward-most ridges indicating that sediment supply was relatively abundant and that accretion was rapid at this time (Hansom and Leafe, 1990). Subsequently, as the rate of eustatic sea-level rise fell below the rate of isostatic uplift of the land, relative sea level fell and a second suite of ridges were formed between 4.4 and 5.5 m OD (Hansom, 1991; Firth *et al.*, 1995). Between 6400 years BP and *c.* 5000 years BP, the limited sea-level fall seems to have been conducive for large amounts of sands to move onshore to produce rapid shoreline regression

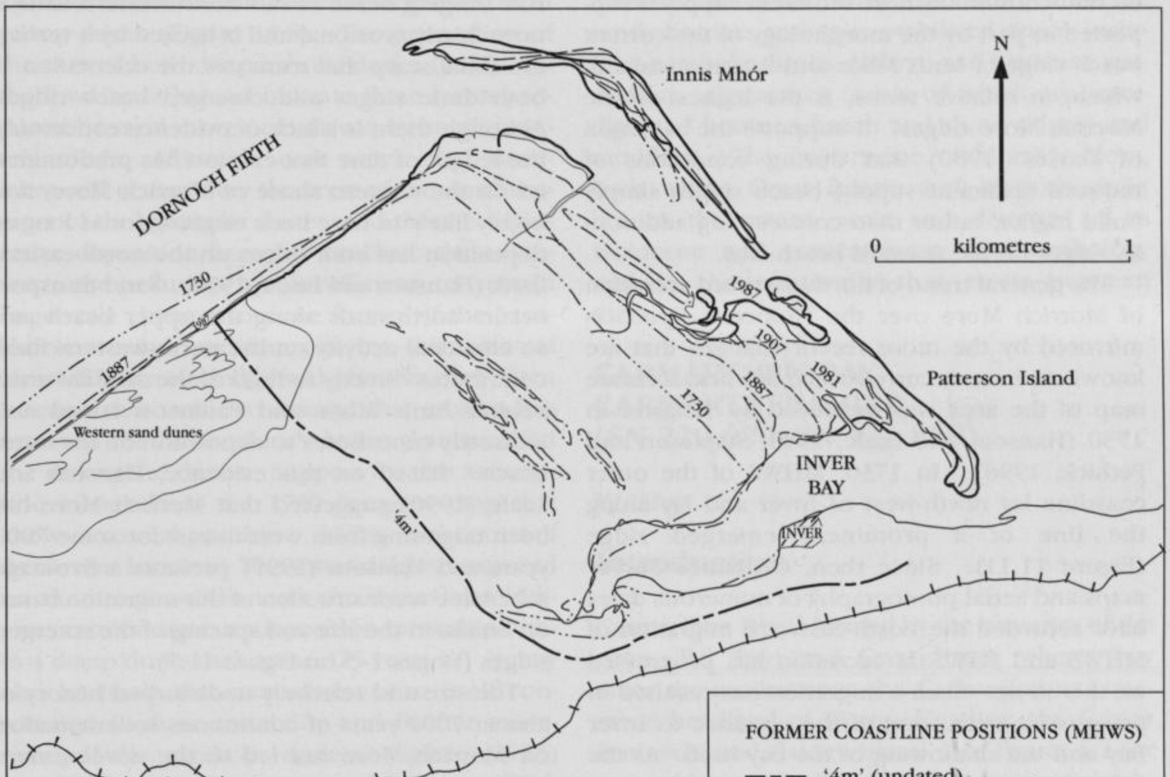


Figure 11.11 Former coastal positions of Morrich More, based mainly on historical sources and Ordnance Survey maps and aerial photography. The north-east coast has extended by about 1 km since 1730, but the western flank has eroded by varying amounts over the same period. Sediment eroded from the west is moved north-east by tidal streams and waves at high tide to be deposited in the area behind Innis Mhór and Patterson Island. (After Hansom and Leafe, 1990.)

and the addition of beach ridges. Although undated (except by regional sea-level curves) Hansom and Leafe (1990) suggest that the bulk of the Morrich More sands higher than 4 m OD, may have been in place by *c.* 5000 years BP. Seawards of the beach ridges at about 4 m OD, the true ridge altitude drops (although covered by sand dunes) and the spacing between beach ridges increases. It is hypothesized that the wider spacing between the most seaward, and thus most-recently deposited, ridges, indicates that rates of accretion and sediment supply have progressively reduced since 6500 years BP and certainly since deposition of the second group of higher ridges (Hansom and Leafe, 1990; Hansom, 1991; Firth *et al.*, 1995). The postulated reduction in offshore sediment supply is supported in part by the morphology of the current beach ridge of Innis Mhór and Patterson Island, which, in relative terms, is the highest of the Morrich More ridges. It supports the assertion of Davies (1980) that during conditions of reduced sediment supply, beach ridges simply build higher, rather than constructing additional, ridges on the seaward beach face.

The general trend of north-eastward accretion of Morrich More over the Holocene Epoch is mirrored by the more recent changes that are known to have occurred since the first accurate map of the area was produced by Sangster in 1730 (Hansom and Leafe, 1990; Stapleton and Pethick, 1996). In 1730, MHWS of the outer coastline lay north-west of Inver and lay along the line of a prominent emerged ridge (Figure 11.11). Since then, Ordnance Survey maps and aerial photography of numerous dates have recorded the north-eastward migration of MHWS and MLWS as accretion has progressed on this shore. Such a migration has resulted in progressive narrowing of the entrance to Inver Bay and the shallowing of the bay itself. As the outer beaches moved north-eastward, the low-lying swales behind were flooded by tidal waters, promoting the development of sandflat and saltmarsh. The development of saltmarsh seems to be a rapid process, since the 1887 Ordnance Survey does not show Patterson Island at all and displays Innis Mhór as a small unvegetated sandbank. Patterson Island had emerged above MHWS by 1946 and although aerial photography shows a small dune area present, the intertidal area behind remained entirely intertidal sandflat until the late 1960s. Infilling is ongoing and comparisons between the 1981 map and 1987 aerial photography shows saltmarsh edge migration of 100 m over the six-year period as a result of accretion and colonization by saltmarsh plants (Hansom and Leafe, 1990).

Accretion on the outer north-eastern coast is matched by erosion on the inner Dornoch Firth coast of Morrich More (Figure 11.11). Erosion along the western flank of Morrich More has occurred at a mean rate of 0.47 m a^{-1}, with some 117 m lost between 1730 and 1990 (Hansom and Leafe, 1990). This has resulted in peat (radiocarbon-dated at 325 years BP), which probably developed in dune-slacks, being buried by dune migration eastwards and now being exposed on the foreshore by erosion. The narrow fringing beach of this north-western flank is now clearly erosional and is backed by a vertical erosional scarp that truncates the orientation of both dune ridges and emerged beach ridges. Although there is a lack of evidence concerning the length of time that erosion has predominated on the western shore of Morrich More, it is highly likely to have been ongoing for as long as deposition has built ridges on the north-eastern flank (Hansom and Leafe, 1990). Sand transport occurs northwards along the upper beach and so erosional activity on the north-western flank contributes directly to infill of the sandflat areas behind Innis Mhór and Patterson Island and indirectly contributes to deposition on the outer beach. Based on this evidence, Hansom and Leafe (1990) suggested that Morrich More has been migrating from west to east for some 7000 years and Hansom (1999) presents a five-stage schematic reconstruction of this migration based on breaks in the size and spacing of the emerged ridges (stages 1–5 on Figure 11.7).

The size and relatively undisturbed history of almost 7000 years of continuous sedimentation on Morrich More has led to the development of a range of successional stages of dune development from embryo dune on the outer shore, through foredune and mature dune forms, parabolic dune forms and low undulating dune plain, some of these in association with interfingered saltmarsh that grades into freshwater marsh and dune slacks. Ratcliffe (1977) describes sand dune vegetation of Morrich More as 'one of the most important and distinctive dune systems in Europe', and Doody (1986) echoes this by regarding it as one of the finest sequences of natural vegetation in Great Britain. Dargie (1989) demonstrates the importance of the vegetational transitions at Morrich More, with those between the saltmarsh and dune systems being of particular complexity and therefore of high conservation value in view of a clear relationship with geomorphological conditions. Vegetational transitions from saltmarsh to sand dune are extremely rare in Britain and the transition on Morrich More from saltmarsh to calcareous dune, wet acid dune or dry dune grassland makes the upper saltmarsh vegetation, and its interaction with geomorphology, uniquely important.

The relationship between the mainly stabilized parabolic dunes in the west and the low undulating dune plain downwind to the north-east is unusual, since neither has an obvious upwind nourishment zone of foredune and young dunes (Figure 11.9). The orientation of the axes of both the parabolic dunes (250°) and the low dunes behind indicate dune forms produced by sand movement driven by south-westerly winds. Although some active sand movement still occurs over the crest of the northernmost of the parabolic dunes, and there remains active deposition from the beach to the south-west, the volumes are insufficient to sustain large-scale changes to dune forms. If the backshore erosion experienced by this side of Morrich More is a long-lived phenomenon, then it seems reasonable to assume that erosion has removed the feeder dune cordon that once fed the downwind dunes. Support for this assumption comes from the 1730 Sangster map that shows a coastal position *c.* 350 m to the west of its current location. The intertidal peat exposed on the beach and beneath the dunes also indicates erosion since its deposition, probably within a damp dune-slack some 325 years BP. It may also be likely that coastal recession itself contributed to dune instability and further movement of the parabolic dunes. Ogilvie (1923) noted that parabolic dunes on the western flank were then mobile and appeared to have moved some 183 m between 1873 and 1913. It seems probable that the earliest parabolic dunes of western Morrich More were fed from a beach and dune system in the west beyond Tain that now no longer exists.

Conclusions

The scientific interest of Morrich More is outstanding both in terms of the variety and scale of its coastal landforms, many of which have well-developed transitional zones between accretionary landforms, and because of a well-preserved morphological and stratigraphical record that records shoreline change and coastal development over the last 7000 years. The development of this large coastal strandplain is related to a shallow offshore zone and abundant sandy material, resulting in a series of sequential beach ridges deposited under conditions of a falling relative sea level. From a stratigraphical and morphological perspective, the extensive emerged strandplain of Morrich More is central to an understanding of the Holocene coastal development of both the Dornoch Firth and the wider Moray Firth. From a contemporary process and form viewpoint, there exists a diverse variety of forms including attached sandy barriers and spits, stabilized dunes including parabolic dunes, embryo and foredune succession, saltmarshes (some of which are interdigitated between beach and dune ridges) and sandflats. The importance of Morrich More, both within Great Britain and internationally, lies in the extent, scale and diversity of its Holocene and contemporary geomorphology and in the continuity that exists between them.

CARMARTHEN BAY, CARMARTHENSHIRE (SN 220 070–SN 421 868)

V.J. May

Introduction

Carmarthen Bay is formed by the estuaries of the rivers Taf, Twyi and Gwendraeth where they enter the sea between the Carboniferous Limestone headland of Worms Head on the Gower Peninsula and Caldey Island (see Figure 1.2 for general location). The bay includes several sub-units that would warrant selection as coastal geomorphology GCR sites in their own right. It is unusual, however, in containing features that are relatively uncommon in England and Wales and in being very little disturbed by human activity. At low tide, three interconnected units (Figures 11.12 and 11.13) are exposed:

1. Whiteford Burrows and Rhossili Bay (see Figures 11.17 and 11.18)
2. Cefn Sidan Sands, Tywyn and Pembrey burrows (see Figure 11.15), and

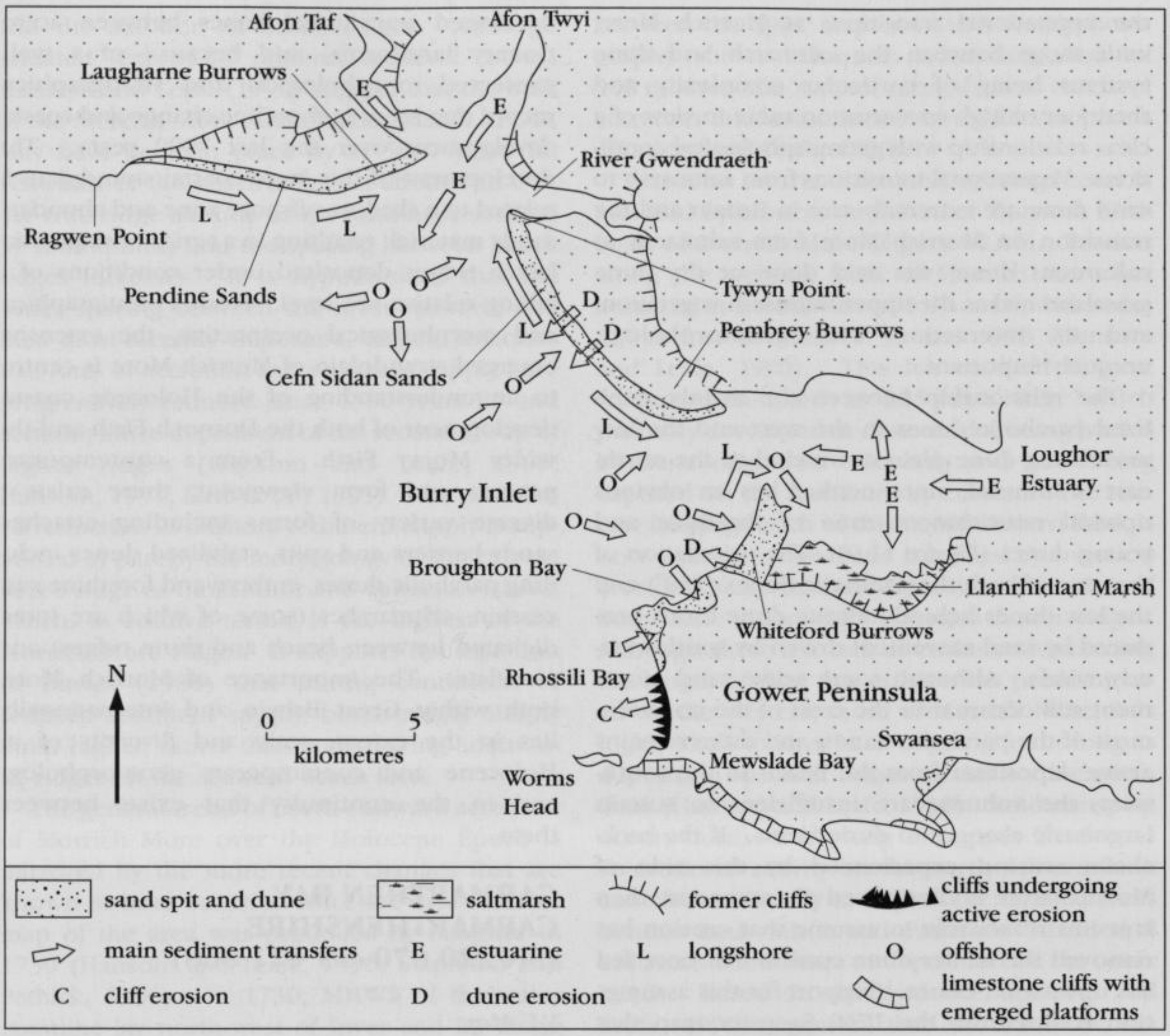


Figure 11.12 Sketch map of the key geomorphological features and sediment transfers of Carmarthen Bay. See also Figure 11.17 for details of the Rhossili Bay area. (Offshore transfers derived in part from Barber and Thomas, 1989.)

3. Pendine Sands and Laugharne Burrows (see Figure 11.14).

These three units can be further subdivided into 8 subsites (see 'Description' below).

The estuaries of the rivers Taf, Twyi and Gwendraeth separate units 2 and 3, whereas units 1 and 2 lie to the south and north of the Loughor estuary respectively. Parts of these estuaries are included in the site.

Both Pendine–Laugharne and Whiteford beaches form spits that trend away from a predominantly rocky cliffed coastline, whereas the barrier beach from Cefn Sidan to Pembrey links to the mainland only by former dunes and reclaimed marshland. This barrier feature is only one of three large barrier systems in England and Wales, the others being Scolt Head Island (North Norfolk Coast) and parts of the Holy Island, Northumberland, site. During the 20th century, the general trend has been for erosion at the proximal end of the spits, accretion at their distal ends and extensions of the forms into the estuaries (Figure 11.13). Cefn Sidan–Pembrey has been an area of general progradation, with extension of the beach as spits into estuaries of the rivers Loughor and Gwendraeth.

Apart from the coasts of north Norfolk and Holy Island, Carmarthen Bay contains the largest assemblage of unmodified sandy beaches in England and Wales, but it has received very limited attention in the literature. North (1929) and Steers (1946a) concentrated mainly upon the hard-rock coastline and the evidence of changes in sea level. Savigear (1952) saw the eastward growth of the Pendine beach as controlling slope development on the abandoned cliffs behind the beach and marsh. Kahn (1968), Potts (1968), Jago (1980) and Jago and Hardisty (1984) described the sediments and the geomorphological processes that act upon individual parts of the site. Barber and Thomas (1989) have considered the whole bay in terms of sediment transport and its effects on the beaches. Emerged ('raised') beaches and periglacial and fluvioglacial deposits occur at several points around the bay and many writers have considered the Quaternary history of the area and Campbell and Bowen (1989) provide a comprehensive summary.

Description

There are eight major subsites, each of which is described in turn from west to east. These subsites form parts of an integrated whole that is bounded in the south-east by Worms Head and in the north-west by Ragwen Point. The eight units (for locations see Figure 11.12) are:

1. Pendine Sands and Laugharne Burrows
2. The estuaries of the Taf and Tywi
3. Cefn Sidan, Tywyn and Pembrey Burrows (including the Gwendraeth estuary)
4. The Loughor estuary (uncluding Llanrhidian saltmarsh)
5. Whiteford Burrows
6. Broughton Bay burrows and cliffs
7. Rhossili Bay
8. Worms Head and Mewslade Bay.

Consideration of processes at other GCR sites led to the decision to treat the whole of Carmarthen Bay as a single unit in the GCR, defined by the low-water limits of the intertidal zone at Ragwen Point and Rhossili. In addition, the cliffed coast around Worms Head, which is an important site in its own right, was integrated with the larger Carmarthen Bay GCR site. The site includes all the intertidal sand banks of the bay and the channels between them. The seaward boundary crosses the channels at their most seaward extent. Because the processes that affect the site extend into deeper water, an appropriate geomorphological boundary lies along a straight line from Ragwen Point to Worms Head.

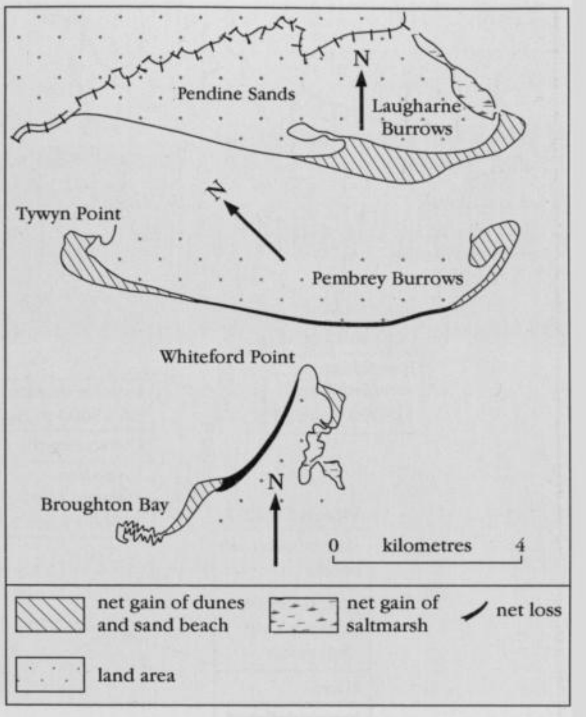


Figure 11.13 Variations in accretion and erosion since 1950, Carmarthen Bay.

The site comprises 32 morpho-sedimentological units of which ten are hard-rock cliffs, seven are saltmarsh, six are stable or prograding beaches and three are sandy beaches affected by erosion. The remainder are till cliffs undergoing erosion (one unit), estuary/ria (two units), shingle beach (two units), and pocket beach (one unit). Depending upon tidal and wave conditions, sediments can move between most parts of the site, with the possible exception of the area south of Worms Head (Figure 11.12). Very large areas of sand are exposed at low tide, especially at the mouth of the rivers Taf and Twyi. At high tide, the behaviour of waves crossing these intertidal flats is affected by changes in channel position and bathymetry. The site is macrotidal, with a tidal range in excess of 8 m and currents that exceed 1 m s^{-1}. The maximum fetch in the direction of prevailing and dominant winds from the south-west exceeds 4000 km. Fetch to the SSE, i.e. across the Bristol Channel, is 70 km.

The north-western extremity of the site at Ragwen Point (SN 220 070) forms the low-water

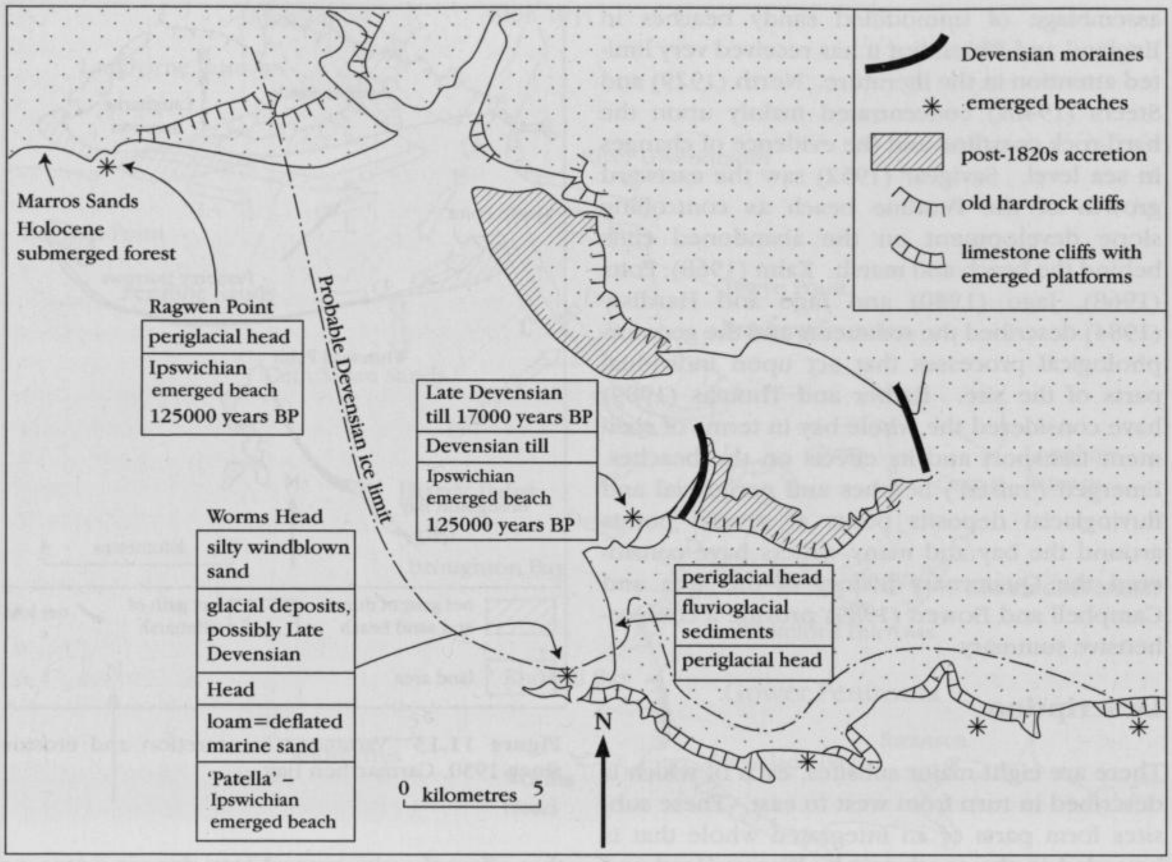


Figure 11.14 The Devensian geomorphology of Carmarthen Bay, with stylized sections through selected emerged beach sites. (After Campbell and Bowen, 1989.)

boundary of the sandy intertidal zone. A small pocket beach separates Ragwen Point from Gilman Point (SN 228 074) whence the cliffs that reach up to 30 m in height trend northwards to Dolwen Point (SN 233 079). The Pleistocene sequence (including emerged beaches) at Ragwen Point (Bowen, 1970, 1974; John, 1971, 1973; Campbell and Bowen, 1989; Figure 11.14) indicates the long time period over which the rock cliffs of this site have developed. As elsewhere in the site, several caves are cut into the cliffs.

Pendine Sands and Laugharne Burrows are dominated by dunes up to 700 m wide that extend some 9.5 km to Ginst Point (SN 331 078). The dunes attain heights in excess of 15 m, except in the vicinity of Wickett Pill where a stream draining marshland and a shallow lake existed up to the 1950s. Since then, there has been considerable accretion of Laugharne Burrows, but the shoreline of Pendine has remained virtually static. The intertidal zone is up to 1 km in width, notably opposite Wickett Pill. As the dunes grew eastwards they protected the rocky cliffs (Savigear, 1952) and the intervening marshland was reclaimed. North of Ginst Point, saltmarsh has developed in the lee of the dunes and in front of artificial embankments. The eastern part of the reclaimed marshland drains via Railsgate Pill into the Taf estuary at SN 306 099.

The 0.5 km-wide Taf estuary is bounded by rock cliffs on its western side, but on its eastern side a cobble spit (Black Scar) narrows the channel, and there has been some development of saltmarsh. Vertical cliffs about 30 m high form the shoreline around Wharley Point (SN 340 093) to the Twyi estuary at SN 352 100. Both sides of this estuary are formed by low vertical cliffs, but the eastern side is much lower than the western side. On the eastern side, the low cliff (SN 361 082) is replaced by a cobble

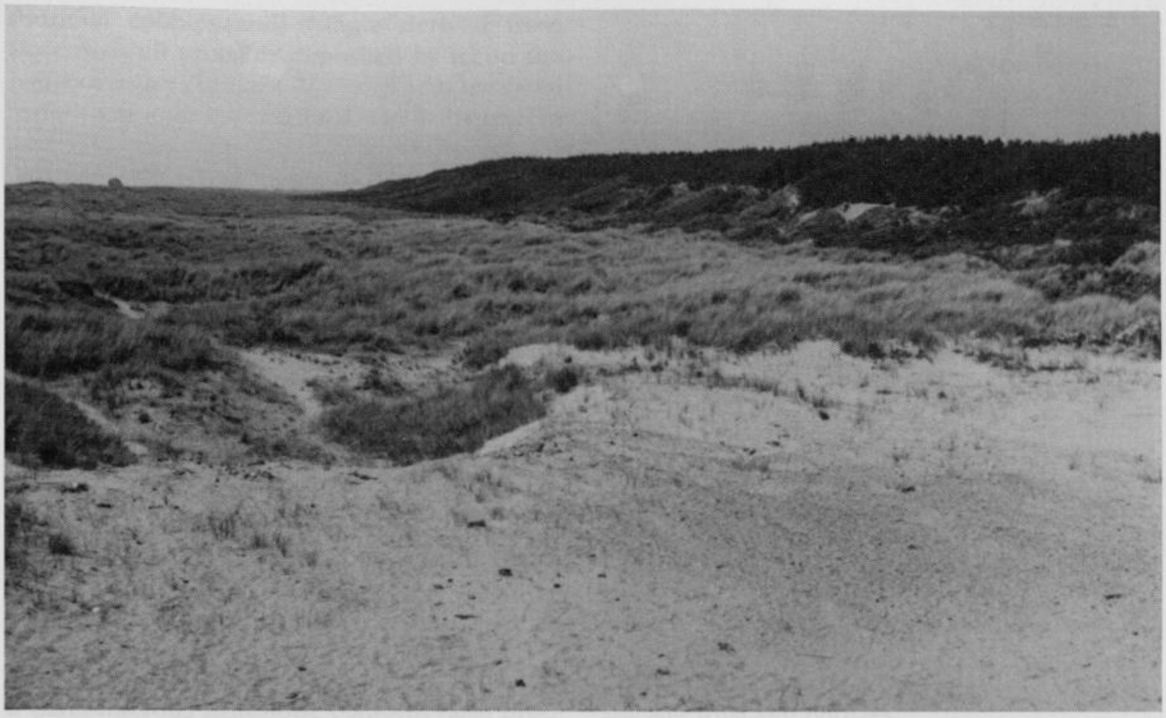


Figure 11.15 Pembrey: older dunes can be seen to the right of the photograph – these are now conifer plantations. Post-19th century accretion is evident in the middle and left background. A blowthrough is present in the foreground. (Photo: V.J. May.)

and gravel beach that widens southwards extending seawards into Salmon Point Scar (SN 355 070) and narrowing the estuary significantly at low tide.

The Gwendraeth estuary is dominated by sandflats and mudflats that merge into a growing saltmarsh in the lee of Tywyn Point (SN 357 065). The sand beach extends about 12 km from Tywyn Point through Tywyn and Pembrey Burrows to just south-west of Burry Port (SN 437 994). Intertidal sands extend seawards over 3 km at Cefn Sidan at the mouth of the rivers Taf and Twyi. Much of the area landward of the beaches of Cefn Sidan–Tywyn–Pembrey is dominated by former dunes in Tywyn Burrows, over 2 km-wide and reaching over 20 m in height (Figure 11.15). Much of the duneland is afforested. Seawards of the main zone of grey dunes, there is a zone of low-lying sandy hummocks, rarely higher than 2 m, fringed by a narrow ridge of younger, mainly active, dunes over 5 m in height, which extend into both the Gwendraeth and Loughor estuaries. Although the central part of the beach has suffered some retreat in recent years, the distal areas have extended several hundred metres during the last 150 years. This is a fine example of a progradational beach to which the supply of sediment is sufficient not only to allow the beach to grow in overall volume but also to be able to sustain the lateral growth of the spits.

The saltmarshes of the Burry Inlet comprise the most extensive area of saltmarsh in Wales: 2121 ha out of a total of 6712 ha (32%), and represent almost 5% of all British saltmarsh. Those of the south shore of the estuary from Whiteford Point to Loughor are of interest for the range of geomorphological features they display, particularly saltmarsh creeks, saltpans, erosion cliffs and range of sediments (Figure 11.16; Gillham, 1977). Berthlŵyd, Llanrhidian and Landimore marshes have developed in a sequence from east to west. The mature marshes at Berthlŵyd display well-developed terraces and a marsh cliff undergoing erosion: at Llanrhidian pans and creeks are present and display much dissection. At Landimore, an intricate and deep creek network is present. The sequence of marshes forms a key area for an understanding of saltmarsh dynamics, sediment transport and sea-level changes.

The marshes extend for about 15 km along

Figure 11.16 A deeply incised saltmarsh channel in the muds of Llanrhidian saltmarsh, Loughor Estuary. (Photo: J.D. Hansom.)

the northern shore of the Gower Peninsula and are up to 1.5 km wide. Landimore Marsh in the west lies in the shelter of Whiteford Burrows and is the youngest of the marshes. Llanrhidian Marsh is more exposed to waves entering Burry Inlet from the west, but Berthlŵyd Marsh is in the more sheltered upper part of the estuary. The marsh sediments have not been dated. The tidal range at springs is 6.6 m and at neaps 3.7 m (Pye and French, 1993). Fine-grained sediment deposition is restricted to the more sheltered upper intertidal zone and upper reaches of the estuaries. According to Carling (1981), grain size typically becomes finer with increasing elevation, and Pye and French (1993) record the mean grain size on the upper tidal flat as sands, on the marsh edge as sandy silts, and on the upper marsh as clayey silts. The marsh-edge is widely marked by a low cliff formed during periodic storm activity. Gently sloping ramped margins occur in areas of pioneer marsh progradation. There are some weakly developed terraces, the transition being marked by low cliff, ramp or residual mud-mound topography. Many creeks on the upper marshes show infilling in response to a reduction in tidal capacity while the marshes grow both vertically and laterally (Pye and French, 1993), but common cord-grass *Spartina anglica* was introduced to Loughor in 1931 and colonized rapidly in the 1950s and 1960s, but appears to have declined since (Hubbard and Stebbings, 1967; Burd, 1989). Smith (1978) identified subsurface piping patterns in this area, and attributes the development of saltpans (Packham and Willis, 1997) to their presence. At Landimore, an intricate and deep creek network is present. Small-scale mass-movements in rills and creeks in the muddy intertidal zone play an important role in the changes in creek morphology, the supply of sediment into the creeks, and in intertidal drainage patterns (Allen, 1989).

Whiteford Burrows extends some 3 km northwards from the northern side of the Gower Peninsula to Whiteford Point (SN 450 968; Figures 11.12 and 11.17), where its distal end is associated with a cobble bank to seaward. The burrows are formed of several lines of dunes reaching a maximum height of 24 m in the north-east. The main dune ridge is generally between 10 and 16 m in height, widening towards its landward end. To the west, a line of dune slacks separate more recently accumulated dunes from the main ridge. On the seaward side of the main ridge, a line of slacks rest on partly rounded cobbles and shingle derived from Devensian till probably deposited by ice in the Loughor valley (Bridges, 1987). There has been some erosion of the proximal end in the recent past, but sand ridges have also extended into this area from Broughton Bay to the west.

The coast westwards to Burry Holms (SN 398 925; Figure 11.17) is dominated by vertical cliffs fronted by dunes up to altitudes of 50 m OD . At Broughton Burrows the dunes extend to sea level between Prissen's Tor (SN 425 937) and Twlc Point (SN 415 931) where the outlines of the bay appear to be fault-controlled. The cliffs are penetrated by several caves that have developed along joints in the Carboniferous Limestone. Since the late 1980s, marine erosion in Broughton Bay has exposed a very important Devensian multiple till sequence (Campbell and Bowen, 1989). Near Twlc Point, the base of this exposure is formed by an emerged beach conglomerate with fragments of marine shells, mainly flat periwinkle *Littorina littoralis,* resting on a Carboniferous Limestone platform (also prob-

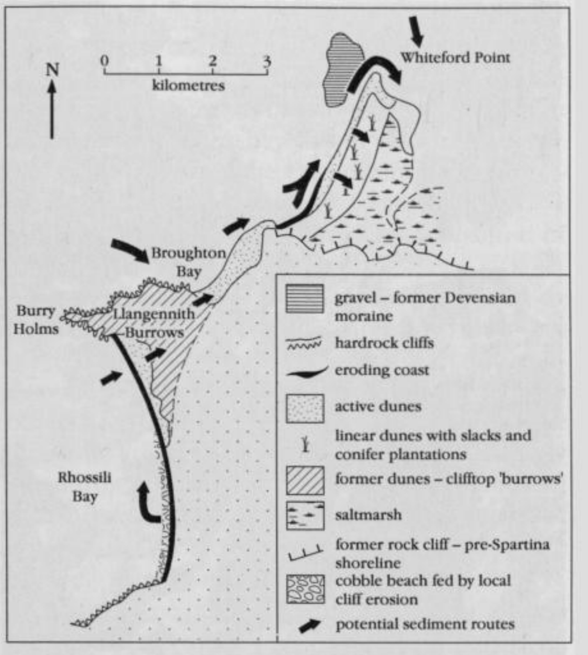


Figure 11.17 Geomorphological features of Rhossili Bay and Whiteford Burrows.

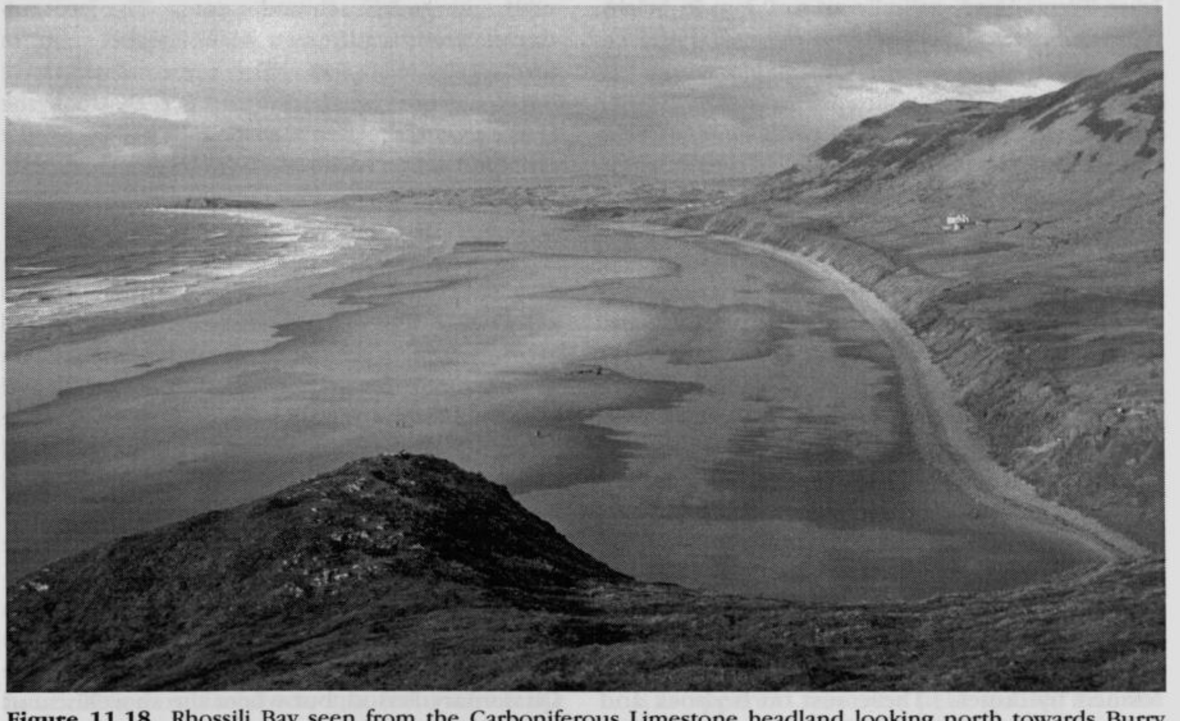


Figure 11.18 Rhossili Bay seen from the Carboniferous Limestone headland looking north towards Burry Holms and Llangennith Burrows. Rhossili Down to the right of the photograph is fronted by low cliffs formed in periglacial head and fluvioglacial material. Erosion of these cliffs feeds the narrow fringing cobble beach. The wide intertidal beach is mainly sand. (Photo: J.D. Hansom)

Figure 11.19 Limestone intertidal solution features near Worms Head, typically up to 0.3 m in height. (Photo: V.J. May.).

ably marine in origin; Campbell, 1984). The emerged beach is overlain by head and tills that include some fragments of wood (willow/poplar Salicaceae). Shelly and stony tills in the upper part of the section show glaciotectonically-induced folds that are also exposed occasionally in plan form on the foreshore (Campbell and Bowen, 1989). The dunes that overlie this sequence are thought to have been in existence by Roman times (*c*. 2000 years BP) and to have been affected by renewed activity during intense late medieval storms (Lees, 1982, 1983).

Burry Holms, an island at high water, forms the northern end of Rhossili Bay, a *c*. 450 m-wide smoothly curving sandy beach directly aligned to the prevailing and dominant south-westerly waves (Figures 11.17 and 11.18). Just over 4 km in length, the bay has a northern shoreline formed by dunes. These rest on bedrock and reach altitudes of about 50 m OD, and are fed by sand blowing from the drying intertidal zone. The southern part of the bay is formed by low active cliffs in till and periglacial sediments (Campbell and Bowen, 1989). The shoreline is cut across the lithological change and is strongly wave-dominated. Shallow slides feed boulders and cobbles into a narrow fringing beach but the contribution of these cliffs to the beach sediment budget is slight. The beach appears to be in deficit, especially as there is no obvious sediment supply from either offshore or alongshore. Sand leaks from the beach via Llangennith and Broughton Burrows towards Whiteford Burrows.

The southern boundary of Rhossili Bay is formed by high limestone cliffs that are continued beyond a gap of 500 m to Worms Head (SN 384 878). Cliffs drop almost vertically into the sea on the northern side of the headland, but a shore platform is well developed around Worms Head and along the southern shoreline, where emerged beach, glaciogenic and periglacial head and colluvial sediments occur widely (Campbell and Bowen, 1989). Cemented '*Patella*' emerged beach deposits rest on the Carboniferous Limestone shore platform (Figure 11.15). Mewslade Bay, bounded to the east by the headland of Thurba (SN 421 868), has similar examples of a platform at present-day sea level and a higher platform planed across dipping strata with emerged beach sediments. The present-day platform is pitted by potholes and solution forms (Figure 11.19). The upper slopes have been severely weathered and screes cloak the lower part of the slopes resting, in places, on the emerged beach materials.

Interpretation

This old cliffed coastline preserves coastal forms of considerable age that have been retrimmed recently to provide the framework within which the extensive recent sedimentation has formed intertidal banks, beaches and saltmarshes. The interpretation of the coastline of Carmarthen Bay involves both explanation of the form and development of the coast during the Quaternary Period and the forms and processes that are active today.

Carmarthen Bay is an excellent example of a coastline whose outline was moulded by marine and subaerial processes throughout the Quaternary Period, but where the shoreline and its detail is much more recent in origin. Each subunit of the site is distinguished by features of major geomorphological interest. For example, the Loughor estuary saltmarshes form a key area for the understanding of saltmarsh dynamics, sediment transport, and sea-level changes, and the platforms and cliffs in Rhossili Bay are excellent examples of hard-rock erosional forms including features linked to former sea levels.

The Quaternary history of Carmarthen Bay indicates that it was affected by several phases of lower sea levels, glacial and glaciofluvial action, and periglaciation superimposed on a framework of river valleys. The interpretation of a number of cave and other sediments containing emerged beach deposits point to a sea level close to the present-day level about 200 000 years BP during Oxygen Isotope Stage 7 (Campbell and Bowen, 1989), and another period of emerged beach formation (sometimes referred to as the '*Patella*' beach) about 125 000 years BP during the Ipswichian (Oxygen Isotope Substage 5e) in which two emerged beach facies have been identified at the western end of Carmarthen Bay at Gilman Point (Bowen, 1970). Extensive periglacial activity led to head deposits forming during the onset of the Devensian and point to considerable cliff instability on parts of the coast. For example, John (1971, 1973) regards the presence of very large quartzite boulders in the head around Ragwen Point as an indicator of an intensive period of slope instability (Figure 11.14). At the time, there was apparently no mechanism removing this material beyond the cliff foot. The limit of Devensian ice probably crossed Carmarthen Bay from just south of Worms Head towards Pendine Point (Bowen, 1981a,b), since in-situ Devensian tills overlie the Ipswichian emerged beach at Broughton Bay (Bowen, 1984) but are absent farther west at Ragwen Point and Marros Sands. At Worms Head, glacial age deposits may be remnants of soliflucted pre-Ipswichian glacial materials or Late Devensian outwash (Bowen, 1970; Bowen *et al.*, 1985; Bowen and Sykes, 1988; Figure 11.14). At Rhossili, two phases of periglacial head are separated by fluvioglacial material. There is some doubt about the precise limit of the Devensian ice, although Stephens and Shakesby (1982) suggested that the bay might have been occupied by a large piedmont lobe. Its effect however was to leave substantial deposits of sand and gravel that were re-worked by a rising postglacial sea, and from which the sand of the coastal dunes and spits was blown. A loam lying above the Ipswichian emerged beach at Worms Head has been interpreted as deflated marine sand. Although there have undoubtedly been periods of localized erosion and trimming of the hard-rock slopes, the distribution of the Ipswichian emerged beach suggests that the broad outline of the bay was in place during the Ipswichian and that the Devensian saw only limited change in the hard-rock coasts, largely as a result of the protection offered by deposition of the Holocene sediments.

Modern processes have served to erode or protect parts of the older shoreline, although there is some doubt as to the extent that protection has lead to significant recent change in the older hard rock slopes. Savigear (1952), for example, argued that as the Pendine beach grew eastwards it protected former rocky cliffs and that the slope profiles demonstrate the effects of progressive protection of the cliff foot on slope profile. Attractive though this interpretation is, there are some difficulties: the slope profiles are not a simple progression from steep at the distal end to gentle at the proximal end of the spit; they have probably been affected by subaerial processes over a much longer time than the period of the extension of the spit, and more recent interpretations of the Pleistocene history of the area indicate that most change in these slopes occurred during intense periglacial conditions during Devensian times. Basal removal would have begun again with sea levels attaining present-day levels about 6500 years BP and would have then ceased sequentially from west to east. This may have done little more than exhume older cliffs.

The modern shoreline is a very dynamic one, as a result of the growth of spits, dune and saltmarsh development, changes in intertidal and deeper water bathymetry and erosion of both beaches and cliffs.

There are few sites in Britain that have been so little affected by anthropogenic interference and which contain such a fine assemblage of coastal forms. Carmarthen Bay is the only coastal assemblage GCR site that is directly affected by the Atlantic wave systems; it also contains four estuaries. Like the other coastal assemblage GCR sites, it gains its greatest importance from its completeness and the fact that it can be defined as a single unit in terms of its overall sediment dynamics.

It is apparent from the field studies that the individual parts of the site are interconnected with sediment moving between intertidal sands and the beaches, and therefore able to move from one subunit to another. Similarly there is evidence of sand movement from Rhossili Bay to the Whiteford Burrows spit and beyond.

In recent years concern about erosion of parts of the beaches, particularly at Pembrey, led the Coast Protection Authorities responsible for to commission studies of the bay treating it as a single coastal 'cell'. The Carmarthen Bay Study (Barber and Thomas, 1989) shows that the shape of the modern coastline is dominated by the high-energy, south-westerly wave regime interrupted by the discharges of the two major estuaries. Tidal streams in the bay have three dominant effects:

1. On the ebb tide they produce significant refraction of waves,
2. direct scour by currents occurs at the distal end of spits, particularly at Ginst and Tywyn Points, and
3. currents are also important mechanisms for moving sediments stirred up by wave action on the intertidal banks.

Waves are affected by refraction especially over the shallow areas of the estuaries, and by currents. Over the shallow inlets there is some partial breaking of waves, and the effects of bottom friction and shoaling on waves are particularly strong over the wide intertidal areas. As a result there is considerable stirring of sediments that can then be moved by tidal streams. Wind action also plays a major role in the movement of sand between intertidal drying areas and the dunes. This is especially important with dominant and prevailing westerly winds. There are distinct differences in the recent patterns of accretion on the three main beaches (Figure 11.13). Pendine Sands and Laugharne Burrows show no change along its proximal half where it is not protected by offshore intertidal banks, but substantial growth along the distal half at Laugharne where the effects of the offshore banks become significant. Pembrey Burrows shows a tendency to periodic retreat and advance along its main central section that faces directly into the main direction of wave approach, but persistent gain at the distal ends where sand appears to be transported from the intertidal banks. The accretion here is more than can be accounted for by longshore transfers from the erosion of the central section. Whiteford spit has shown most gain at its distal end within the Burry Inlet, probably by transfers from the offshore banks and by redistribution alongshore. Rhossili beach is a fine example of an Atlantic swell-dominated beach of considerable width (Figure 11.18), but for which there are very limited local sources of sediment, other than coarse shingle and cobbles from the till cliffs and sand from offshore.

Modelling of wave conditions in Carmarthen Bay (Barber and Thomas, 1989) showed that changes in bathymetry between 1977 and 1988 had significantly changed both the direction and the intensity of wave attack within the Loughor estuary and the joint estuary of the rivers Taf and Tywi. Sediment transport was also affected. According to the model, nearshore wave conditions were critically affected by the direction of approaching waves and the magnitude and direction of tidal streams. For example, during a model SSE storm with significant wave height (H_S) = 2.7 m and wave period (T_S) = 6.3 s), wave attack was concentrated on the central part of Cefn Sidan–Tywyn–Pembrey area two hours before high water. This could account for the observed erosion on this beach and the tendency for transport towards both ends of the beach. However, the most significant feature of both the model and the empirical studies is their definition of the bay as a single sedimentary unit.

Barber and Thomas (1989) argued that the approach of the Carmarthen Bay Study provides a 'modern' tool to aid decision-making regarding development and conservation proposals affecting a specific shoreline and its neighbours within a recognizable coastal 'cell' (Figure 11.12). From the point of view of coastal geomorphology, this recognition of the integrated characteristics of coastal processes within a large site provides considerable support for the designation of this area as a single site.

Further interest is added by the saltmarsh morphology. The saltmarshes of the Burry Inlet comprise the most extensive area of saltmarsh in Wales, and those of the south shore of the estuary from Whiteford Point to Loughor are of particular interest for the range of geomorphological features that they display, particularly saltmarsh creeks, saltpans, marsh terraces, erosion cliffs and the range of sediments. Understanding of the long-term dynamics of saltmarshes in the Bristol Channel has been focused mainly in the Severn estuary and there has been comparatively less attention given to those of the Burry Inlet. Within the Severn marshes, geomorphological and sedimentological techniques were used by Allen and Rae (1987, 1988) to elucidate the oscillations of late Holocene shorelines and to describe vertical saltmarsh accretion since the Roman period (*c.* 2000 years BP). Allen (1990a) has, however, voiced caution about relying upon saltmarsh sedimentation rates as a source of estimates of sea-level change especially because reworking of muddy intertidal sediments is an important process (Allen, 1987). Compaction, the intricate patterns of sedimentation, and local changes of elevation can each lead to errors. Postglacial stratigraphy of the Severn estuary indicates a long-term sea-level rise (about 3–4 m during the last 2000 years (Allen and Rae, 1988; Heyworth and Kidson, 1982) upon which are superimposed several periods of still-stand (Kidson and Heyworth, 1976; Allen, 1990a–c, 1991b, 1992). These interpretations probably also apply to the Burry Inlet, but there has been very limited investigation of them and the magnitude of change is thought to have been less in the Burry Inlet. Relative sea level continues to rise in the region: mean sea level at Avonmouth increased by 1.12 ± 0.62 mm a^{-1} between 1925 and 1980 (Woodworth *et al.*, 1991) and relative sea-level rise in Carmarthen Bay is estimated at between 1 and 2 mm a^{-1} (Pye and French, 1993).

Conclusions

Carmarthen Bay has perhaps the most varied assemblage of coastal features in the British Isles and is one of the few sites with limited anthropogenic disturbance. There are major dunes, sand spits and barrier beaches, both hard-rock and easily eroded cliffs, rias, emerged ('raised') beaches, extensive intertidal sand-flats and some of the most important saltmarshes in England and Wales. Ages of features in the site range from about 245 000 years old to modern, and the site is crossed by the probable limit of the Devensian ice in Britain.

There is no other site in England and Wales that has such well-developed spit and barrier beaches in a macrotidal regime dominated by south-westerly Atlantic wave conditions, and the site can be regarded as a single sedimentary unit. The interest of the site is heightened by the well-documented Quaternary sequences that occur within it at Ragwen Point, Broughton Burrows, Rhossili Bay and Worms Head, since it is possible to relate the modern features to earlier ones. The comprehensive dating that confirms the longevity of many of the features, notably the cliff–platform sequences and some of the cliff-top dunes at the northern end of Rhossili Bay, is rare and of considerable significance to the understanding of glaciomarine margins and their subsequent development.

The saltmarshes of the Burry Inlet are of major regional and national interest for the range of geomorphological features they display, particularly saltmarsh creeks, saltpans, erosion cliffs and range of sediments, in a macrotidal environment.

THE COAST OF CAERNARFON BAY (NEWBOROUGH WARREN AND MORFA DINLLE)

V.J. May

Introduction

Newborough Warren and Morfa Dinlle are major dune areas on opposite sides of the western mouth of the Menai Strait (see Figure 1.2 for general location). Newborough Warren lies on the south-west facing shoreline of Anglesey (Ynys Môn) and is one of the three largest west coast dune systems in England and Wales, the others being Ainsdale, Lancashire and Braunton Burrows, Devon (see GCR site reports in Chapter 7). Morfa Dinlle forms the south-eastern coast of Caernarfon Bay, comprising a complex area of coast undergoing erosion, together with shingle ridges and dunes (Figure 11.20). Its geomorphology is linked both to the progressive erosion of the coast and to the long-term dynamics of the Menai Strait. The separation of Anglesey from the mainland of Wales by the Menai Strait is of major geomorphological significance. The gradual evolution of Caernarfon Bay owes much to the influence of the Menai Strait in providing a mechanism for moving and transporting large volumes of sediment. The action of the tidal flows has been to partition and transport various components of the sediment population, especially the gravels and the sands. Individually, Newborough Warren and Morfa Dinlle are of national significance, but taken together they are of major importance for understanding of the evolution of the coastline of north Wales and for the effects of sea-level change on coastal form and processes.

The Menai Strait

The double estuary that formed in the Menai Strait in the early postglacial period (see, for example, Greenly, 1919; Embleton, 1964) changed as sea level rose around 6500 years BP into the present-day complex tidal system that floods from both the east and the west. There is a residual flow towards the south-west (Harvey, 1967, 1968) owing to a combination of a higher tidal range at the north-eastern end and the relative phase of the tides. High water at Fort Belan (opposite Abermenai Point) is 1 hour prior to high water at Beaumaris (at the eastern end of the Menai Strait) and is 3 m lower. The resulting hydraulic gradient means that tidal flow in the western entrance to the Menai Strait is markedly ebb-dominated, leading to a pronounced ebb-tide delta whose outer ramparts are known as the 'Caernarfon Bar'. The flood tide in the Irish Sea sets from south to north and a flood-tide rampart has developed to the south of the entrance to the Strait, i.e. immediately west of Morfa Dinlle. Within the Strait, east of Fort Belan and Abermenai Point, flood-tide deltaic deposits have also developed, less extensive than the ebb-tide delta but nevertheless extremely important in their control of the estuarine dynamics. As the tidal delta deposits within the Strait developed during the Holocene Epoch, so the tidal prism in the estuary decreased. In response, the tidal flow velocities decreased in the entrance to the Strait and this allowed sedimentation to proceed, so reducing the entrance cross-sectional area (Pethick, 1997). Holocene infill of the Strait reduced the width from more than 3 km to less than 2 km and mean depth from 20 m to the present-day 10 m, with extensive sandflats across both east and west entrances. It is suggested by Pethick (1997) that the gravel ridges of Morfa Dinlle and the Abermenai spit are direct results of this gradual decrease in the tidal prism of the Menai Strait during the later part of the Holocene Epoch. As deposition proceeded in the Strait, so the cross-sectional area of the mouth decreased,

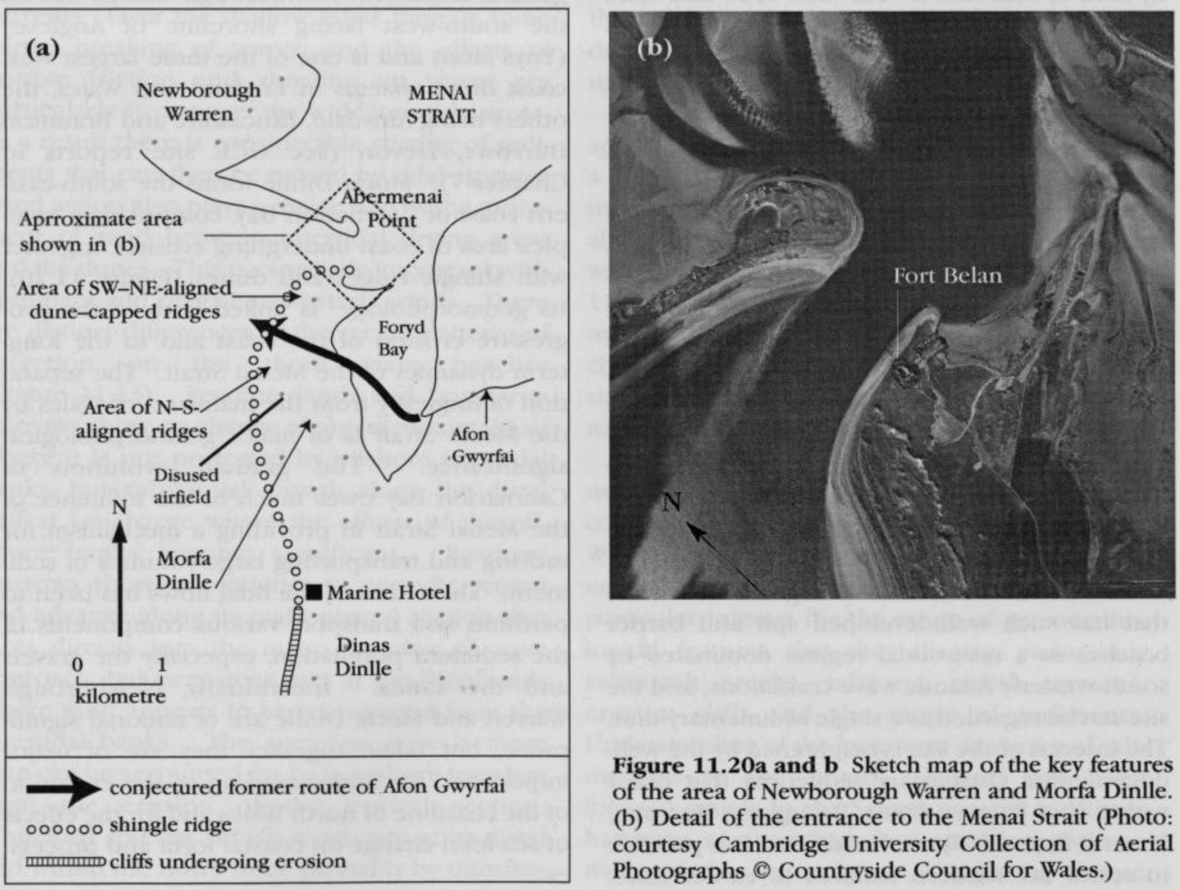


Figure 11.20a and b Sketch map of the key features of the area of Newborough Warren and Morfa Dinlle. (b) Detail of the entrance to the Menai Strait (Photo: courtesy Cambridge University Collection of Aerial Photographs © Countryside Council for Wales.)

and the Morfa Dinlle gravel ridges extended northwards to define an increasingly narrow mouth (now less than 400 m) between Abermenai Point and Fort Belan.

NEWBOROUGH WARREN, ISLE OF ANGLESEY (YNYS MÔN) (SH 367 648–SH 444 615)

V.J. May

Introduction

The shoreline of the major coastal dune system of Newborough Warren is controlled by the Menai Strait to the east, Afon Cefni to the west and Llanddwyn Island (Ynys Llanddwyn), which divides the shoreline between Malltraeth Bay and Llanddwyn Bay. There are large expanses of actively evolving and stabilized dunes, although much of the latter is afforested. East of Llanddwyn Island, parts of the dunes are cliffed and these are in a state of net sediment deficit, as sand is transported eastwards towards a spit that extends (in association with an artificial breakwater) to Abermenai Point. In Malltraeth Bay, the dunes exceed 30 m OD and rest upon and mask the rock outcrop landward of Llanddwyn Island. North-westwards, the beach extends into extensive intertidal sandy flats in the Malltraeth estuary. Like many coastal dunes, Newborough Warren was described by Steers (1946a), but Ranwell (1955, 1958, 1959, 1960) provided the most complete study of dune formation. The orientation of dunes to wind direction is demonstrated well here (Landsberg, 1956). More recently, Robinson (1980b) examined the links between the development of the dunes, the spit and the sandbanks at the mouth of the Menai Strait.

Description

The sand dunes at Newborough Warren are very mobile and it is one of the most-exposed west-coast dune areas; in the past sand travelled inland to cover agricultural land several kilometres from the shoreline (Wortham, 1913). Much of the western area of dunes has been planted with conifers masking the underlying geomorphological interest. This area is excluded from the GCR site. The site comprises six main morphological units.

1. The lower estuary of the Afon Cefni, much of which is formed by sandy, intertidal banks. The western side is formed by cliffs in Precambrian rocks.
2. Malltraeth Bay, where a large area of dunes extends about 2 km into, and about 1.5 km across, the Malltraeth estuary.
3. Llanddwyn Island (Ynys Llanddwyn), which projects about 1.75 km seawards of the beaches and divides the site into two separate beaches.
4. The beach and frontal dunes in an area stretching for about 2 km east of Llanddwyn Island; the area behind this is afforested and now has little geomorphological interest.
5. The eastern dunes of Newborough Warren.
6. The Abermenai spit, which is about 2.5 km in length.

Except for part of the afforested dune area within Malltraeth Bay, the GCR site area falls within the boundary of the Newborough Warren–Llanddwyn Island (Ynys Llanddwyn) National Nature Reserve.

Malltraeth Bay occupies the largest of the low valleys (traeths) that cross Anglesey (Ynys Môn) from north-east to south-west. Precambrian rocks of the Gwna and Fydlyn groups crop out along the western side of the bay and are overlain by dunes on its eastern side (Figure 11.21). The crests of the dunes are generally about 10 m OD, but there are three zones of higher dunes. The first (from SH 398 649 to SH 390 653) lies at the northern end of the dune area and is dominated by an undulating ESE–WNW ridge that exceeds 20 m in height. About 600 m seawards of this ridge, there is a second, more linear, feature (from SH 395 645 to SH 391 649), again exceeding 20 m in height. The present-day shoreline is backed by a wide zone of dunes generally higher than 15 m (between SH 392 639 and SH 388 647) but declining to about 10 m as the beach swings northwards into the Cefni estuary where it cuts across the ends of the two inner ridges. Each of these ridges becomes progressively aligned to SSE–NNW towards the alignment of the present-day beach. Whereas the earliest of the three ridges appears to have faced the dominant direction of wave approach, the later ones were less well adjusted to it. This may be a function of changing water depth and reduced sand supply. Robinson (1980b) suggests that it is probably a result of the sediment circulation within the estuary.

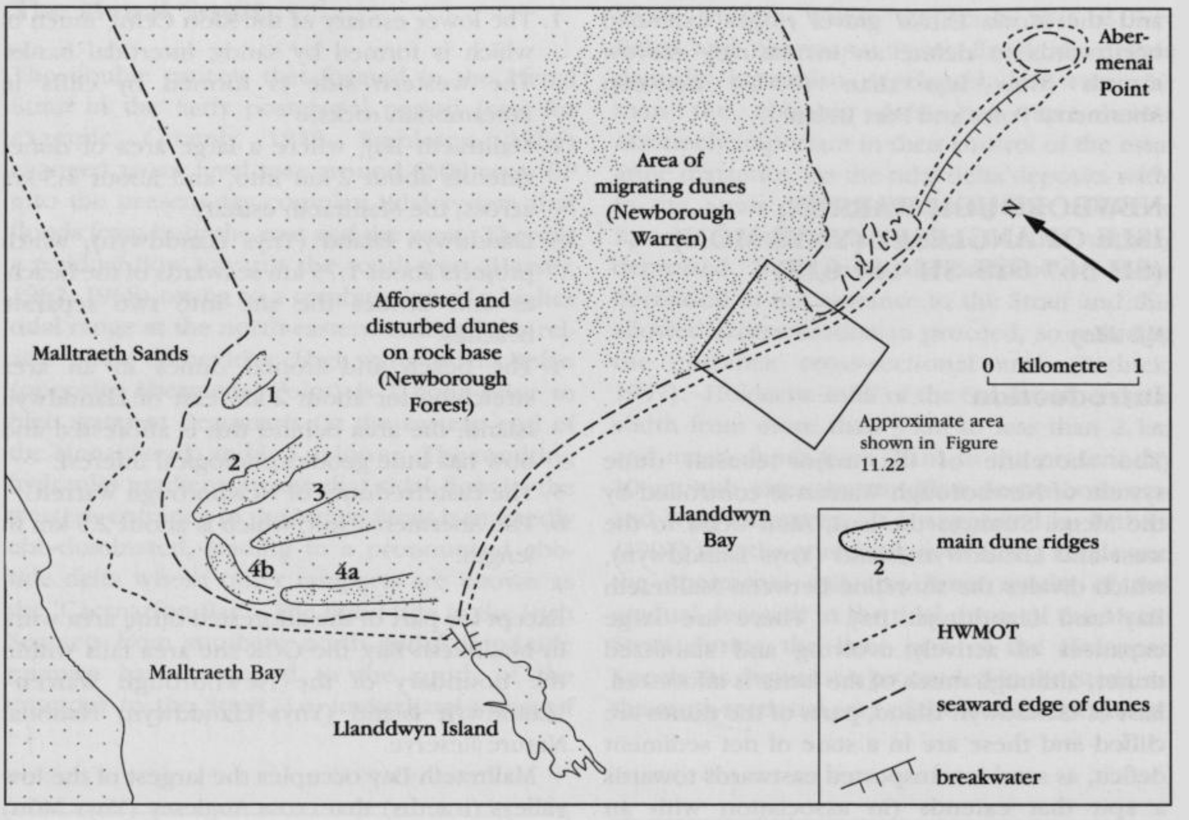


Figure 11.21 Key features of Newborough Warren. The western part of the site has a series of sand spits and dunes extending from a former rocky shore, of which Llanddwyn Island (Ynys Llanddwyn) is a seaward extension. The eastern shore changes from low, climbing dunes on a rock base to an extensive area of migrating dunes on a sandplain. The Abermenai spit owes its form in part to strengthening by an artifical breakwater.

Parts of the shore west of Llanddwyn Island have been artificially nourished in the past to reduce erosion and prevent loss of the forest. Of the three ridges constructed, the outermost was removed by storms in the 1970s, but the other two ridges remain fairly stable (Hansom, 1988).

Llanddwyn Island reaches about 12 m OD and is tied to the mainland by sand beaches that are banked on its landward connection with the rocks that underlie the rocky hill at Cerrig-Mawr. It not only divides the beach into the two bays (Figure 11.21), but also provides some protection to the western end of the beach in Llanddwyn Bay. As a result, the beach shows some of the characteristics of zeta-curve beaches in which wave energy is reduced by refraction and the planform of the beach is controlled by waves approaching from an easterly direction (Figure 11.21). But for the underlying rock ridge, this would be an excellent example of a sand tombolo.

Eastwards from Llanddwyn Island (SH 392 635 to SH 410 632), the GCR area comprises the beach and the fringing dune ridge only; the old dunes behind the line of younger 'yellow' dunes have been afforested. The fringing dunes are affected by erosion both from wave action and from recreational trampling, which is most concentrated in this area. The retreat of the beach is geomorphologically important to the beaches to the east, since it releases sand into the intertidal zone from where it is transported alongshore to feed both the active dunes of the eastern block of Newborough Warren and the Abermenai spit. Some parts of the intertidal area of Llanddwyn Bay are charactertised by gravels underneath the sand. These are lag gravels produced by erosion of till deposits.

The eastern part of Newborough Warren is characterized by fine examples of migrating dune systems (Ranwell, 1955, 1958) that extend about 2 km inland. As on the western side of the site in Malltraeth Bay, the dunes tend to form linear sub-parallel ridges, although they are

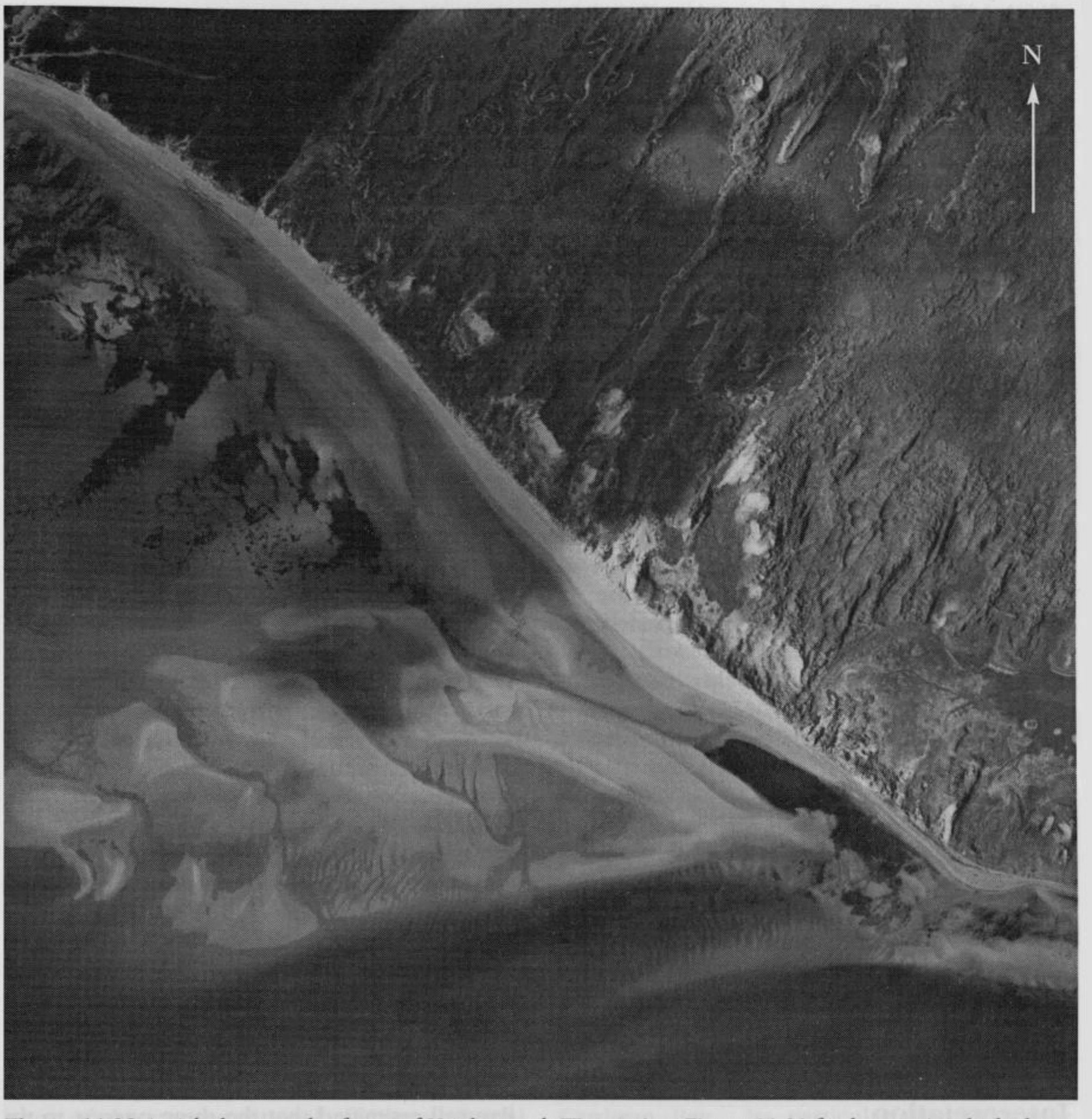


Figure 11.22 Aerial photograph of part of Newborough Warren (see Figure 11.21 for location), which shows the contrasts between the coastal active and migrating dunes, the linear sub-parallel ridges that extend inland and area of mostly stabilized parabolic dunes. Intertidal sand ridges may provide a pathway for sand transport feeding the dunes in the east, but gravels underlie parts of the intertidal area in the west. (Photo: courtesy Cambridge University Collection of Aerial Photographs © Countryside Council for Wales.)

broken by areas of erosion and separated by well-developed slacks. As a result of the differential growth towards maximum height, and irregular erosion, much of the area is composed of parabolic dunes (Figure 11.22), the more landward of which stand above a sand plain.

The Abermenai spit is formed by two areas of low, recurved sand ridges on a shingle and gravel base. The spit was breached in 1868 and the distal part of the spit was separated from the mainland. After another breach in 1889, the Caernarfon Harbour Authority constructed protective works, now represented only by a line of broken stakes (Robinson, 1980b), which link the two areas of sand ridges. The spit, which exceeds 2.5 km in length, has an inner section about 1 km in length comprising several recurves almost at right angles to the main beach that are up to 450 m in length. Eastwards, for a further 1 km, the spit is dominated by washover forms and many low recurving ridges that represent steady extension eastwards along the line of the artificial breakwater. They are, in effect, a new distal part of the spit that is growing eastwards as sand is carried alongshore from the west.

Abermenai Point is the pre-breaching distal end of an older spit. The feature appears on all Admiralty charts and Ordnance Survey large-scale plans since the early 19th century (Robinson, 1980b), but is much older. The recurved end of the spit was named 'South Crook' during the late 13th century (Davies, 1942 quoted by Robinson, 1980b), but Robinson believed that other historical evidence, notably visits to the harbour of Abermenai by Grffydd ap Cynan in the late 11th century, suggests the possibility of an even older feature at this point. Although the breakwater has provided some armouring to the gap that existed after breaching, the growth of the western part of the spit demonstrates that sufficient sand has been available for continued growth to occur.

The presence of two relatively erosion-resistant points in the shoreline of Llanddwyn Bay, at Llanddwyn Island and an intertidal area of lag gravels produced from till erosion fronting the western set of recurves on Abermenai spit, has maintained the shoreline in its alignment towards the prevailing and dominant waves and there has been some growth of the dunes eastwards in the lee of the spit. Substantial amounts of sand also travel over the spit into Traeth Melynog, but there is at present no direct evidence of the volume or location of the seabed sources that are still capable of feeding the beaches.

Interpretation

Newborough Warren is of particular geomorphological interest because (i) the processes of dune-building and migration have been examined in detail (Ranwell, 1955, 1958, 1959, 1960, 1972), (ii) there is a marked contrast in the development of the beaches east and west of Llanddwyn Island, and (iii) the Abermenai spit is a good example of a major feature at the mouth of an estuary that has grown, been breached and rebuilt. In this respect it provides a good contrast with Spurn Head, Yorkshire, both in its relationship to wave conditions and in the pattern of breaching and rebuilding. First, it faces directly into the dominant and prevailing waves. Second, the tidal range is less (by about 2 m) than that of the River Humber, and third, the sediment supply to the Abermenai spit is substantially less, not least because much of the sand is blown inland. Steers (1946a) commented that there was no physiographical description of the site. There is still no interpretation of the ridges in Malltraeth Bay, but this is essential if the relationship between events on both sides of the Menai Strait are to be interpreted. Despite Ranwell's (1955, 1958) description of the key physiographical features of the dunes, there is no detailed analysis of the dynamics of the spit, although Robinson (1980b) describes the historical changes in the spit and the seabed in the approaches to the Menai Strait.

The migration of the dunes was examined by Ranwell (1955, 1958) who argued that the mechanics of dune development could be understood by studying a location where maximum erosion could be expected. Such a situation occurs at Newborough Warren where the prevailing and dominant south-westerly winds flow across a coastline oriented at right angles to its direction. Landsberg (1956) found a perfect correlation at this site between a calculated wind resultant and the orientation of parabola- or U-shaped dunes. Subsequently the rate of dune-building and dune travel in a region where entire dune ridges are successively moving landwards were measured by means of time-series levelled transects (Ranwell, 1958). The theoretical point of maximum erosion was shown to be at 18 m to windward of the crest of 15 m-high dunes. Zones of maximum accretion varied from 0 m to 18 m behind the crest in low, stable dune sections, to as much as 164 m to 183 m to leeward of the crest in high, unstable sections. Ranwell estimated that the dune nearest to the shoreline would need at least 50 years to grow to maximum height. Its mean rate of travel inland near the coast was estimated at 6.7 m a^{-1}. At least another 20 years or so would elapse while the dune travelled sufficiently far inland for a new embryo dune to develop. As a result, the cycle between the start of successive episodes of dune-building would take some 70 to 80 years to complete. Linear ridges, such as those found at Newborough Warren, reflect its ideal position for maximum uniform erosion, but it is rare for whole ridges to migrate uniformly (Ranwell, 1972). More commonly, blowthroughs occur in parts of the ridge (as occurs, for example, at Braunton Burrows, Morfa Harlech, Morfa Dyffryn and Ainsdale – see GCR site reports in Chapter 7). Even in this optimally located system, parts of the coastal dunes reach maximum height more rapidly than others. As a result, irregular erosion of ridges produces parabolic or U-shaped dunes. Ranwell (1960) suggested that the cycle between dune-building and slack formation is about 80 years, i.e. very similar to the coastal dune-building cycle, but did not examine the implications of this similarity.

The volume of sand supplied to the dunes has been substantial. There is evidence of considerable deepening of Caernarfon Bay since the mid 18th century (Ranwell, 1955). During this period, the shallow-water seabed profile moved landwards; Ranwell argued that this probably accounts for much of the sand transported into the dunes. Robinson (1980b) argued that the continuing stability of the recurved end of Abermenai Point indicates that most of its sediment is derived from the tidal streams at the mouth of Menai Strait rather than from longshore sediment transport.

The beach systems of Newborough Warren also warrant considerable further investigation both with regard to their geomorphological history and their present-day dynamics. In particular, the effects of further retreat of the shoreline around Llanddwyn Island, perhaps isolating it from the mainland, should be investigated in order to assess the effects upon sand transport between the two bays. Robinson (1980b) argued that the varying curvature of the shoreline of Newborough Warren reflects the differing degree of shelter from dominant south-westerly waves, the full impact of the dominant waves in the central part of the spit and finally the influence of the transportational efficiency of tidal streams in the entrance to the Menai Strait. He regarded the complex system of sandbanks and channels as demonstrating the influence of ebb and flow channels on shallow-water sediment transport. The flood channels cross North Sands and run eastwards along the Abermenai spit and so may carry sand to the stable end of the spit.

Newborough Warren differs from the other large dune systems at Ainsdale and Braunton Burrows (see GCR site reports in Chapter 7) in the contrasts between its east and west parts. The western part of Newborough Warren is partially underlain by bedrock and extends into a small estuary, in contrast to the eastern part, which includes a recurved spit that extends into a large, deep channel. The dune cycle is better understood than in many other dune systems. The western part of the site has been marked by several separate phases of ridge building, a feature found in other dune systems such as South Haven Peninsula (see GCR site report in Chapter 7). The site is most important because it is possible to relate the dune succession to the geomorphological processes associated with dune-building and erosion (Ranwell, 1972).

Conclusions

One of the largest west-facing dune systems in England and Wales, Newborough Warren includes a recurved spit at the mouth of the Menai Strait, which has been breached periodically but has a distal end that is probably about 700 years old. Newborough Warren includes both very dynamic and very stable and long-lived features. The effects of two estuaries on the dynamics of the beach, especially in providing major nearshore sources of sediment, makes this site particularly important for geomorphological studies. The breaching and rebuilding of the Abermenai spit indicates the availability of large sediment inputs, as do the continuing growth and migration of the dunes where they have not been stabilized by afforestation. The site combines in one location features seen at Spurn Head (breaching and rebuilding, see GCR site report, Chapter 8) and Hurst Castle Spit (the effects of different wave directions at the mouth of an estuary on the development of recurves, see GCR site report, Chapter 6) with the major dune-building processes of large west coast dunes such as Braunton Burrows (Chapter 7) and those in Carmarthen Bay (Chapter 11) and Cardigan Bay. Its particular interest comes, then, from its hybrid form rather than from any single feature. Within the coastline of England and Wales, it forms an important member of the network of dune–beach–spit structures that range from the simple (e.g. East Head, see GCR site report, Chapter 8) to this complex site.

Its ecological importance (it is a National Nature Reserve and part of a Special Area of Conservation) depends on the relationships between sand supply and colonization and stabilization by vegetation. With a steepening nearshore slope, there is the likelihood of increased change and retreat associated with migration inland of the dune system, and this is already occurring in both the south-east and west parts of the site. Long-term conservation management of the site will depend on a better understanding of the shallow-seabed processes that control sediment supply.

MORFA DINLLE, GWYNEDD (SH 435 557–SH 450 612)

V.J. May

Introduction

Morfa Dinlle, on the southern side of the western mouth of the Menai Strait (see Figure 11.20), comprises a complex coast undergoing erosion together with shingle ridges and dunes. At Dinas Dinlle, low cliffs about 25 m in height expose folded and faulted Devensian glaciogenic sediments that provide evidence for a possible advance of the Late Devensian ice-sheet (Campbell and Bowen, 1989). The sediments of the cliffs are also important in providing evidence that help elucidate the development of the western end of the Menai Strait (Bedlington, 1995; Harris *et al.*, 1996). Marine erosion of glacial deposits south of Dinas Dinlle has supplied a heterogeneous mix of sediments to the mainly north-eastwards moving drift system along Pen Llŷn (the Lleyn Peninsula) (Carter, 1990; Pethick, 1997). At the northern end of the cliffs, the coast has been re-inforced to protect the Marine Hotel (Figure 11.20a,b). A single shingle ridge extends northwards from Dinas Dinlle for about 2.5 km and has been protected, since 1976, by gabion mattresses along the ridge crest between Dinas Dinlle and an airfield. In places the lower seaward face of the ridge has been undermined leading to collapse of the gabions. The low-lying area between Dinas Dinlle and Morfa Dinlle village is believed to have been formed by deposition of gravel ridges, but these have been obliterated by the construction of the airfield. Morfa Dinlle itself comprises a series of shingle ridges capped in parts by low sand dunes. This area forms the GCR site.

There has been very little research into the character and dynamics of Morfa Dinlle. Steers (1946a) recorded that there was no physiographical description of the spit and noted that Morfa Dinlle is 'bordered by shingle which fans out in normal fashion at the distal end' (p. 120). He also regarded it as despoiled compared with the unspoilt Newborough Warren. Pethick (1997) also described and interpreted the site, upon which the following account is largely based. Both Carter (1990) and Pethick (1997) believe that the shingle features have grown northwards from Dinas Dinlle probably since about 4000–5000 years BP.

Description

Although the cliffs and shingle ridge to the south of Morfa Dinlle are not included in the present GCR site boundary, the geomorphological development of features within the boundary has depended upon their dynamics. The cliffs south of Dinas Dinlle are retreating irregularly, with occasional slumps and slippages across the face. Since 1875, the cliff at Dinas Dinlle has retreated by about 20 m, giving an annual rate of recession of less than 0.2 m a^{-1}. However, the rate of production of shingle-sized sediment from the erosion of the Dinas Dinlle cliff is considerably less than the rate of shingle accumulation on the north shore of Morfa Dinlle. Carter (1990) provided a first approximation for the rate of shingle input from the erosion of the Dinas Dinlle cliffs, suggesting that 1000 $m^3\ a^{-1}$ is released by erosion, of which only 15% is gravel (shingle). This total gravel input of 150 $m^3\ a^{-1}$ from the cliff would be insufficient to allow the observed rate of growth of the ridges, and it is concluded that erosion represents only a small proportion of the total input of gravel to the modern ridge system.

The modern shingle ridge system, in the north of Morfa Dinlle, is connected to the Dinas Dinlle cliffs by a shingle beach ridge running approximately north–south for approximately 2.5 km before the ridges curve along a SSW–NNE line. Although this beach ridge has been protected by coastal defences and received artificial sediment nourishment, several washover fans suggest a potential for landward movement. It is likely that the gabions (in place since 1976) have restricted the natural movement of the ridge leading to their ultimate destruction. The hard point at the Marine Hotel may now be beginning to impede down-drift sediment transport and so starve the ridge, but the field evidence for this is hard to assess without further study (Pethick, 1997).

Morfa Dinlle is characterized by a well-developed series of sub-parallel shingle ridges, partly obscured by wind-blown sand. The ridges in the northern region of Morfa Dinlle appear to be grouped into three sets.

1. Along the modern shoreline the shingle ridges run shore-parallel and are of recent origin. Nine distinct gravel ridges may be identified west of the relict dune field on Morfa Dinlle.
2. North of Warren Farm the shingle ridges run south-west–north-east and merge with the deposits that form the peninsula south of Fort Belan.
3. South of Warren Farm, the ridges run almost north–south and may indicate a period when the tidal mouth of the Afon Gwyrfai was at the location of Warren Farm. One of the most distinctive features of Morfa Dinlle is its separation from the mainland by the tidal inlet Foryd Bay, the estuary of the Afon Gwyrfai. South of the line of high sand dunes, traces of shingle ridges extend up to and in some cases into Foryd Bay, two of these ridges appearing to merge with the unnamed peninsula south of Fort Belan.

Between 1980 and 1990 approximately 250 m of new ridge formed along the northern shoreline of Morfa Dinlle (Carter, 1990). Although much of this new ridge was formed during a single storm event, the average rate of its development was 25 m a^{-1} (Pethick, 1997). The average volume of shingle contained in 1 m length of the ridge is 60 m^3 (Carter, 1990) so that the modern rate of accumulation of shingle is 1500 m^3 a^{-1} (not 900 m^3 a^{-1}, as reported by Carter (1990) and Pethick (1997)), albeit probably deposited during a single event. Detailed surveys of the extreme landward and seaward ridges show that their crest elevation increases from east to west by 0.7 m (Pethick, 1997). They are partly obscured by sand dunes. High dunes form a single line some 300 m landward of and parallel to the present-day shoreline (trending approximately SSW–NNE). The maximum elevation of the dune crest is 14 m OD and average crest elevation is 10 m OD (Pethick, 1997). The dunes are formed over the shingle ridge basement, providing a highly permeable substrate so that the slacks are dry and deflation down to the underlying shingle is possible. As well as this line of high dunes, the area is characterized by extensive, low, sand dunes whose structure is again related to the underlying shingle ridges. These low dunes continue to form on the present-day shoreline as sand from the nearshore ebb delta ramparts is blown onshore. The wind carries sand over the unvegetated seaward shingle ridge to be deposited as new embryo dunes on the vegetated second dune ridge.

Interpretation

The interpretation of the features at Morfa Dinlle depends on evidence from present-day rates of change, the evidence of the shingle ridge patterns and the Holocene history of the wider area.

The volume of material entering the system from cliff erosion has not been determined accurately, but Carter's approximation (1990) indicates it could be around 800–1200 m^3 a^{-1}, of which about 15% is probably gravel. The receding cliff exercises an important control over the recession and planform of the gravel spit (particularly at its proximal end near Dinas Dinlle). Carter (1990) and Pethick (1997) estimate that the solitary barrier is retreating landwards at a long-term (over a timescale of several centuries) rate of about 0.2 ma^{-1}, probably by phased storm overwashing. Pethick suggests that this landward movement continued during most of the Holocene Epoch. As the beach ridge transgressed the western extremities of the ridge systems, they would have been exposed on the shore and their sediments reworked and incorporated into the beach ridge. Longshore movement would then carry this reworked sediment to the north to form new ridges. A small proportion of material entering the system may also come from the seabed adjacent to the beach.

Harris *et al.* (1996) propose that the Dinas Dinlle hills, south of Morfa Dinlle, formed part of a more extensive push-moraine complex that extended westwards into the nearshore. The Dinas Dinlle moraine is one of a number of morainic ridges, possibly four in total, cut by the present-day coastline. They are composed of till units lying below an upper sand and gravel facies that would act as an easily eroded sediment source as Holocene sea level rose. This source was, and to some extent still is, responsible for the sediments that constitute the Morfa Dinlle complex (Pethick, 1997). The large quantities of sand and gravels produced by erosion of the morainic ridges during Holocene sea-level rise (perhaps 7000–6000 years BP) were moved northwards by prevailing longshore drift to form a series of spits connected to the seaward end of each of the morainic ridges. The rock-head immediately seaward of the present-day Dinas Dinlle coastline lies at –35 m (Harris *et al.*, 1996), suggesting a considerable depth of glaciogenic and Holocene coastal deposition.

It is also possible that a further moraine extended across what is now the mouth of the Afon Gwyrfai and formed the peninsula immediately south of Fort Belan. Pethick (1997) suggests (based upon preliminary study of surficial deposits and morphology) that such a morainic ridge would explain the complex topography of both the north-eastern area of Morfa Dinlle and the tidal section of the Afon Gwyrfai.

Pethick (1997) argued that the gravel ridges and sand dunes of Morfa Dinlle are a late Holocene phenomenon, certainly dating from post-4000 BP and probably much later than this. Dating the ridges themselves has, however, not been possible. As sea level continued to rise in the period 6000–4000 years BP, the coastline was forced eastwards and the continued erosion of the morainic ridges provided abundant sediment for the northward extension of the spits that consequently merged to form a single gravel beach between each of the morainic ridges to the south of Dinas Dinlle and extending to the north, perhaps as far as the present-day airport.

Peat deposits found in the intertidal area immediately west of Dinas Dinlle (Carter, 1990) are thought to date from 4000 years BP and confirm that a brackish-freshwater deltaic environment existed here at that time. This evidence, together with estimates of long-term cliff retreat, suggested to Carter that the coastline was then over 1 km west of its present-day position and that the gravel beach had already limited marine incursions to the east, although the Afon Gwyrfai would still have reached the open sea through a tidal inlet north of Dinas Dinlle (Figure 11.20a).

Successive shingle ridges extend north and east from the cliffs at Dinas Dinlle across the low marshlands towards this tidal inlet. Pethick (1997) conjectured that between 6000 and 4000 years BP the Afon Gwyrfai tidal inlet was pushed gradually northwards as the gravel beach continued to extend from Dinas Dinlle. However, the Gwyrfai was prevented from flowing north on its present-day course by the presence of the moraine that extended across the mouth of the present-day tidal mouth of the Gwyrfai from the eastern shore of Foryd Bay to just south of Fort Belan.

As the gravel spit extended northwards and eastwards, so the tidal mouth of the Gwyrfai was increasingly confined between the distal ends of the gravel spit and the moraine. At some stage it appears from the topographical evidence that the northern end of the gravel spit joined the western end of the moraine and blocked the mouth of the Gwyrfai. An extensive brackish lagoon was initially formed in Foryd Bay, but the waters of the Afon Gwyrfai eventually breached the moraine and tidal flow into the bay was re-established. Further detailed research is essential to test the validity or otherwise of the hypothesis. More recently, extensive land-claim of intertidal areas within Foryd Bay has reduced the tidal prism. The impact of these changes on the tidal entrance to the Bay may have been to reduce the overall dimensions of the tidal opening by northward extension of the shingle ridges. The impact of the changing tidal prism of Foryd Bay on the morphology of the Menai Strait is less obvious, owing to the relative discharges involved.

As the mouth of the Menai Strait narrowed, the coastal gravel beaches of Morfa Dinlle steadily advanced northwards and eastwards. The eastward movement of the coastline, which also resulted in the continued erosion of the morainic cliffs such as those at Dinas Dinlle, caused reworking of the gravel beach ridges as they were rolled landwards. Fresh sediments, eroded from the cliffs from Maen Dylan and Dinas Dinlle, were added to this reworked material. Today, however, the supply of new sediment from these sources is considerably less than the sediment inputs that were available from glacial debris present in early Holocene times.

As sediment moves north it falls more and more under the influence of the sediment circulation patterns of the Menai Strait. There is almost certainly a long-term exchange of material between the shoreline and the offshore area which, when understood, should explain the observed shoreline changes, including the supply of sand for the development of dunes above the gravel ridges. The evidence suggests that Morfa Dinlle is an active gravel-beach system, albeit with a relatively low rate of sediment input. This type of situation is increasingly unusual in England and Wales (especially on the west coast), since, over the past two centuries, human activities (notably shore protection) have acted to restrict sediment sources. Measurement of shingle characteristics over the northern sequence of shingle ridges shows a weak relationship between elevation and shingle mean diameter, and grain size increases towards the modern coastline. In general however, the shingle grain-size distribution seems to indicate a lack of pronounced structure suggesting that in-situ reworking of ridges has taken place, and lending support to the offshore seabed source hypothesis outlined above (Pethick, 1997).

The outgrowth of the gravel ridges supports an extensive 'dry-core' dune system in which the water table is usually below the deflation level, so that standing water is rarely, if ever, found in the system. The dunes have a degree of natural instability associated with geomorphological changes, themselves associated with grazing, pedogenesis and impact of human activities (Carter, 1990; Pethick, 1997). The main line of dunes is a relict formation (Carter, 1990) which has no direct sand supply from the beaches at the present time. However, the occurrence of blowthroughs suggests that some redistribution of sand is occurring and an extensive marram *Ammophila* cover exists. The crestline of the relict dunes follows a distinctive rectilinear line (Figure 11.20b) that seems to be caused by the interaction between the dunes and the underlying shingle ridge structure. The dune crestline appears to be held in position by the underlying shingle structures but, because the orientation of dune crestline and shingle ridges is slightly offset, at intervals the dune crests 'jump' from one underlying shingle ridge to another so forming the characteristic rectilinear pattern (Pethick, 1997). Reasons for the offset between dune crest and shingle ridge crests may be due to the difference in the prevailing wind direction, responsible for the dune orientation, and the orientation of the shoreline on which the shingle ridges formed. Wind-waves approach the shore at an oblique angle, so driving longshore currents towards the north. Further research on these dune systems is needed to interpret the sequence of coastal changes and related climatic variation.

The shingle ridges of Morfa Dinlle, with their superficial dune fields, represent the morphological response to two major postglacial events: the drowning of the Menai Strait to form a tidal estuary and the erosion of a series of glacial moraines to the south. The chronology of events is difficult to determine but it is suggested that the development of a number of shingle ridges along the open coast pre-dated the formation of the Menai Strait. As tidal flow was initiated into the Strait, so these shingle features extended and coalesced to form, in conjunction with the Abermenai spit, the mouth of the Strait. The subsequent decrease in the tidal prism of the Menai Strait, owing to sedimentary deposition, led to the progressive decrease in the width of its tidal entrance and consequently to the northerly movement of the Morfa Dinlle shingle ridges. The spatial pattern of shingle ridges displayed in the area consequently provides a record of the complex Holocene history of this region.

Conclusions

In spite of artificial protection at the southern end, Morfa Dinlle is now one of the last active drift-aligned gravel-ridge systems in the west of England and Wales. The dunes and the gravel ridges are of international geomorphological interest, because the shingle ridges complex of Morfa Dinlle together with the integral Newborough–Abermenai shingle system and their superficial sand dunes represent an extremely important, but relatively rare, geomorphological feature. Although single gravel ridges are widely distributed along the UK coast, few multiple ridge systems exist. Of these, the Dungeness (see GCR site report in Chapter 6), Culbin and Morrich More (see site reports in the present chapter) systems are the most extensive and best-known.

The geomorphological importance of the Morfa Dinlle site also rests in the topographical record of Holocene development of the shoreline of north Wales and in particular the Holocene development of the Menai Strait. The present-day pattern of shingle ridges provide an important record of the development of the Menai Strait during the Holocene Epoch, since their morphologies are directly related to tidal and sedimentary conditions in the Strait.

As a consequence of the relationship between the geomorphology of the Menai Strait and its western tidal entrance, the Morfa Dinlle and Newborough–Abermenai dunes and gravel ridges must be seen as integral components of a single system, defining the mouth of the Strait and responding to past changes. The relationship between the Morfa Dinlle ridges and the tidal dynamics of the Menai Strait, recorded in the topographical features of this site and the adjoining Abermenai–Newborough Warren area that together form the mouth of the Strait, is of international importance. The relationship between the mouth area of an estuary and its tidal dynamics is central to an understanding of estuarine management and, owing to the loss or destruction of comparable sites elsewhere, the Morfa Dinlle–Abermenai sites provide a unique opportunity for research into this complex interaction of open coast and tidal geomorphology.

HOLY ISLAND, NORTHUMBERLAND (NU 035 481–NU 171 362)

V.J. May

Introduction

The Holy Island GCR site (see Figure 10.1 for general location) includes one of the largest sandy beaches on the coastline of England and Wales. About 25% of the coastline between Edinburgh and Whitby is formed by predominantly sandy beaches (European Commission, 1998). To the north of Holy Island, the coast is predominantly cliffed, whereas to the south, hard-rock cliffs alternate with small sand beaches backed by narrow lines of dunes. The largest of these beaches is at Druridge Bay, but it lacks any substantial geomorphological interest, other than the effects of the removal of sand from its foreshore between 1960 and 1996.

Holy Island forms part of a suite of large sandy beach and dune systems along the British east coast that include the north Norfolk coast, Gibraltar Point, Lincolnshire, and the Sands of Forvie, and Rattray Head in Scotland. Similar to other English beaches, it is relatively narrow in comparison to larger Scottish dune systems such as the Sands of Forvie and the much more extensive beach–dune systems of the west coast. Unlike all except Rattray Head, its outline is controlled by the presence of major rocky outcrops that act as hinge points for sediment deposition and beach development. It lacks large amounts of gravel, although parts of the dunes lie upon a gravel base. It is dominated by progradation and there has been no interference with coastal processes by protection works and its relative remoteness has restricted pressures from recreation.

Geomorphological interest in the site has been comparatively limited, although Steers (1946a) drew attention to its considerable potential for research, and Carruthers *et al.* (1927) described the main features of the site. More recently, Robertson (1955) described the main ecological features of part of the site at Ross Links; Farquhar (1967) identified it as a key locality for tied island development; and King (1976) outlined its main geomorphological features. None of these later workers considered the site as a unit, though this is how Steers (1946a) described it. The description and discussion that follow regard the site as a single complex entity.

Description

A key area for coastal geomorphology, the Holy Island GCR site comprises three main units (Figure 11.23):

1. the dunes and the barrier beaches of Cheswick and Goswick Sands,
2. the dunes of the Snook and the cliff-top dunes and cliff–beach system on the north coast of Holy Island, and
3. the dunes and sandy beaches of Ross Links and Budle Bay.

In addition, there are hard-rock cliffs, an emerged ('raised') Holocene beach, saltmarsh and intertidal sandflats and mudflats. The site extends for about 20 km from Far Skerr in the north (NU 035 481) to Bamburgh in the south (NU 171 362). In the north, a predominantly sandy beach and dunes extend south-eastwards across Cheswick and Goswick Sands diverting eastwards the northern channel of the intertidal flats that lie between Holy Island and the mainland. The central part of the site is dominated by Holy Island whose eastern cliffs, cut into limestone and shales, provide the only erosion-resistant feature in the central part of this large site. Holy Island extends westwards in a large dune area known as 'the Snook'. South of Holy Island the main tidal inlet divides the rocky southern shore of the island from the northern sandy beaches of Ross Links. The plan form of Ross Links results from the wave refraction and energy distribution between Holy Island and Bamburgh. A prograding sandy shoreline extends southwards as a low sandy spit across the mouth of Budle Bay, a small tidal inlet floored mainly by sandy sediments. Its southern shore is formed by dunes banked against a hard-rock cliffline,

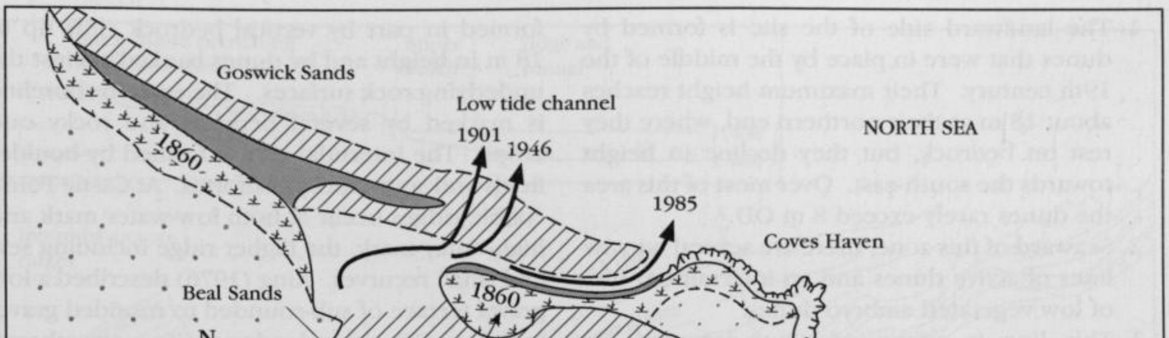


Figure 11.23 Sketch map of the key geomorphological and historical changes to Holy Island. Bold arrows show the dates of the main channels draining estuaries.

whose easternmost extremity is formed by the Whin Sill.

Despite the limitations of cartographic evidence, Ordnance Survey maps and plans of the area from the mid-19th century onwards show that there has been considerable accretion at both Goswick Sands and Ross Links (Figure 11.23). Steers commented (1946a, p. 452) that 'Unfortunately the physiography and ecology of the coast between Black Rocks and Budle Point have not been fully investigated. They should afford many interesting problems for research purposes.' There appears to have been no comprehensive examination of the coastal geomorphology of the whole site. Bird (1985) suggested that, similarly to the northern side of Rattray Head, the Sands of Forvie and the north Norfolk coast, the sand accumulation here may be derived from the seabed.

At its northern end at Cheswick and Goswick the site is bounded by low rock-cliffs formed in Lower Carboniferous shales. Rather more resistant limestone beds (Lowdean or Sandbanks Limestone) form small headlands and a number of reefs that extend seawards from the cliffs. About 250 m of reefs are exposed between high and low tides, acting as low groynes. No other exposures of bedrock occur for some 9 km to the south, until Holy Island itself.

Between Cheswick–Goswick and Holy Island, the shoreline is formed in sand. There are four main zones:

1. The landward side of the site is formed by dunes that were in place by the middle of the 19th century. Their maximum height reaches about 18 m at their northern end, where they rest on bedrock, but they decline in height towards the south-east. Over most of this area the dunes rarely exceed 8 m OD.
2. Seaward of this zone, there are several narrow lines of active dunes and an intermittent line of low vegetated embryo dunes.
3. This line is continued south-eastwards in Goswick Sands as a barrier beach extending towards Holy Island.
4. The final zone is an active intertidal beach that appears to be dominated by progradation. The sand that stands above high-water mark has gradually increased in area from the mid-19th century and extended towards Holy Island. It lacks any evidence of recurves and appears to have extended not as a result of longshore transport, but as a result of a gradual onshore accretion.

Over the same time period, the channel draining the northern part of the Beal Sands has been diverted eastwards and its dimensions have decreased (Figure 11.23). The shoreline alignment is strongly dominated by a swash-related curve between its two rocky extremities at Cheswick and Holy Island.

Holy Island itself was described by Farquhar (1967) as a situation where sand spits and sandbars were prevented from joining the island to the mainland by tidal streams. He also referred to 'the breached bars connecting Holy Island to the Northumberland coast' (p. 120). Steers (1946a) and King (1976) noted that shingle beaches have joined what were originally three or more separate islets to form the present-day Holy Island. Galliers (1970) suggested that the outline of Holy Island and its westward projection at the Snook have changed little between the publication of a map in 1610 and the present day.

The eastern part of Holy Island is formed mainly by Lower Carboniferous shales and thin, limestone strata, including the Lowdean or Sandbanks Limestone. Much of its surface is also covered by till and emerged beach sediments. On the northern side of the island, these are covered by dunes. In bays such as Coves Haven (Figure 11.26), where the dunes are aligned from north-west to south-east, and around Emmanuel Head, the shoreline is formed in part by vertical bedrock cliffs up to 18 m in height and by dunes banked against the underlying rock surfaces. The eastern shoreline is marked by several benches and rocky outcrops. The intertidal area is formed by boulder fields and some rocky platforms. At Castle Point, cobble ridges occur at both low-water mark and high-water mark, the higher ridge including several small recurves. King (1976) described a low gravel terrace of sub-rounded to rounded gravel at 3.6 m OD rising landwards to unweathered gravels at 5.5 m OD. This site has been identified as the only known emerged beach of Holocene age on the east coast of England (see GCR site report in Huddart and Glasser, 2002), and is an important reference site as an isostatic marker. King (1976) described the Snook as underlain by gravel ridges up to +3.6 m OD (a similar level to the Holocene beach) overlain by dunes that reach about 15 m OD. The dunes form both low ridges about 10 m in height roughly parallel to the shoreline (i.e. east–west) and crescentic-shaped mounds that vary in height between 10 m and 12 m. Absent from the earliest maps of the area, the Snook appears on 18th and early 19th century maps as a series of separated ridges. At Snipe Point, the dunes are aligned south-west–north-east. King (1976) suggested that the Snook dunes receive sand from the ridges to the north and north-west, that is Goswick Sands, and from the Holy Island Sands to the south. According to King, the symmetry of the dunes may reflect these two sources. The underlying gravels are exposed only in hollows, these forming most commonly where recreational access has produced local deflation.

South of Holy Island, the shallow lagoon between Holy Island and Ross Links drains the intertidal flats that are almost enclosed by the Snook and Goswick Sands to the north. Although there is some saltmarsh, much of this area is formed by extensive sandy and muddy areas crossed by very well-developed dendritic channel patterns. The more elevated sections of sandflat, where tidal inundation is of lower frequency and duration, are colonized by saltmarsh vegetation and in the west, dense stands of common cord-grass *Spartina* exist. Guile Point is the northernmost part of Ross Links, but the dunes that cover it are broken at Ross Point. There are several small rocky outcrops close to low-water mark seaward of Guile Point. Most of Ross Links is underlain by till, generally at about +3.8 m

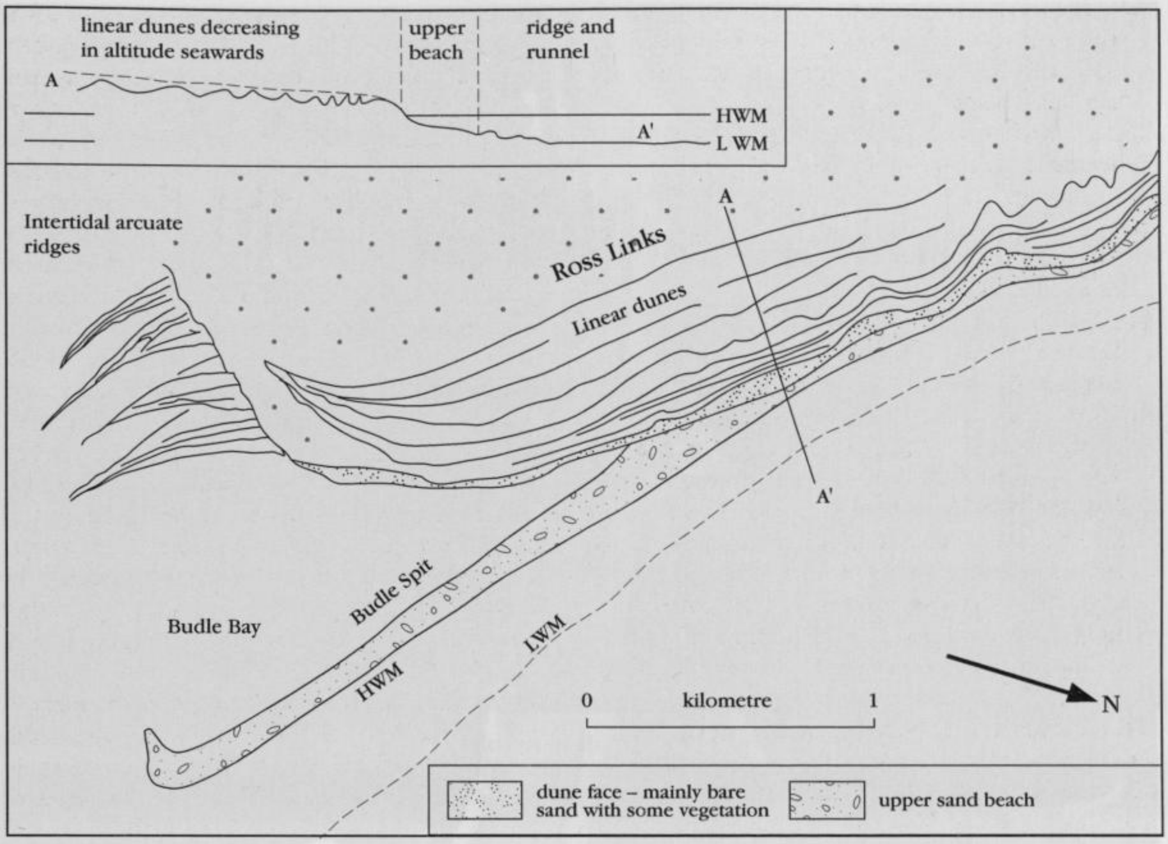


Figure 11.24 Cross-section and profile of the main geomorphological features of Budle Bay and Ross Links. (based in part on interpretation of aerial photographs, see Figure 11.25.)

OD, which is exposed between Guile Point and Ross Point. The relative resistance to erosion of this material has played a part in the recent development of Ross Links since it has fixed the northern end of the sand shoreline curve. Robertson (1955) divided the dunes of Ross Links into four zones from west to east:

1. The oldest part of Ross Links, wind-blown sand is underlain by glacial sand, regarded by Robertson as late-Glacial. The $CaCO_3$ content of this sand is very low. Blowthroughs expose buried podzols throughout this zone, the upper one having Bronze Age pottery in its A1 horizon. Brewis and Buckley (1928) suggested this surface could as a result be dated at about 3600 years BP.
2. Robertson's (1955) 'ancient beach' in which the sand is 'distinctly calcareous'. This has similar blowthroughs to the previous zone and is separated from the next zone by a single almost continuous dune ridge. Long Bog represented this feature best in Robertson's view because farther north it had been covered by dunes and was directly observable only in the blowthroughs.
3. The main area of Ross Links formed by linear dunes that rise from about +7 m OD at the landward boundary of the site to over +18 m OD. From a single ridge about 18 m high at Ross Point this zone widens from about 30 m to over 600 m in the south. There are between 7 and 16 sub-parallel sand dune ridges, each of which marks a period of dune-building (Figures 11.24 and 11.25). At the time of Robertson's 1955 survey the southern part of this zone was about 550 m wide and there were only 14 ridges.
4. The beach, Ross Back Sands and the sand-bar across Budle Bay. Robertson believed that this bar had built up following the 1953 storm surge, but it is an identifiable feature on 19th

Figure 11.25 Aerial photograph mosaic showing the main features of Ross Links and Budle Bay. 1, cliff-foot dunes; 2, sand-waves in Budle Bay; 3, intertidal sandflats and mudflats; 4, Budle spit; 5, prevailing wave direction; 6, saltmarsh and intertidal mudflats; 7, possible former beach ridges; 8, dunes of Ross Links; 9, linear shore-parallel dunes decreasing in altitude towards shoreline. (Photo courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

Figure 11.26 Coves Haven, on the northern coast of Holy Island. The underlying Carboniferous Limestone is covered by till and emerged beach sediments, which are covered by dunes aligned from north-west to south-east. (Photo copyright English Nature.)

century maps.

King (1976) suggested that the curve of Ross Links shore results from the pattern of refracted swell. The refraction patterns would tend to move sand to north and south, and this accounts for the development of spits in both directions. The shoreline appears to have advanced as much as 250 m during the last 100 years (2.5 m a^{-1} is among the more rapid rates nationally). There has been much greater accretion across Budle Bay where a sand ridge narrows the mouth of this estuary to under 300 m at high-water mark. Evidence that this is the result of longshore transport is sketchy, and the detailed surface forms suggest that this beach may be the result of gradual seaward building of the shoreline. The low-water mark has always had an outline that has been tied strongly to the more resistant features of Guile Point and Bamburgh. It appears that during the last few decades sufficient sand has accumulated to sustain this beach and build it across the estuary.

Budle Bay and its southern shoreline show considerable evidence of sand movement by currents on parts of the intertidal estuary floor, and wave and wind action where sand has been banked up against the rocky outcrops (Figure 11.25). Here, as elsewhere on the site, the sand appears to have been derived from offshore, since there are no large inland or longshore sources.

Interpretation

Holy Island has been given surprisingly little attention by coastal geomorphologists, yet it is one of a small number of sites where accretion appears to dominate. On the coastline of Great Britain, fewer than 25% of all beaches are accreting. Sites in which progradation occurs throughout the site are thus very rare, for many are characterized by both erosion and accretion (e.g. see site reports for North Norfolk Coast, Dungeness, South Haven and Morfa Harlech). Growth in the distal parts of these beaches usually takes place at the expense of their landward parts. This is not the case in the Holy Island site (although sediment arriving here has been eroded from elsewhere). Barrier beaches are also rare on the British coast. In this site, the beaches at Cheswick and Goswick have many of the characteristics of such barrier beaches, i.e.

narrow strips of low-lying land formed entirely of beach sediments and frequently overwashed by waves. However, the Holy Island barriers are more properly described as bay barriers since they enclose embayments north and south of the island, unlike true barrier islands that lie separately from the land mass. The most important feature of the Holy Island barriers is the lack of significant longshore sediment feed to them. They appear to have grown primarily as a result of the addition of sand to the seaward face. Lengthening alongshore, which characterizes the Goswick Sands, is a function of beach growth in gradually deepening water rather than of spit extension. However, Hansom (pers. comm.) suggests that there is a southerly feed into these beaches.

The origins of the plentiful sand both offshore and nearshore have not been investigated in detail. One possible source is the reworking of glacial sediments filling depressions in the Carboniferous seabed rock surface, such sediments having a high ratio of glacial sand and gravel to till (Clayton, pers. comm.). There are only very limited fluvial sources. Robertson (1955) drew a distinction between the non-calcareous shell-free sand of the inner part of Ross Links and the calcareous sand containing marine shells, which formed his 'ancient beach' that developed in the British post-Mesolithic era (*c.* 8000 years BP). Since Mesolithic times, relative sea-level change along the Northumberland coast has been only about 2.6 m (Plater and Shennan, 1992). Plater and Shennan identified a transgressive phase up to 7630–7970 years BP, but consider that low rates of relative sea-level change (<1 mm a^{-1}) combined with local variations in sediment supply have been the most important processes here.

Holy Island differs from other large progradational sites in lacking extensive development of saltmarsh behind the beaches. Human activity along the beaches has been minimal. There has been no coast protection and there is little evidence that land-claim has been a significant process. There is saltmarsh in both the ineer Budle Bay and along the western shore of the National Nature Reserve (NNR). Parts of the dunes at Ross Links bear the scars of past use as a bombing range. Nonetheless, the site has some of the most pristine features anywhere on the English coast. The site's similarities to the features of Rattray Head on the Scottish coastline make for interesting comparison because Holy Island appears to represent along its northern side conditions comparable to an earlier stage of the development of Rattray Head and Strathbeg (see Chapter 8).

The southern extension of the sand ridge at Budle Bay poses a question as to its origins. It appears to result from gradual accumulation of sand across the bay as an extension of the shoreline curve to the north. There is, however, one piece of evidence that conflicts with this hypothesis. The Geological Survey Memoir (Carruthers *et al.*, 1927) describes an area in a similar location to the sand ridge as 'raised beach', although Steers (1946a) was unconvinced by the account in the Memoir. If such materials were exposed in the past there is now no surface evidence of them. However, they would provide a base for the development of the present-day sand ridge. Further investigation of this location is needed to elucidate its history.

Both the cartographic evidence and the progradation of the dunes and beach throughout their length argue against any significant redistribution of sand alongshore. Although the development of the sand ridges, at both Ross Links and Goswick Sands, could be seen as resulting from longshore transport, both sediment cells are dominated by overall accretion. If longshore transport is occurring, there must be substantial inputs of sand to the beaches at Cheswick in the case of Goswick Sands and at Old Law in the case of Ross Links. There is some erosion from Far Skerr northwards towards Berwick, but it appears too limited to provide the volumes needed for the growth of the Goswick system. At Ross Links, the older dune ridges all have a predominantly linear sub-parallel form and there is no evidence of old recurves within the dunes. Robertson (1955) argued that on the basis of cartographic, soil and archaeological evidence that these ridges had formed between the beginning of the 16th century and the middle of the 18th century. The whole system is dominated by progressive movement seawards. Even considerable surface damage to the dunes as a result of bombing has not initiated shoreline retreat. There are, however, blowthroughs throughout the dunes mostly with an alignment SSE–NNW. The dune and beach system appears to have a strongly positive sediment balance.

Farquhar's (1967) suggestion that this site has been affected by breaching of beaches thus separating the islands from the mainland is not supported by either the cartographic or the field evidence. The only point at which there appears to have been an erosional break in an otherwise symmetrical shoreline is at Ross Point. Here the mid-19th century high tides appear to have passed between Ross Point and Old Law. Such a cut in the coast occurred in the underlying till and not in the beach. Robertson (1955) used cartographic evidence to suggest that although Old Law first appeared on Armstrong's map of 1769, it had been separated from the mainland by the time of Fryer's 1820 map. There is now sufficient accumulation of sand to ensure that the shoreline is a continuous one. There is no other evidence of breaching.

There is evidence in the cobble beaches of Holy Island itself of higher relative sea levels, but the general reduction in altitude of the dune ridges on Ross Links may be indicative of a falling relative sea level. However, such a hypothesis requires a fuller investigation of the site.

In summary, four issues needing further research are raised by the features of the Holy Island site, i.e.

1. the relationship of the dunes and beaches to any underlying till,
2. the development of the tied islands by beach growth or breaching,
3. the sources of sand for the substantial progradation at this site, and
4. their relationship to changes in sea level and wave climate.

Conclusions

Sand spits and barrier-type beaches characterize this predominantly prograding site. Holy Island is unusual in Britain in combining tied islands with barrier-beach development. The positive sediment budget for the site cannot be explained by longshore sediment transport alone and so an offshore source has to be postulated. The early development of Rattray Head in Scotland appears to have followed a similar pattern.

The significance of Holy Island lies, first, in the extensive progradation of sandy beaches, a rarity not only worldwide, but also on the coastline of Britain. Second, it illustrates well the role of different wave energy distributions through its contrasting beach forms and processes to the north and south of Holy Island. Third, the total assemblage and variety of contemporary and older coastal features makes it unusual. Fourth, it is a rare example of tied islands, in which several rocky islands have been joined by beaches. This is a very unusual form in England and Wales, although it is more common in Scotland. Finally, this site is one of only three locations in England and Wales where barrier-type beaches occur and is the only one that co-incides with conditions of coastal emergence.

The site is also of national and international importance as a National Nature Reserve, Special Area of Conservation (SAC) and Special Protection Area (SPA) under the Habitats and Birds Directives, a Ramsar site and a site of great archaeological and historical importance.

NORTH NORFOLK COAST, NORFOLK (TF 673 413–TG 153 437)

V.J. May

Introduction

The North Norfolk Coast GCR site extends from Hunstanton to Sheringham (see Figure 5.13). It includes not only internationally renowned locations such as Blakeney Point (see Figure 10.9) and Scolt Head Island, but also many smaller, but no less significant, beaches that form an integral part of the coastal system. Much of the site is characterized by a low upland fronted by gently sloping abandoned cliffs separated from sand and shingle beaches by extensive saltmarshes and intertidal flats. The saltmarshes of north Norfolk have been described as the finest coastal marshes in Great Britain (Steers, 1946b) and are among the best-documented and researched in the world. The marshes exhibit a progression of age and development from east to west, manifested through changes in marsh height and assemblage of geomorphological features. Creeks, saltpans and marsh stratigraphy are well exhibited on the north Norfolk marshes. The marshes have been a prime research site for the investigation of rates of saltmarsh accretion and tidal creek processes. At both the east and west ends of the site the beaches rest against retreating Chalk cliffs. Together with the intertidal flats and saltmarshes, the beaches of north Norfolk form one of the outstanding assemblages of coastal forms in Britain. Each of the

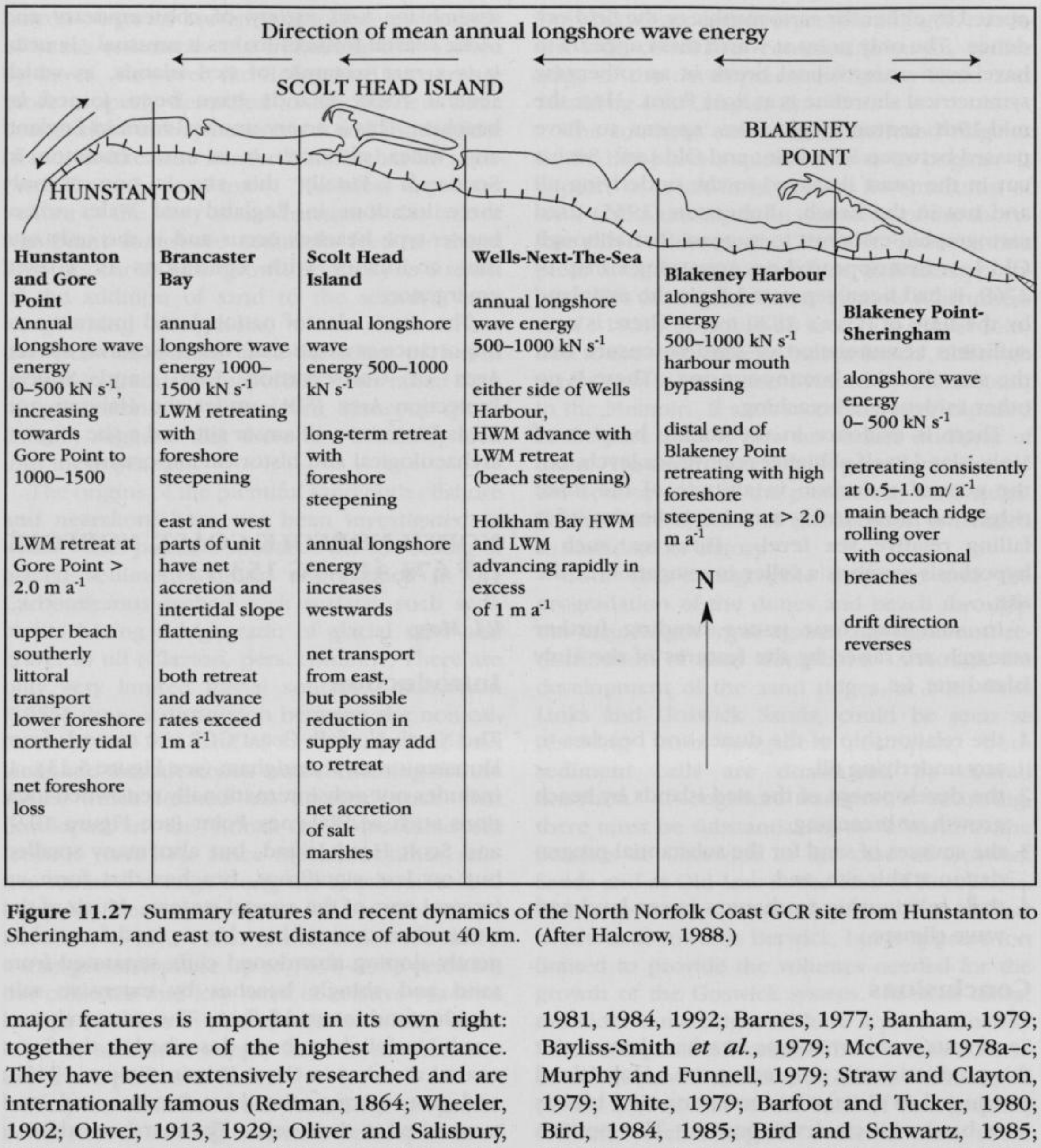


Figure 11.27 Summary features and recent dynamics of the North Norfolk Coast GCR site from Hunstanton to Sheringham, and east to west distance of about 40 km. (After Halcrow, 1988.)

major features is important in its own right: together they are of the highest importance. They have been extensively researched and are internationally famous (Redman, 1864; Wheeler, 1902; Oliver, 1913, 1929; Oliver and Salisbury, 1913; Hill and Hanley, 1914; Kendall, 1926; Steers, 1926a–c, 1927, 1929, 1934a–c, 1935a,b, 1936a,b, 1938a,b, 1939a, 1940, 1942, 1946a,b, 1948a,b, 1951a, 1952, 1953b, 1954, 1960, 1964a,b, 1971b, 1977, 1981; Steers and Kendall, 1928; Steers and Thomas, 1929a,b; Steers and Slater, 1932; Chapman, 1939, 1959; Burnaby, 1950; Grove, 1953; Steers and Grove, 1954; King, 1959, 1972b; Peake, 1960; Williams, 1960; Kidson, 1961; Hardy, 1964; 1966; Ranwell, 1964, 1968, 1972; Steers and Haas, 1964; Evans, 1965; Battarchaya, 1967; Roy, 1967; Zenkovich, 1967; Cambers, 1973, 1975; Pethick, 1974, 1980a,b, 1981, 1984, 1992; Barnes, 1977; Banham, 1979; Bayliss-Smith *et al.*, 1979; McCave, 1978a–c; Murphy and Funnell, 1979; Straw and Clayton, 1979; White, 1979; Barfoot and Tucker, 1980; Bird, 1984, 1985; Bird and Schwartz, 1985; Goudie and Gardner, 1985; Carter, 1988; Funnell and Pearson, 1989; Stoddart *et al.*, 1989; French *et al.*, 1990; Pye *et al.*, 1990; Bridges, 1991; Allen and Pye, 1992; French and Stoddart, 1992; Pye, 1992; French, 1993; Allison and Pye, 1994). The site is amongst those most quoted by textbooks concerned with physical geography, physical geology and geomorphology. Within the last decade, a major interdisciplinary collaborative study has gathered information allowing a more detailed and better-dated understanding of the Holocene evolution of this coastline (Chroston *et al.*, 1999; Andrews *et al.*, 2000; and Andrews and Chroston, 2000).

Extending for some 50 km from Hunstanton in the west to Sheringham in the east, the features owe their origins in large part to the efficacy of longshore sediment transport both in the past and at present. The site comprises many separate morphological units that form six sediment cells (Cambers, 1975). Although Sir William Halcrow and Partners (Halcrow, 1988) also divide the coastline into six units, they identified slightly different boundaries, the units being lengths of shoreline that have 'coherent characteristics' but are not necessarily independent of adjacent cells (Figure 11.27). Here Cambers' cells are used as follows:

1. Hunstanton to Holme-next-the-Sea: Chalk and Carstone cliffs that are undergoing erosion are fronted by a wide sand and shingle beach that extends northwards beyond the cliffs to Holme-next-the-Sea where the fringing dunes reach their widest extent.
2. Holme-next-the-Sea to Brancaster: an area of dunes and beach ridges behind which lie both claimed marshland and natural saltmarsh.
3. Scolt Head Island: the best example of a barrier island on the British coast (Steers, 1981). Regular surveys since the early part of the 20th century make this one of the best-documented coastal sites anywhere in the world.
4. Gun Hill to Wells-next-the-Sea: dominated by a line of dunes known as 'Holkham Meals'.
5. Wells Channel to Blakeney Spit: a large number of small bars of sand, shingle and shells, and an unusual, recurved cuspate beach.
6. Blakeney Point to Sheringham: an excellent example of a recurved spit formed mainly of a single shingle ridge (over 9 km in length) extending from a shingle beach at the foot of retreating till cliffs between Weybourne and Sheringham. Generally, but not exclusively, the inland boundary is marked by a low bluff (an earlier now degraded cliffline) or land-claim embankments.

Description

Taken as a whole, this is a region of wide sand-flats, a barrier island and a spit backed by tidal flats, saltmarshes or dunes. The seabed off the western part of the site is very shallow. Burnham Flats has depths of only 6 m as far as 10 km offshore. Tidal streams reach 0.77 m s^{-1}. East of Wells-next-the-Sea, a bank 7 km offshore has a water depth of only 3 m, but is separated from the coast by water of about 9 m depth between 1 and 2.5 km offshore. The tidal stream here reaches 1.08 m s^{-1}.

McCave (1978b) described the sediment characteristics of the area in detail, the main features being a long shingle barrier ending in Blakeney Point and tidal flats and saltmarshes dominated by muds, and dunes whose sand is better sorted than the beaches that feed them. The key trends along the shore are an increase in mean sand size towards the west and an increase in shingle on the beach eastwards from Blakeney Point. The size of this shingle increases eastwards from Blakeney to Sheringham (Hardy, 1964). Cambers (1975) estimated a potential west to east movement of sand along this coast of about 300 000 m^3 a^{-1}. Sir William Halcrow and Partners (Halcrow, 1988) show that the mean annual alongshore wave energy increases from between 0 and 500 kN s^{-1} at Sheringham to between 1000 and 1500 kN s^{-1} at Gore Point. However, the standard deviation is of a similar magnitude to the mean values, suggesting that the direction of alongshore energy could change from year to year.

Cambers (1975) measured coastal change by comparing the 1:10 560 Ordnance Survey maps for the 1880s with those of the 1950s, and showed that for East Anglia as a whole the total area gained from the sea was 58 370 m^2 compared to a loss of 134 817 m^2. The north Norfolk coast was, however, mainly characterized by accretion, the only areas of erosion being at Brancaster Spit, the central part of Scolt Head Island and at the eastern end of Blakeney spit. Between Burnham Harbour and Wells, accretion was greater than 8 m a^{-1}, and between Holkham Gap and Wells the dunes advanced seawards over 100 m between the 1880s and the 1950s. The *Anglian Coastal Management Atlas* (Halcrow, 1988) indicates that erosion has become more widespread in the 1980s. In particular, although annual rates of retreat of high-water mark have been lower than 1.5 m over the last 100 years (Figure 11.27), low- water mark has retreated by up to 4 m, so that the foreshore has generally been becoming steeper. There are in contrast many points along this coast where progradation has occurred, and the high-water mark has shifted seawards as the foreshore has steepened. In places the high-water mark and the low-water mark have both moved seaward and the foreshore slope has been maintained or even become shallower.

Open-coast and back-barrier saltmarshes, both active (2127 ha: Burd, 1989) and land-claimed (1500 ha), extend for about 35 km from Holme -next-the-Sea in the west to Cley next the Sea east of Blakeney Point. Much of the saltmarsh lies behind coastal barriers of sand (for example at Brancaster and Titchwell (Steers, 1934c, 1936a; Pye, 1992), shingle (Blakeney Point) or mixed sand and shingle (Scolt Head Island). Open-coast marshes landward of wide intertidal sandflats occur mainly at Thornham and Warham. Land-claimed marshes, which are not included in this GCR site, occur at Thornham, between Burnham Deepdale and Wells-next-the-Sea and landward of Blakeney Point. The marshes at Holme-next-the-Sea have been almost entirely reclaimed. Between Thornham and Titchwell the active marshes are mainly back-barrier marshes on which there has been some embanking. At Thornham and Gore Point, new back-barrier marshes have formed since the 1950s) (Pye and French, 1993). Between Brancaster and Overy Staithe, parts of the predominantly back-barrier marshes have been reclaimed, but there are extensive active marshes in Brancaster Marsh, on Scolt Head Island and in Overy Marsh. At Brancaster, migration of the dune ridge landwards has covered parts of the back-barrier marsh (Pye and French, 1993).

The westernmost division lies between Hunstanton (TF 673 414) and Holme-next-the-Sea (TF 727 450). At Hunstanton, the coastline is dominated by near-vertical cliffs about 25 m in height cut in Carstone, Red Chalk and Lower Chalk (Figure 11.28). The Carstone forms a shore platform in which clearly visible rectangular jointing patterns have been only slightly eroded. The Lower Chalk collapses as the cliff is undermined and topples as large, tabular blocks. The cliffs are being eroded at about 0.3 m a^{-1}. Steers (1971b) suggested that their very steep nature results from the combined effects of the rate of marine erosion, the nature of the bedding and the strength of the rocks. In particular, the strength of the tabular Chalk forming the upper cliffs sometimes produces an upper overhang. A beach of sand and shingle extends northwards to Holme-next-the-Sea, where a line of fringing dunes that extend from the northern end of the Chalk cliffs reach their widest. Although the dune and beach ridges have been breached occasionally in the past, the general pattern is of gradual progradation fed by sediment moving north from the vicinity of Hunstanton. Ridges such as Gore Point, which extends westwards, are not permanent features, their presence and alignment appearing to depend upon the predominance of growth from the south or sediment supply from the north. East of Holme, the sand dunes are partially embanked and have built up over a former sea-wall (Steers, 1946b).

Steers (1981) described the role of shingle and shells in forming ridges upon which sand dunes subsequently form by reference to an example at Thornham. In 1914, a crescent-shaped sand and shell island developed in which dune plants colonized the ridge and played a significant role in raising its level by trapping wind-blown sand. Small dunes grew at each end of the ridge, behind which there are small recurves. Bridges (1991) cites a similar example that formed between 1930 and 1935. Here, as elsewhere in the site, saltmarshes have developed between the beaches and the former sea cliff (Peake, 1960).

For much of the distance between Holme-next-the-Sea (TF 728 450) and Brancaster (TF 797 452), the shoreline is formed by dune ridges up to 400 m in width (Figure 11.29). Behind the dunes at East Sands and at Brancaster Golf Course there are extensive saltmarshes that have not been subject to land-claim (Murphy and Funnell, 1979), whereas the central 2 km of this beach has no dune belt and is backed by embanked and land-claimed marshland. Accretion is dominant at both ends of the beach but the central part is affected by erosion, notably along the frontage of the Golf Course. A short length of armoured embankment has been constructed to control shoreline retreat. Erosion at Brancaster revealed two peats, one at between –0.08 m OD and –0.15 m OD that included forest remnants and beech *Fagus* sp. seeds, the other higher at between 2.5 and 3.5 m OD (Bridges, 1991). Funnell and Pearson (1989; see also Andrews *et al.*, 2000; Chroston *et al.*, 1999) showed that there were over 8 m of Holocene sediment with a broad channel running parallel to the main dune ridge. The modern ridges are dynamic, the eastern ridges have grown eastwards, but were farther seawards in 1937 than in 1951, a trend that has continued. The spit at East Sands has grown considerably since Steers' 1935 survey, although the reason is

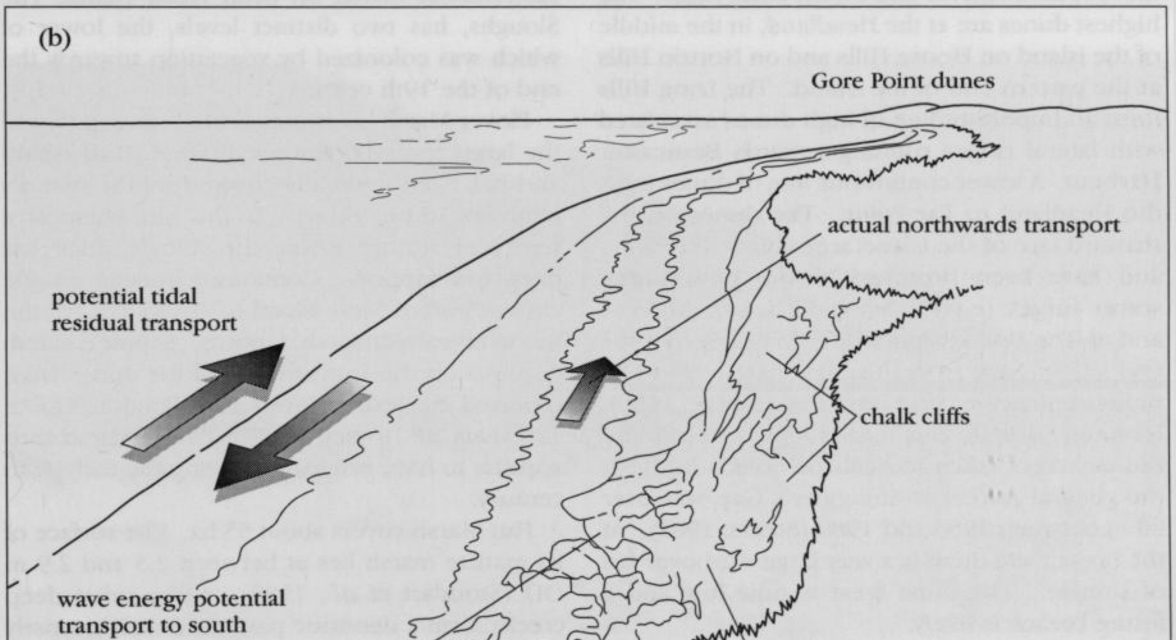


Figure 11.28 (a) The distinctive tabular chalk cliffs of Hunstanton, looking north. (b) Cartoon of potential transport mechanisms of rockfall debris from the failure of the chalk cliffs. (Photo: V.J. May.)

not clear. Cambers (1975) suggested that it may be associated with material deposited via the Harbour Channel, but it is difficult to conceive how this channel, draining a mainly muddy marshland area, could provide sufficient sand for the growth that has occurred. The channel has moved away from the beach and so it seems more likely that sand is moving within the intertidal area between Holme and East Sands.

Scolt Head Island (TF 793 467–TF 847 460; Figure 11.30) has been the subject of regular surveys since the early part of the 20th century, most of the early work being described in Steers (1960). The island is about 7 km in length with a predominantly sand beach about 900 m wide at low spring tides. Shingle patches occur, but most accumulates towards the top of the beach. More than 20 lateral shingle ridges run inland from the main beach: these trend south-west then turn towards the south. All the ridges are dominated by flint, most of which is well rounded (Roy, 1967). The western end of the island known as 'Far Point' is the youngest recurve, suggesting progressive growth of the island towards the west. Dunes have accumulated on most of the recurves and on the main ridge. The highest dunes are at the Headland, in the middle of the island on House Hills and on Norton Hills at the eastern end of the island. The Long Hills form an important line of high dunes associated with lateral ridges running towards Brancaster Harbour. A lower continuous line of dunes joins the Headland to Far Point. The dunes on the seaward face of the island are subject to erosion and have been breached in the past during storm surges (e.g. at Smuggler's Gap in 1938 and at The Breakthrough (TF 833 463) in 1953 and 1978). Sand from the intertidal beaches naturally replenished the breaches (Steers, 1960). However, despite this local supply of sand and the measures taken to heal the breach in 1953, the general retreat at Smuggler's Gap was over 20 m between 1953 and 1980 (Steers, 1981). At the breach site there is a very large washover fan of shingle. The dune crest is now low and a future breach is likely.

The erosion of the central part of the island contrasts with the accretion that is taking place at both ends, although it is much more substantial at the western end at Far Point. Erosion of the main beach is consistent with a gradual retreat of the shoreline as the beach extends westwards. Each lateral lobe represents an earlier beach at a more seaward position, as the island has moved westwards. Steers commented that the laterals form sharp angles with the main beach and also develop a further sharp bend along their length. He suggested that there is no completely satisfactory explanation of the formation of lateral ridges 'here or elsewhere' (1981, p. 360), but the Shoreline Management Plan (Halcrow, 1988) discusses their formation.

The marshes at Scolt Head Island have been a focus of attention since the 1920s (Steers, 1946b). They are separated by shingle recurves and appear to become younger to the west, i.e. from Plantago Marsh through Plover and Hut Marshes to Missel Marsh. The lowest parts of the saltmarshes at Scolt Head Island generally have a cover of glasswort *Salicornia* spp., cord-grass *Spartina anglica* and sea aster *Aster tripolium*. Sea purslane *Atriplex portulacoides*, sea lavender *Limonium vulgare* and sea meadow-grass *Puccinellia maritima* are more characteristic of the more mature marshes. The oldest marshes commonly have a cover of sea thrift *Armeria maritima*, long-leaved scurvy grass *Cochlearia anglica*, red fescue *Festuca rubra* and sea plantain *Plantago maritima* (Pethick, 1981). The easternmost marsh on Scolt Head Island, The Sloughs, has two distinct levels, the lower of which was colonized by vegetation towards the end of the 19th century.

Plover Marsh, in contrast, lies between two of the large recurved laterals of Scolt Head Island and has been gradually covered by the island's migrating dune ridge. At this site there is a washover feature where the shingle ridge has been overtopped. Continuing retreat on the eastern end of Scolt Island (c. 0.5 m a^{-1}) continues to reveal saltmarsh deposits. Exposed marsh deposits on the seaward side of the dunes were reported by Grove (1960) and dated at 441 ± 120 years BP (Joysey, 1967). Plover Marsh thus appears to have originated during the early 16th century.

Hut Marsh covers about 55 ha. The surface of its mature marsh lies at between 2.5 and 2.9 m OD (Stoddart *et al.*, 1989). Steep-sided deep creeks form a dendritic pattern, draining mostly into Hut Creek, which attains a width of over 15 m. In contrast, many of the small first-order creeks draining the upper marsh are usually less than 1 m wide and 0.5 m deep. The marsh had no vegetation in 1818 but had become vegetated and developed a creek system by 1880. The upper part of Hut Marsh lies about 7 cm higher than its eastern part, suggesting to Pethick

Figure 11.29 (a) Brancaster beach-dunes, sand and shingle beach with regular shore-normal cusps. (b) Eroded dune-face remnants of World War II defence structures and associated retreating foredune scarp. (Photos: V.J. May.)

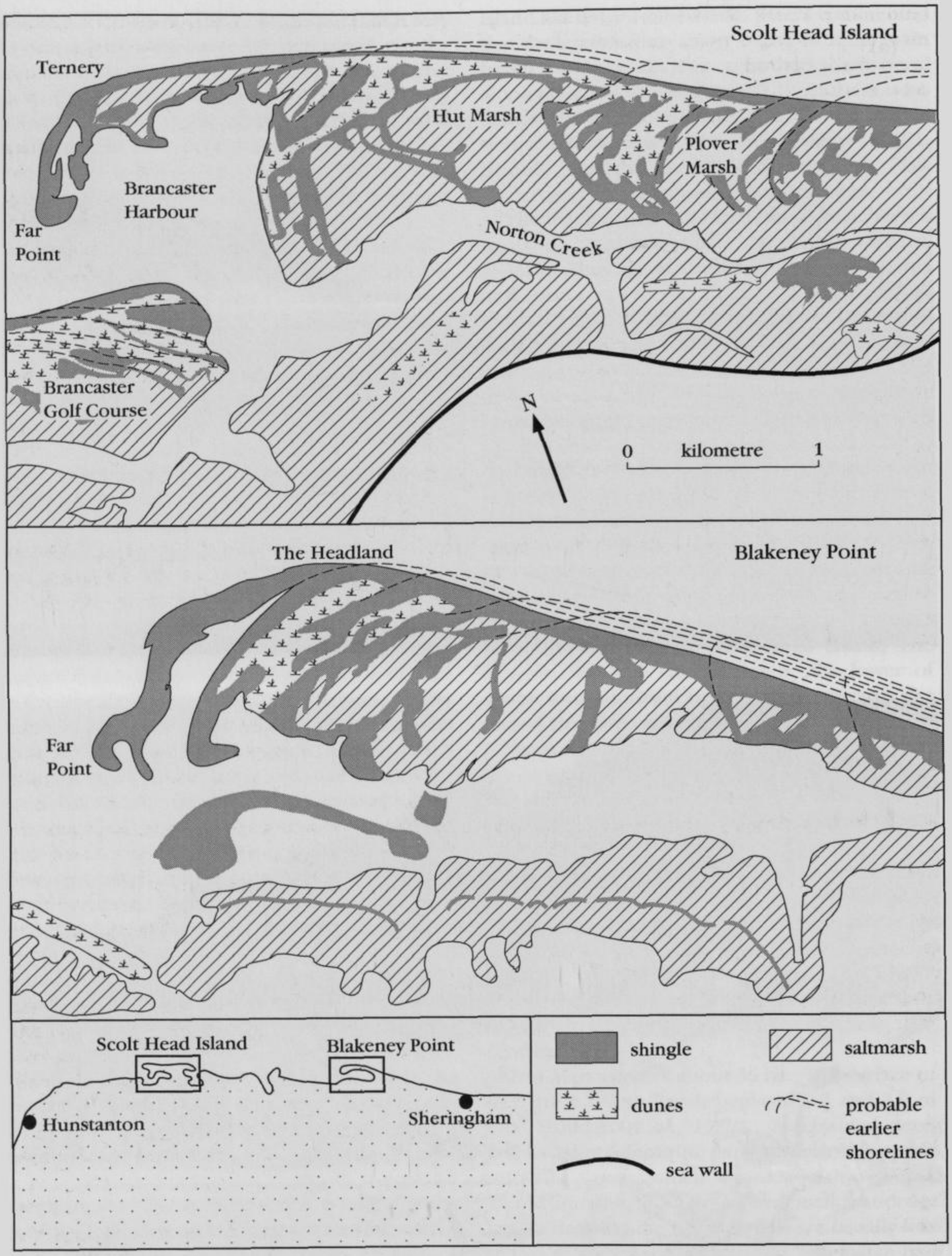


Figure 11.30 (a) Scolt Head Island geomorphological features. (Based mainly on Steers, 1946b, 1960; Bird, 1984, 1985; Halcrow 1988.) (b) Blakeney Point geomorphological features. (Based mainly on Steers, 1946b; Bird, 1984, 1985; Halcrow, 1988.)

(1980b) that it is about 50 years older. The highest rates of accretion occur in the central part of the marsh between the two major draining creeks, whereas the lowest rates occur on the highest parts which are least frequently flooded (Stoddart *et al.*, 1989). Stoddart *et al.* (1989) show that in the middle part of Missel Marsh, shrubby seablite *Suaeda vera* occurs on slightly higher areas. Samphire *Salicornia* spp. and green seaweed *Enteromorpha* spp. are seasonally abundant below the rims of the creeks. Pethick (1980a, 1981) has shown that the inception of the saltmarsh at Missel Marsh at the western end of Scolt Head Island occurred between 1880 and 1907. Steers (1960) estimated the rate of vertical accretion at 8.4 mm a^{-1} over a 22-year period from 1935 until 1957.

Between Gun Hill (TF 847 457) where the Burnham Overy channel drains the marshes at the eastern end of Scolt Head Island and Wells (TF 915 456), the coastline is dominated by a line of dunes known as 'Holkham Meals'. Accretion is predominant with dune crests reaching over 16 m to form the highest point within this site. With winds from the north-west, north or north-east, sand is blown off the beach surfaces very soon after they are exposed. Except at Overy Marsh, the former saltmarshes have mostly been landclaimed. The first enclosure took place in 1660 (Dutt, 1909), but Pethick (1980a) uses archaeological evidence (Clark, 1936, 1939) to show that the marshes are over 2000 years old and lower in altitude (Table 11.3). It appears from documentary evidence discussed by Steers that a channel flowed through Holkham Gap before the land-claim of the saltmarsh. The sandflats are at their widest either side of the Wells Channel, but it is not clear why this is the case. Holkham Bay is marked by slow progradation; dune barriers have been growing in the bay since the 1950s and the area behind the landward barrier is now muddy and colonized by samphire *Salicornia* and other saltmarsh plants (Clayton, pers. comm.). The dune front between Gun Hill and Holkham Gap (TF 890 450), which rises to 15 m, continues the alignment of the main beach at Scolt Head Island, but the dunes east of Holkham Gap have an arcuate form. Steers (1946b) regarded them as an offshore bar of shingle that became stabilized by dune-building. They were further fixed by afforestation during the mid-19th century.

From Wells to Blakeney Point (TF 991 444), there is less development of both dunes and beach ridges, but there are a large number of small offshore bars of sand, shingle and shells. Small beach ridges with limited dune growth fringe the marshes at the Stiffkey Meals, while on the eastern side of Wells Channel, a larger cuspate feature has developed. The growth of recurves at its eastern end suggest sediment transport towards the east, whereas its western tip has grown south-westwards. The role of the wide intertidal flats in modifying wave-energy distributions may also be important here.

Between Wells and Blakeney Point (TF 991 444), the marshes are open to the North Sea and include Wells, Warham, Lodge and Stiffkey marshes. This part of the North Norfolk Coast site is unusual in being the only lengthy stretch where saltmarsh, albeit with a narrow shingle fringe fronted by sand, forms the main feature of the coastline. Some of this marsh originated during the 1950s, with parts being colonized by vegetation only since the 1980s (Pethick, 1980a). The marshes are exposed to the north-east but locally sheltered by a 1.5–2.0 km-wide belt of intertidal sandflat with low onshore-migratory bars. The marshes are 800–1000 m wide and divided by a low shingle ridge. The upper marshes reach 2.8 m OD and are characterized by incised creeks and a floristically rich 'General Saltmarsh Community' (Spencer *et al.*, 1998b). The low marsh varies in height between 2.8 m OD just seaward of the ridge to 2.5 m OD at its seaward edge and is dominated by a pioneer community of common cord-grass *Spartina anglica* and sea-aster *Aster tripolium* and clumps of sea-purslane *Atriplex portulacoides*. Lateral growth of new marshes has taken place at Warham in the last 50 years (Pye and French, 1993). For example, *S. anglica*, first planted in 1907, covered 81 ha by the mid-1960s (Hubbard and Stebbings, 1967) and 149 ha by the late 1980s (Burd, 1989). The organic content of the marsh sediments is less than 15% by weight (French and Spencer, 1993). Aerial photographs show that the present-day low marsh at Stiffkey developed in the 1950s and 1960s (Spencer *et al.*, 1998b; Pethick, 1980a), but has been undergoing erosion since the late 1970s. The seaward margin has degraded into a hummocky topography drained by poorly defined anastomosing channels (see Figure 10.9; Pye and French, 1993). According to Cambers (1975), there is little change in the coastline here.

Blakeney Point (Figure 11.30) is a large shin-

Table 11.3 Summary of saltmarsh development in north Norfolk.

Time	Development
7500 years ago	First signs of marine incursion at *c.* –7 m OD
Until 5500 years ago	Sediments accumulate as sea level rises
Between 5500 and 4500 years ago	Peats within saltmarsh muds and silts imply stability or perhaps fall in sea level
About 4000 years ago	Barrier features at Scolt Head and Blakeney probably in place (Allison, 1989)
About 3000 years ago	Coastline at Holkham is 3km north of its present position
About 2000 years ago	Romano-British remains indicate inner marshes at Brancaster and Burnham
Last few hundred years	Outer marshes develop at Scolt Head Island, Blakeney and at Warham
Since 1900	Open coast marshes grow rapidly with *Spartina* colonization between Wells and Stiffkey
Since 1950	New marshes at western Scolt, Thornham, Morston, western Blakeney. Dune ridges transgressing onto marsh at Brancaster

gle spit, comparable in size to Spurn Head. The shingle beach extends from Sheringham westwards for over 17 km, the first 5.5 km fringing low (up to about 30 m) till cliffs (Burnaby, 1950), and the central section forming a ridge fronting Salthouse Marsh and Fresh Marsh. The ridge is about 200 m wide and between 9 and 10 m in height. Hardy (1964) estimated that the whole structure contained about 2.3×10^6 m^3 of shingle. The western part continues as a single ridge for a further 3 km before developing a series of long recurves trending southwards that are the most recent members of a set of over 20 shingle laterals of varying length. Blakeney Point has extended and shortened several times during the last 150 years. The morphological and cartographic evidence demonstrates that the spit has grown westwards. Steers (1927) estimated that the spit lengthened by 86.4 m a^{-1} between 1886 and 1904 and by 45.7 m a^{-1} between 1904 and 1925. Between 1649 and 1924 the ridge moved inland by an average of about 1 m a^{-1} (Hardy, 1964). There is some debate about the extent to which longshore transport is consistently in this direction and it is possible that shingle moves one way and sand in the other (Battarchaya, 1967; Hardy, 1964; Steers, 1964b; Cambers, 1975). In recent years the ridge has been eroded by storms and then re-shaped by bulldozing material back into the increasingly narrow profile, similar to Hurst Castle Spit (see GCR site report in Chapter 6). This has led to a reduction in the shingle volume of the beach and in February 1995 a 200 m-wide breach through the ridge occurred. If the loss of shingle continues it is likely that Blakeney Point will become an isolated island such as Scolt Head, unless coast protection works are carried out to provide protection for low-lying settlements such as Salthouse. The geomorphological interest lies in allowing natural processes to continue unimpeded, though with the lost shingle restored by beach nourishment.

There are active marshes either side of the Blakeney Channel, but east of Blakeney, they have mostly been land-claimed. The marshes behind the shingle ridge from Salthouse to Blakeney Point increase in age eastwards, with the oldest probably developing first during the 15th century (Pethick, 1980a). Most recently, lateral growth of new marsh has taken place at the western end of Blakeney spit since the 1950s (Pye and French, 1993). Carey and Oliver (1918) reported thin coverings of samphire *Salicornia* spp. in the central marshes, whereas the marsh closer to Blakeney Point itself appears to be older (between 1818 and 1880: Pethick, 1980a).

Interpretation

Despite the long and detailed documentation of the north Norfolk coastline, the sources of the sediments forming the beaches and the direction of sediment transport is still open to debate. The direction of longshore transport has generally been described as eastwards and southwards along the Norfolk coast east of Sheringham, whereas the shingle features on the North Norfolk Coast site have been shown to develop towards the west (Redman, 1864; Wheeler, 1902; Steers, 1927, 1946b). This would suggest a division in the drift direction in the vicinity of Sheringham. Work by Sir William Halcrow and Partners (Halcrow, 1988) demonstrates that the direction of mean, annual, alongshore wave-energy west of Sheringham is from east to west.

Earlier, however, Hardy (1964) used marked shingle in a series of experiments, concluding that shingle moved eastwards except when winds were between north-east and south-east. With the prevailing westerly conditions at the time of his experiment, he found no evidence of a divergence of drift. A consideration of the distribution of shingle suggested that the only sources were the cliffs between Sheringham and Weybourne or small former islands landward of the spit. He also believed, on the basis of estimates of the volume of drift, that the spit was losing material by a slow net-transfer eastwards and that the grading of the shingle supported this view. Steers (1964b) believed that changes in wind and wave direction would explain the apparent paradox raised by Hardy's thesis. Variability of direction of alongshore wave energy and transport certainly occurs and the interpretation of the alongshore transport of sediment on this coast needs to take account of the higher-energy events that can cause transport in a direction different from the prevailing conditions.

The detailed examination of the sediment budget of the east Anglian coast reported by Cambers (1975) also addressed longshore drift in some detail. Cambers' general conclusion was that sand on the beaches of north Norfolk becomes finer-grained towards Sheringham to the east and that the gravel between Sheringham and Blakeney similarly becomes coarser towards the east. Cambers argued that present-day transport rates at Sheringham show an overall drift direction from west to east, but that a change in the orientation of the beach by between 4° and 5° could result in a pattern of no overall transport. A change greater than 5° would result in a reversal of the direction of drift, as would a similar change in the direction of wave approach. Although the spit formation at Blakeney was a response to wave energy and orientation in the past, the present-day changes in the orientation of the spit, with erosion at its eastern end and accretion at its western end, demonstrate that it has not reached equilibrium with the present-day energy conditions. Straw (1979) has described the 'eyes' (small ridges) landward of Blakeney Point as vestiges of a spit of Ipswichian age. This would suggest that wave and sediment transport conditions during the last interglacial were generally similar to those that produced the present-day spit.

The trend for the sand grain-size on the North Norfolk Coast site to become coarser towards the west was explained by Cambers as resulting from longshore transport during which the fine-grained fraction is preferentially moved (winnowed) offshore. The further the sand is transported, the longer the time period that it is exposed to processes that tend to winnow out the fines (McCave, 1978a–c). However, gravel is more likely to be sorted by selective transport and there is no reason why the dominant direction of transport for shingle should be the same as that for sand. More recently, Pethick (pers. comm.) has suggested that sand moves onshore from offshore banks (themselves probably supplied from the erosion of the Holderness (East Yorkshire) cliffs) and is then moved eastwards, crossing the major tidal inlets from time to time.

The age of the major spits and barriers was discussed by Steers, who concluded that about 500 to 600 years BP was 'at best a reasonable guess'. The cartographic and documentary record offers few clues to an earlier origin. Most land-claim has taken place since the mid-18th century. Steers (1946b) noted that there is evidence of occupation of the coastline as early as the Roman period, that the medieval ports of the north Norfolk coast were prosperous, and the earliest maps, from the late 16th century, include features that might have been forerunners of the present-day spits and barriers. The subsequent silting of the ports may be attributed to the more sheltered environment offered by the growth of Scolt Head Island and Blakeney Point spits, but it is not possible to date the shingle ridges as a result. Certainly sedimentation at the heads of the major tidal inlets and the consequent abandonment of such ports as Cley next the Sea long pre-dates the decline in the tidal prism resulting from the embanking of the former saltmarshes.

The well-developed saltmarshes that lie landwards of the ridges and, in particular, the saltmarshes between the laterals offer both further opportunities for dating of the origins of the spits and barriers (Pethick, 1980a, 1981) and for examination of the development of saltmarsh creeks and pans in marshes of different age. Pethick's (1980a) view that parts of the marshes are of pre-Roman date (before *c.* 2000 years BP) provides a potential earliest date for the initiation of the major beach structures has been superseded by later work; first by Funnell and Pearson (1989) and most recently by Andrews *et al.* (2000).

Under the 'Land-Ocean Interaction Study' (LOIS), it has been shown that a west–east channel cut in Chalk is now filled with Holocene sediments. It lies close to the present-day coastline; to seaward from Holme Point to Brancaster, and to landward from Scolt Head Island to Salthouse (Chroston *et al.* 1999). The channel has a very low eastward slope and probably carried water from the River Trent and the Wash rivers along the ice front of the Devensian glaciation some 18 000 years ago. West of Brancaster the coastline has moved landwards to lie south of the buried channel by at least 2 km during the last 6000 years, but east of Scolt Head Island the outer barrier lies on the northern end of the buried channel. Boreholes have penetrated the Holocene sediments to the Chalk floor, showing that the basal sediments lie between −7 and −11 m OD. The Holocene record includes terrestrial peats dated from >9000 to 7000 years BP, after which a steady rise of sea level deposited mud and silt (with rare saltmarsh peats) after 6000 years BP. Seven lithofacies are described, peat, back barrier muds and silts, muddy sand (marking tidal channels), pebbly sand (including washovers), rooted sand (vegetated dunes), interbedded sand (tidal flats) and gravel (beaches and barriers). Sedimentation behind the coastal barrier was fairly continuous, though datable peats suggest a period of stable or falling sea level about 5000 ± 500 a BP. The sand-gravel ridges known as 'meols' or 'meals' on Stiffkey Marsh are similar to cheniers and probably result from severe storms in the Little Ice Age, 300–500 years ago (Boomer and Woodcock, 1999; Knight *et al.*, 1998).

The LOIS investigations have yielded new data on the long-term, landward barrier movement along this coast. The sandy barrier facies have moved south and aggraded more or less in pace with rising sea level (Andrews *et al.*, 2000; Orford *et al.*, 1995). It is likely that the present landward movement of *c.* 1 m a^{-1} has been typical of the period of steady sea-level rise from 7400 years ago to the present, and this suggests that the present-day Holocene coastal prism, currently 3 km wide at Holkham, was 6 km wide 3000 years ago (Andrews and Chroston, 2000). This rate of retreat (which has destroyed virtually all of the Holocene sediments to seaward of the present barrier) matches that of the cliffs farther east (Clayton, 1989b), and it is likely that both are controlled by the rate at which water depths off East Anglia have increased as sea level has risen (and perhaps the sea floor been eroded) over several millennia.

Many of the barriers are backed by belts of sand dunes, and they form a further important feature, dated in places, but often of undetermined age (Knight *et al.*, 1998; Orford *et al.*, 2000). In their natural state they are stabilized by marram *Ammophila arenaria*, but around Holkham Bay they have been planted with Scots Pine trees as part of the land-claim carried out by the Holkham Estate over the last two centuries. Along the more exposed parts of the barriers (e.g. Scolt Head Island) the dunes are cliffed during storm surges and recover with the growth of a foredune in the years between. A few active blowthroughs survive, despite intermittent attempts to revegetate them.

Pethick (1980a) argues that the present-day north Norfolk marshes fall into three broad age groups that co-incide with the three periods of rising sea level of the last 2000 years (Table 11.3). They are the pre-Romano-British marshes about 2000 years old and associated with the Romano-British transgression (Godwin, 1940), medieval marshes about 400 years old developed during a 12th–14th century transgression (Tooley, 1974; Green and Hutchinson, 1961), and recent (post-1850), present-day sea-level rise. The marsh surfaces approach an asymptote at about 0.8 m below the highest tide level (Pethick, 1981). Kestner (1975) found similarly that levels of saltmarshes in the Wash always remains between 0.6 to 0.9 m below high-water ark of ordinary spring tides (HWMOST) Pethick identified a clear fall in the sedimentation rate with elevation and 'a very striking' co-incidence between the modal tide at 2.4 m OD and the marsh surface asymptote at 2.385 m OD (Figure 11.31b). This could probably be attributed to the infrequent flooding, and subsequent minimal accretion, of any marshes that attained 2.4 m OD.

On Hut Marsh, a tide-dominated back-barrier marsh on Scolt Head Island, 95% of total deposition is by direct settling (French and Spencer, 1993). Annual accretion varied between 8 mm a^{-1} adjacent to the larger channels and less than 1 mm a^{-1} on the saltmarsh surfaces farthest from the channels, i.e. on the highest parts of the marsh. Along the longest transport pathways, there was a reduction and then 'exhaustion' of suspended sediment. Storm events by causing surges, and thus higher water levels, accounted for a significant proportion of long-

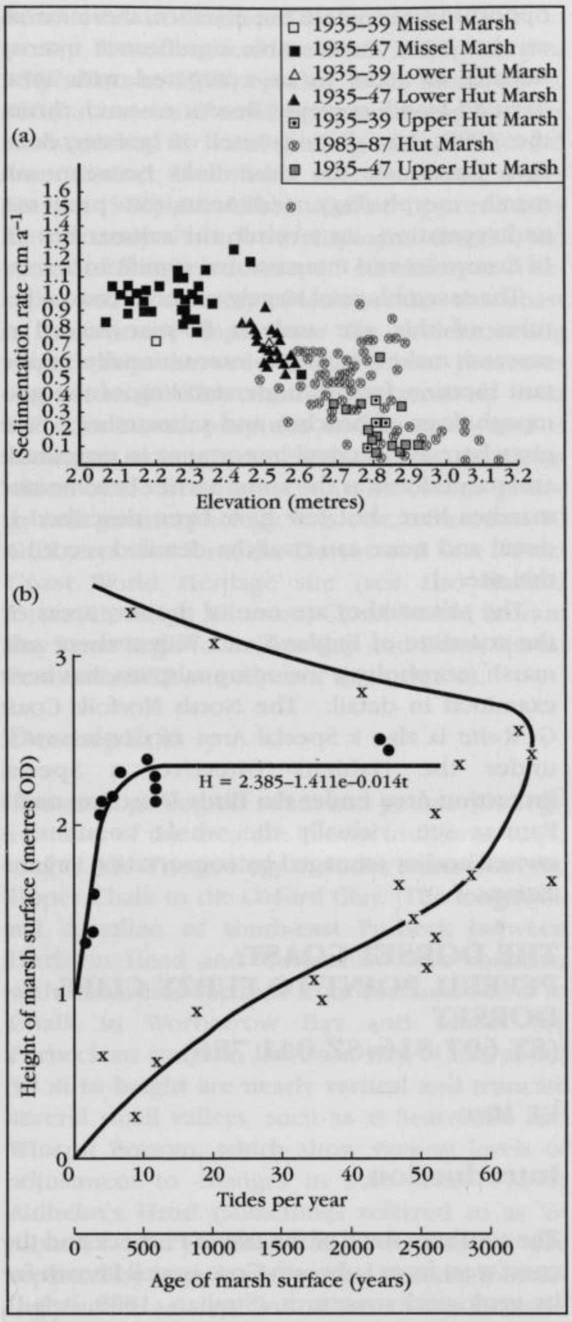


Figure 11.31 Relationship of saltmarsh elevation to tides and age of the marsh surface at Missel Marsh, Lower Hut Marsh, upper Hut Marsh and Hut Marsh. H = 2.385 – 1.411 e – 0.014t is a best-fit line based on the relationship between marsh height (H), tides per year (e) and age of marsh surface (t). (After Pethick, 1980b; 1981.)

term accretion on the highest surfaces. Although there is a general relationship between predicted tidal height and sediment deposition (Figure 11.31b), French and Spencer (1993) showed that this is disrupted by meteorological conditions and resuspension of muddy sediments within the creek system. The arithmetic mean vertical accretion rate for the marsh was 3.9 mm a^{-1}, which is higher than the present-day local rate of sea-level rise (1.5–2.0 mm a^{-1}: French and Spencer, 1993), a significant finding.

Although local rates of sedimentation within the marshes appear to have been fairly constant over recent decades, there are considerable variations across the marshes (Stoddart *et al.*, 1989). Sedimentation is determined not only by the density of the drainage network, but also by channel size and velocity regime. Sediment is deposited in creeks during neap tides, but is mobilized by higher velocity pulses during spring tides (Bayliss-Smith *et al.*, 1979; French, 1985; Green *et al.*, 1986; Healey *et al.*, 1981). They also carry sediment on to the marsh surface. The presence of sea-purslane *Atriplex portulacoides* along creek banks enhances deposition. Stoddart *et al.* (1989) recommended, on the basis of their studies on north Norfolk marshes, that future studies of sedimentation in macrotidal marshes should concentrate particularly upon the interaction between creeks and the vegetated surfaces and the transport pathways for sediment within marshes. More recent studies have shown that unsteady flows in creeks exhibit well-developed velocity and stress transients (French and Stoddart, 1992), which result from a discontinuous tidal prism and the interaction of shallow water tidal inputs with the hydraulically rough vegetated surfaces of the saltmarshes.

Investigation of fossiliferous concretions in the marshes and sandflats shows that they are both abundant and consist mainly of siderite, calcite and iron monosulfides (Allison and Pye, 1994). Siderite–magnesium–calcite–iron sulphide concretions form in oxygen-reduced sediments with active sulphate-reducing bacteria (Pye *et al.*, 1990). Whole concretions form within tens of years, with mineralization becoming visible within months. Iron diagenesis is described (Allison and Pye, 1994) as 'exceedingly active', although the concentration of dissolved iron in pore water rarely exceeds 1 ppm here. Tidal pumping produces both horizontal and vertical movements of up to 60 cm per day.

The north Norfolk marshes have an important role internationally in providing both long-term, and shorter-term – but more detailed – bases for future comparative studies. The LOIS work has greatly increased our knowledge of the older Holocene sediments and the changes that occurred as sea level reached the present line of barriers some 7500 years ago. The saltpans that characterize many of the marshes also form an important element that has been examined both here and in Essex (St Osyth and Dengie marshes, see GCR site reports). Saltmarshes form an integral part of this site and are particularly important as one of 11 GCR sites identified as being geomorphologically characteristic for their saltmarsh morphology (see Chapter 10). Much of the work carried out by Steers and others on this coastline concentrated upon marsh sedimentation within the sheltered environment landward of the beaches. Because of the length of record and the opportunities to date the marshes, these marshes also have considerable significance internationally as areas to be compared with other detailed marsh surveys (for example, Richards, 1934; Chapman, 1938; Guilcher and Berthois, 1957; Ranwell, 1964; Pestrong, 1965; Harrison and Bloom, 1977).

Steers (1981) described the Scolt Head Island complex of beaches, recurves and saltmarshes as the best in Britain and probably also in Europe, on the basis of the assemblage of such features in a relatively small area. The inclusion of other major features such as Blakeney Point adds to the significance of the site. The North Norfolk Coast GCR site is especially important because the 70-year record of regular surveys provides an unrivalled baseline against which assessment of the changes in coastal dynamics associated with present-day sea-level change can be judged.

Conclusions

The coastal features on the North Norfolk Coast GCR site are of outstanding geomorphological importance. It is an extensive site, over 50 km in length, which includes such internationally renowned coastal features as Scolt Head Island, a major barrier island, and Blakeney Point, a large shingle spit. Both have been studied for many decades, the former regularly for over 80 years. Smaller, less well-known parts of the site, intertidal flats, beaches, dunes, saltmarshes and cliffs, are integral to its patterns of sediment transport.

The north Norfolk marshes have an important international role in providing both long-term and short-term bases for future comparative studies. Because of the length of record and the opportunities to date the marshes, these marshes also have considerable significance internationally as areas to be compared with other detailed marsh surveys. Recent research during the 1990s has demonstrated in greater detail than previously the close links between saltmarsh morphology, sedimentation processes and vegetation. As a result, the saltmarshes are of European and international significance.

The assemblage of largely unspoilt coastal features of this site and its 80-year record of research make this site an internationally important location for the understanding of the geomorphology of beaches and saltmarshes. Sites elsewhere are of equal importance in magnitude and naturalness as the spits, barrier beaches and marshes here, but few have been described in detail and none can rival the detailed record of this site.

The saltmarshes are one of the few areas on the coastline of England and Wales where saltmarsh morphology, including saltpans, has been examined in detail. The North Norfolk Coast GCR site is also a Special Area of Conservation under the Habitats Directive, a Special Protection Area under the Birds Directive, and a Ramsar site; virtually the whole coastline is owned and/or managed by conservation organizations.

THE DORSET COAST: PEVERIL POINT TO FURZY CLIFF, DORSET (SY 697 816–SZ 041 786)

V.J. May

Introduction

The southern flank of the Isle of Purbeck and the coast west from Lulworth Cove is well known for its geological structures (Strahan, 1898; Arkell, 1947; House, 1993), and this predominantly cliffed coast is one of the most important locations in Britain for demonstrating relationships between rock structure, rock strength and coastal landforms (Horsfall, 1993; see Figure 1.2 for general location). The whole site forms one of the most frequently described British examples of a longitudinal coastline (e.g. Holmes, 1965; Bird, 1984; King, 1959, 1972). Within it, there are several classic coastal localities, of which Lulworth Cove is probably the most well known. This scale and range of features has attracted most attention (for example, Allison, in press; Brunsden and Goudie, 1981; Burton, 1937; Komar, 1976; Sparks, 1971; Small, 1970, 1978). A series of small bays containing beaches distinguished by local grading of sediment fed from distinct, identifiable sources (Arkell, 1947; Heeps, 1986) provides unrivalled opportunities for the study of beach development. Overall, the range of features developed on different rock-types and at a variety of scales makes this coast of paramount importance for understanding relationships between coastal form, processes and materials. This coastline is extensively used for educational purposes and tourism, and is attracting increasing research interest. In recognition of the site's importance for coastal geology and geomorphology, it is one of around 70 GCR sites that form the Dorset and East Devon Coast World Heritage site (see also Ballard Down, Budleigh Salterton, Chesil Beach, Ladram Bay Lyme Regis to Golden Cap and South Haven Peninsula GCR site reports, this volume).

Description

The main geological strata and geomorphological units of the area are shown in figures 11.32 and 11.33. The geology includes strata from the Upper Chalk to the Oxford Clay. The longitudinal coastline of south-east Purbeck between Durlston Head and Worbarrow Tout contrasts with transverse sections from Portland Stone to Chalk in Worbarrow Bay and across the Purbeckian strata in Durlston Bay. Cliffs about 30 m in height are nearly vertical and truncate several small valleys, such as at Seacombe and Winspit Bottom, which show varying levels of adjustment to changes in base level. At St Aldhelm's Head (sometimes referred to as 'St Alban's Head'), these simple cliff-forms are replaced by large landslips that become increasingly active as clays and shales of the Portland Sand and Kimmeridge Clay are exposed around Chapman's Pool. The role of landslide debris in cliff protection is well exemplified here. The cliffs exceed 120 m but fall to 60 m or less west of Hounstout where Kimmeridgian rocks form both near-vertical cliffs and extensive platforms that extend several hundred metres offshore. To the west of Kimmeridge, the cliffs are dominated by resistant outcrops of Portland and Purbeck beds that are seen in alternating high, often vertical, cliffs and narrow submarine ridges that occasionally appear at low tide, as at Man o'War Rocks, immediately east of Durdle Door. The overall development of the bays, which include Lulworth Cove, has been seen as exemplifying different stages of coastal evolution. The relationships between structure, rock material and coastal form are well exemplified between Lulworth Cove and Bat's Head as caves, arches, rock offshore reefs, headlands and bays are developed to a greater or lesser degree.

The complex structural patterns of the cliffs and platforms between Ringstead and Black Head give rise to a great variety of forms providing an excellent location for examination of differential erosion processes. From Black Head westwards to Furzy Cliff, the cliffs are dominated by several different mass-movement systems that feed the beaches with a variety of sediment ranging in size from clay to boulders.

The area is microtidal, with a range less than 2.0 m, and tidal streams are generally weak. The prevailing and dominant wave trains are south-westerly, at times with origins in the southern Atlantic Ocean, and periods of 10 seconds or more are common. Waves from the south-east are characterized by a period of 5 seconds and are restricted in fetch. They tend to degenerate with the onset of south-westerly or northerly winds. Nevertheless they can be important locally in moving beach material within the semi-enclosed bays and exposing bedrock to erosion (Heeps, 1986).

The western end of the site lies at the north-eastern extremity of Weymouth beach. The beach is in deficit, and erosion of the Oxford Clay has contributed to mass-movements in Furzy Cliff. Cliff-top retreat has averaged about 1 m a^{-1} in recent years (Figure 11.34); most change occurs in relatively infrequent landslides. May (1964) described a rotational slip at the western end in January 1964, and more recently the whole of the cliff has become affected. Within a matter of weeks much of the material brought to the cliff foot by the slides is removed by wave activity. Slides occur frequently, with spatially separated larger events taking place about every eight years. In contrast, the cliff foot east of Bowleaze Cove (cut in Osmington Oolite and Bencliff Grit overlying Nothe Clay and Nothe Grit) is naturally armoured by boulders derived from rockfalls and reveals very little retreat of the lower cliff face. However, there have been two major failures on the upper slopes, separated by some 70 years (1900 and

1971). The first, described by Richardson (1900) affected the whole cliff, but the area remained largely unchanged apart from progressive degradation and establishment of a mature vegetation cover of brambles and grasses, interspersed with waterlogged hollows dominated by rushes *Juncus* behind the slip elements. During the 1970s this cliff once again became very active with a series of shear planes dividing a staircase of slide blocks reaching some 80 m inland of the cliff edge of the early 1970s. This part of the site thus demonstrates very vividly the effects and interplay of marine and subaerial processes on this coast.

Between Redcliff Point and Bran Point, the nature of the cliffs varies greatly with lithology and structure, and also upon the form of the cliff foot and intertidal zone. At the western end there is a small shingle beach that normally protects the cliff foot from direct erosion, whereas farther to the east the Nothe Grit forms a resistant foot to the cliff and a beach is absent. Eastwards from Osmington Mills, outcrops of the Corallian strata marked by a series of struc-

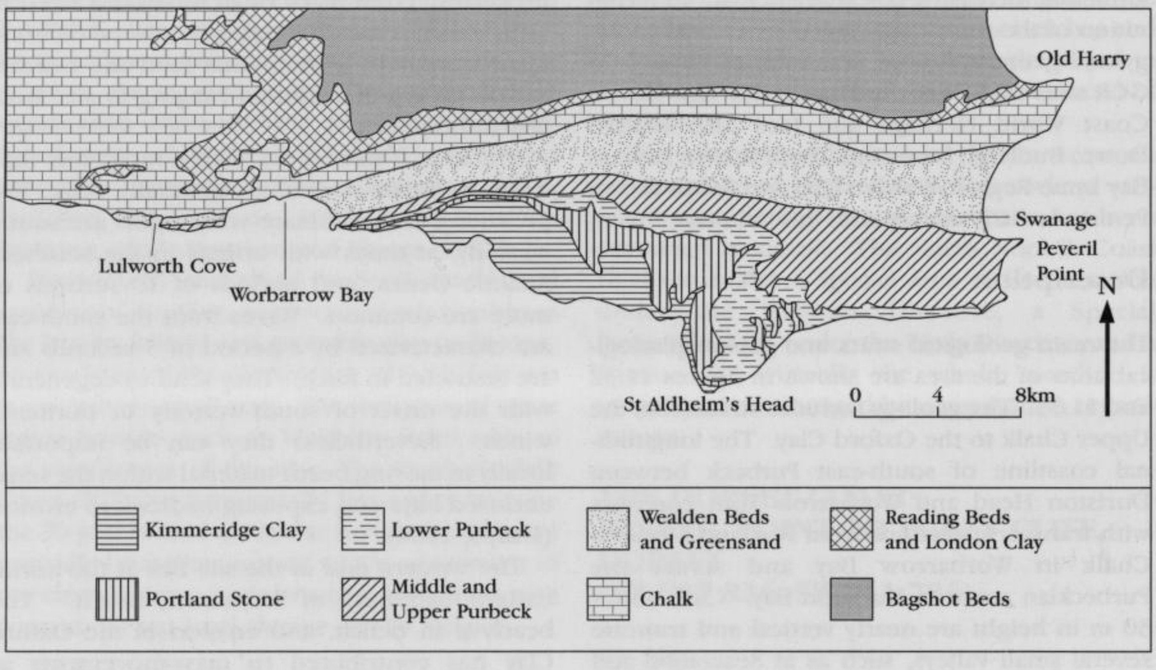


Figure 11. 32 Geological map of the Dorset coast from Lulworth Cove to Studland Bay.

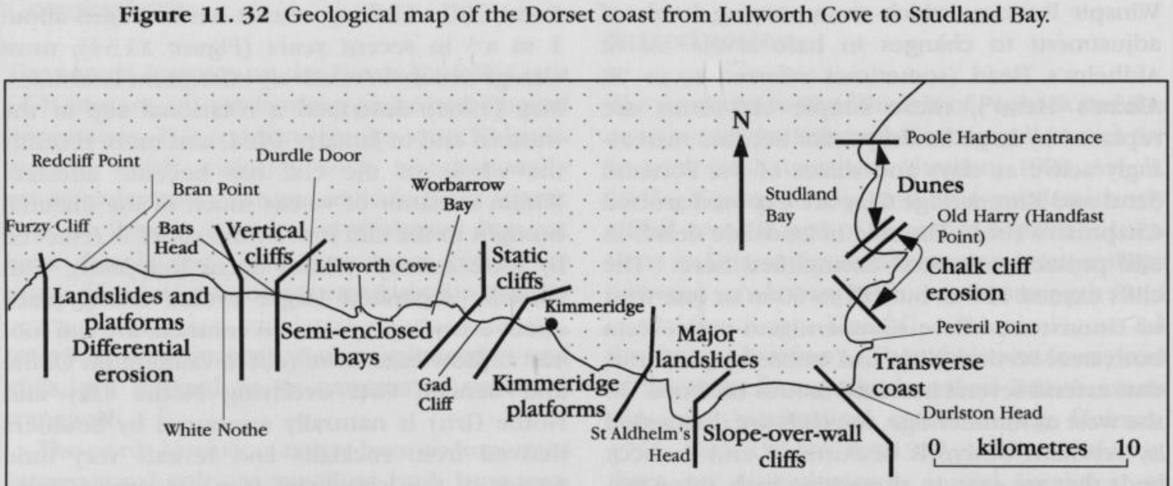


Figure 11.33 Summary geomorphological character of the coast between Furzy Cliff and Poole Harbour.

turally controlled stepped platforms. Some erosion of the detail of the platforms depends upon cobbles that are rolled along the weaker junctions. Arkell (1947, 1951a, 1955) suggested that rare events (such as the Martinstown storm of 18 July 1955, when over 280 mm rain fell, over 180 mm of which fell in 4.5 hours) may have played a significant role in re-shaping much of the coastal slope east and west of Osmington where it is dominated by clays.

Ringstead Bay, cut into the Kimmeridgian strata, lies between Bran Point and White Nothe. From cliffs about 30 m high at Bran Point it falls to a series of slumped and heavily vegetated slopes that are only 5 m high at Ringstead Bay (Figure 11.35). At its eastern end there is an active cliff between 2 and 35 m in height that retreated more than 3 m between 1996 and 1998 into the foot of the White Nothe landslide complex. The cliff top behind the landslides, however, attains an altitude of 150 m.

The beach at Ringstead is formed almost entirely of rounded oxidized flint, ranging in size from coarse sand to cobble, the latter mainly where Chalk enters the beach from the White Nothe cliffs. Heeps (1986) showed that this beach has a balanced sediment budget although considerable movements of sediment occur within Ringstead Bay. This beach, like most others to the east, has a very abrupt seaward boundary about 20–30 m offshore, where it rests on a rock platform. The beach moves between the ends and centre of the bay and between the upper and the lower beach. Thus over the period of about 15 months (1983–1984) when profiles were surveyed, a loss of about 440 m^3 was balanced by deposition of almost exactly the same amount. There are extensive submerged and intertidal platforms formed mainly in Corallian strata, and these filter reduce the wave energy approaching this beach. Seaweed growth has been observed on much of the platform and Heeps (1986) recorded weed-rafting of material from platform to the beach, but suggested that it plays only a small part in augmenting the sediment within Ringstead Bay.

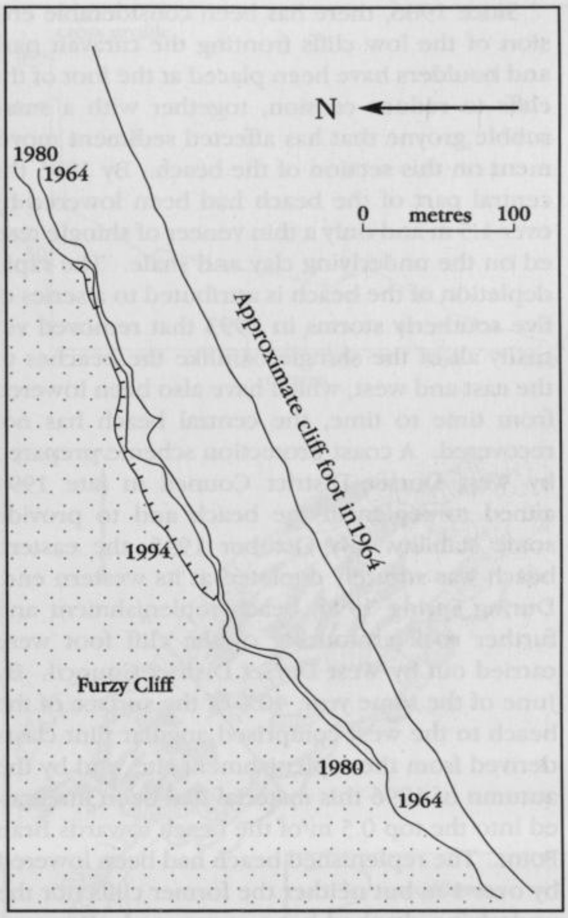


Figure 11.34 Cliff retreat at Furzy Cliff.

Table 11.4 Rates of cliff-top retreat since *c.* 1900 on the Dorset Coast.

Mean annual rate (m a^{-1})	Rock type	Location of retreat
0.01	Portland Stone	Durlston Head to Winspit
0.18	Chalk	Hambury Tout to White Nothe
0.22	Chalk	Worbarrow Bay
0.25	Purbeck Beds	Durlston Bay
0.37	Jurassic clays	Furzy Cliff to Shortlake
0.38	Wealden	Worbarrow Bay
0.39	Kimmeridge clays and shales	Kimmeridge
0.41	Kimmeridge clays	Ringstead
0.43	Kimmeridge clays	Chapman's Pool
0.50	Wealden	Lulworth Cove

Since 1986, there has been considerable erosion of the low cliffs fronting the caravan park and boulders have been placed at the foot of the cliffs to reduce erosion, together with a small rubble groyne that has affected sediment movement on this section of the beach. By 1995 the central part of the beach had been lowered by over 1.5 m and only a thin veneer of shingle rested on the underlying clay and shale. The rapid depletion of the beach is attributed to a series of five southerly storms in 1993 that removed virtually all of the shingle. Unlike the beaches to the east and west, which have also been lowered from time to time, the central beach has not recovered. A coast protection scheme prepared by West Dorset District Council in late 1994 aimed to replenish the beach and to provide some stability. By October 1995, the eastern beach was severely depleted at its western end. During spring 1996, beach replenishment and further rock armouring of the cliff foot were carried out by West Dorset District Council. By June of the same year, 40% of the surface of the beach to the west comprised angular flint clasts derived from the replenishment site, and by the autumn of 1996 this material had been integrated into the top 0.5 m of the beach towards Bran Point. The replenished beach had been lowered by over 1 m but neither the former cliffs nor the underlying clay had been re-exposed. Between spring 1996 and mid-February 1998, parts of the clay cliff at the western end of the replenishment site had retreated by up to 2.8 m.

At the eastern end of Ringstead Bay, the coastal landscape is dominated by the high complex cliffs between Burning Cliff and White Nothe (Figure 11.35). The profile from the cliff top to the beach is distinguished by a near-vertical upper cliff that is interspersed with gentler grassed slopes almost reaching the cliff-top edge. Some of these slopes comprise angular flint screes cloaked by vegetation and a vestigial soil cover. In places, however, the screes themselves are exposed, forming distinct features at angles between 27° and 32° that fall to a hollow formed behind the large rotational-slip blocks that characterize the middle cliff (Figure 11.36). Below these the cliff has become active in recent years and large areas are affected by shear planes, slide scars and several zones of movement. Former-slip blocks are exposed within some of these areas.

The Kimmeridge Clay crops out at the eastern end of the bay, but is progressively cloaked by chalk landslide forms. Failures in the clays are partly responsible for a complex 'staircase' of rotational-slip blocks and active mass-movements that feed chalk to the eastern end of Ringstead Bay. The beach here, however, receives only small quantities of such material and is composed mainly of rounded flint clasts. Chalk boulders and fresh flint nodules are transported to the beach by a series of landslides. Many of the boulders remain in the intertidal zone and provide effective protection to the foot of the cliff. Both chalk and flint are broken down into shingle-sized fragments, but little reaches the main beach in Ringstead Bay because it is trapped behind the boulder ramparts on the middle and lower shoreline.

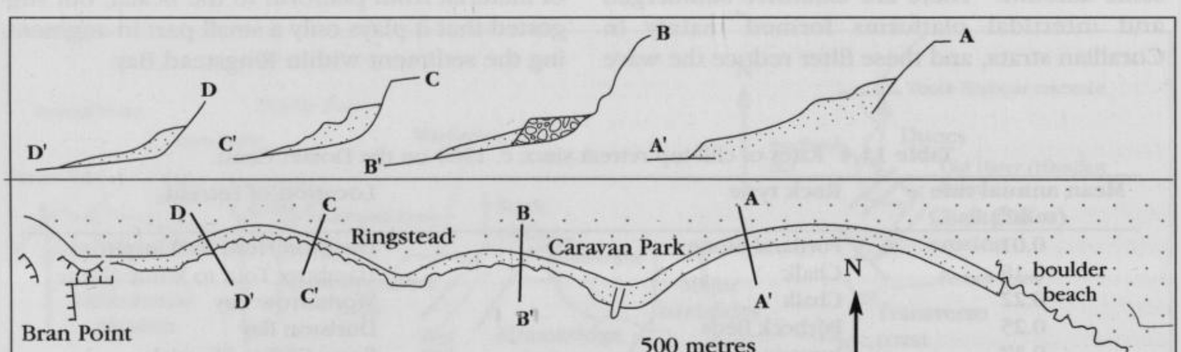


Figure 11.35 Cross-sections of the beaches of Ringstead Bay, and sketch map showing locations of sections.

At White Nothe itself, the cliffs are much less complex, the whole cliff is composed of Chalk here. From White Nothe to Bat's Head, the cliffs truncate a series of dry or 'combe' valleys. The beach is formed of newly deposited chalk and flint mixed with subsidiary amounts of rounded oxidized flint, the range of clasts showing a diversity in the degree of roundness. Although the beach rests on a Chalk platform, the platform is poorly developed. This is the only beach within the Chalk sector of the English coast where recently produced Chalk and flint clasts dominate the beach. The erosion of the eastern side of White Nothe, together with some landslide debris transported from the eastern end, provide the main source of clasts. There is little evidence of major falls from the cliffs behind the beach, although many small falls occur; much of the contemporary erosion is of the toes of relict talus slopes. Offshore, side-scan sonar surveys (Heeps, 1986, 1987) have shown that there are important extensions of the reef features that characterize the coast to the east and extend from off White Nothe to Worbarrow Tout. Geological structures are revealed particularly well in many of the seabed forms, despite some cloaking by thin veneers of rippled sand. The foresyncline of the Purbeck monocline that is cut by the cliffs west of Bat's Head forms a distinctive feature of the submerged coast (Figures 11.37– 11.39.)

The section of coast from Bat's Head to Man o'War Bay has been described in detail by Heeps (1986). It has three main morphological elements, high Chalk cliffs, lower cliffs or bay floors cut into the Lower Cretaceous and Upper Jurassic strata, and a discontinuous rock reef formed in Portland Beds. Its best-known feature is Durdle Door, an arch cut through the near-vertical strata of the Portland Stone. The reef continues across the bays both to the east and west of Durdle Door. Because it reduces much of the wave energy approaching the beaches and prevents the beach sediments from leaving the bays other than in suspension, the reef plays a significant part in making these bays closed sediment cells. Heeps (1986) showed that, whereas there is some supply of flint and Chalk into the beach, the overall volume of sediment held within the bay west of Durdle Door changes little although there can be substantial changes in form from time to time depending upon wave conditions. The mainly flint shingle beach rests upon a narrow chalk platform that is exposed

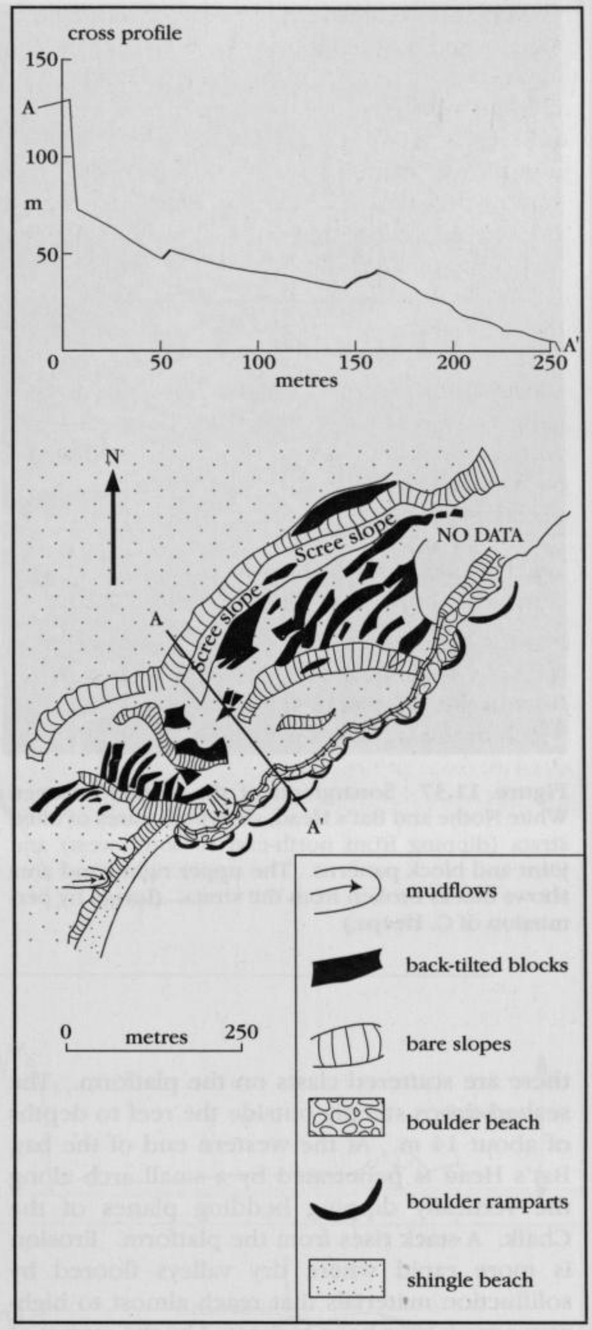


Figure 11.36 Geomorphology and cross profile of the White Nothe landslides in the Dorset Coast GCR site.

when shingle is re-distributed within the bay. The platform slopes at angles of up to 10°, is about 15 m in width, and is covered by fine shingle beach rarely thicker than 1 m, with little berm development. Beyond the beach edge,

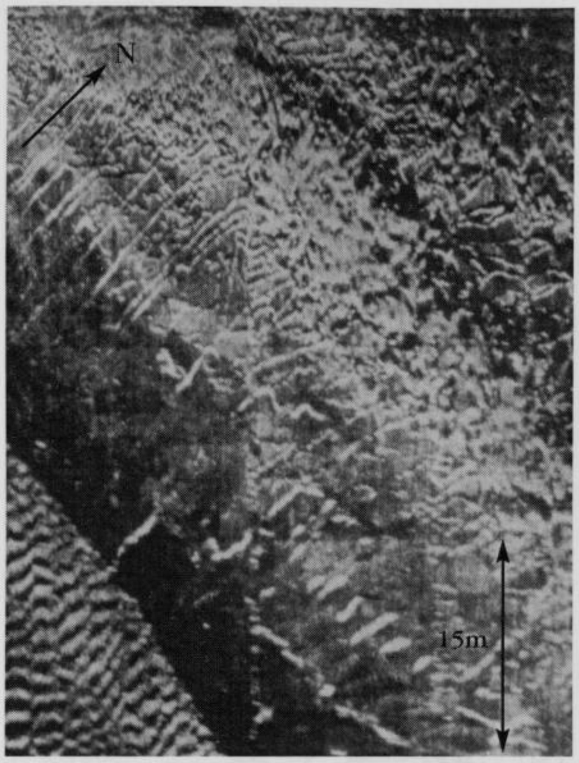


Figure 11.37 Sonargraph of the seabed between White Nothe and Bat's Head, showing an area of tilted strata (dipping from north-east to south-west) and joint and block patterns. The upper right hand area shows blocks broken from the strata. (Image by permission of C. Heeps.)

there are scattered clasts on the platform. The seabed drops steeply outside the reef to depths of about 14 m. At the western end of the bay, Bat's Head is penetrated by a small arch along the vertically dipping bedding planes of the Chalk. A stack rises from the platform. Erosion is more rapid where dry valleys floored by solifluction materials that reach almost to high-water mark have been truncated by the retreat of the coastline.

Daily surveys of the Durdle Door beach (Heeps, 1986) for a month in the winter of 1983 show that prolonged exposure to easterly wave regimes resulted in changes that although small in magnitude were significant with respect to sediment circulation within a morphologically constrained unit (Figure 11.40). Storm action (associated with south-westerly waves) accounted for large changes in the beach volume, but the process was a simple onshore–offshore exchange, the material being returned by post-storm conditions. Easterly waves occurred less frequently, but their effect was much greater. In particular, swell from the east initiated longshore drift that brought about exposure of the Chalk platform in the west. Heeps regarded such conditions as the 'extreme event' experienced by beaches along the south-east Dorset coast. During the longer 15-month period of Heeps' survey, the beach showed almost no variation in volume with 618 m^3 removed against 605 m^3 deposited. Her survey also suggested that within this bay there is a tendency for a sediment parting towards the western end of the Durdle Door bay.

Man o'War Bay has a small shingle beach, sheltered by Man o'War Rocks, which develops a partial cuspate form in the lee of the easternmost part of the barrier. Cusps are commonly present on the beach with a distinctive grading of their dimensions from large in the centre of the bay to smaller at both extremities. Sediment size is also graded from smaller (– 2 phi) material at the ends of the bay and larger in the centre (> –3.5 phi). Both the cusp and sediment grading are characteristic of these bays. Remnant upper berms as well as contemporary berms, both with cusps, are common.

The cliffs rise eastwards from Durdle Door to a height of 138 m at Hambury Tout. Stair Hole and Lulworth Cove form the best-known features of this coast. The rounded cove cut into the Chalk back wall contrasts with the more linear form of the adjacent Stair Hole. The mudslides in the Wealden strata of Stair Hole are gradually cutting back its landward side, and wave action has opened out a series of arches in the hard Jurassic limestones that form its outer side. Waves now access the toe of the mudslides, and during storm periods and after prolonged rainfall, they become very active. Lulworth Cove is known internationally as the classic form of a near-circular bay resulting from the differential erosion of weaker strata behind a resistant and protecting outer wall of harder rock. It is described in almost all texts on physical geography both within the British Isles and worldwide.

Both east and west of Lulworth Cove, the coast is formed by vertical cliffs in the Portland Stone. At Mupe Bay, the coastline is cut into the younger beds and a small bay with a shingle beach has formed. The Portland and Purbeck strata that dip steeply here have been eroded to close to sea level but extend seawards across

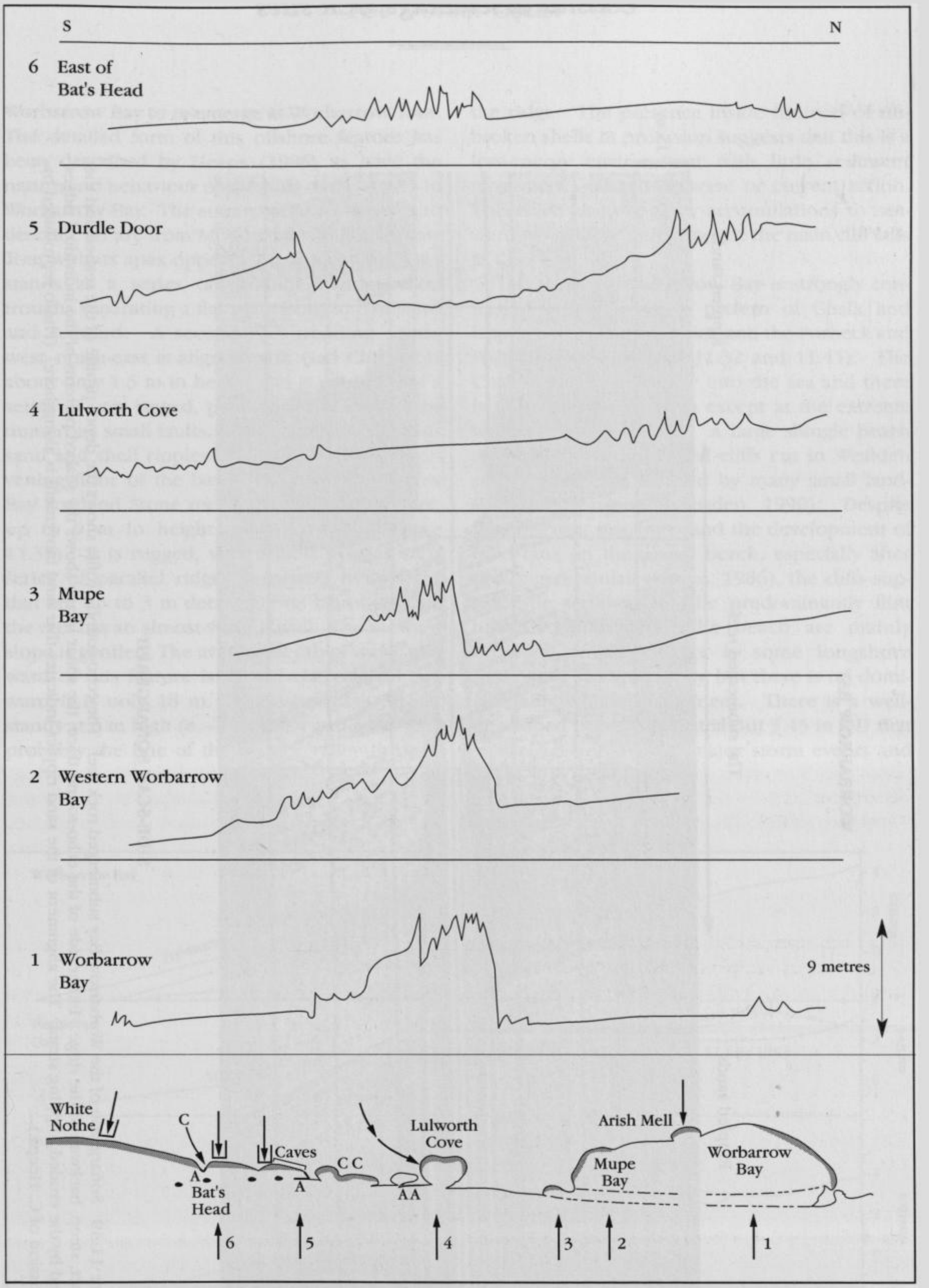


Figure 11.38 Profiles of the submerged rock ridges between Bat's Head and Worbarrow Tout. The ridges are formed by steeply dipping Purbeckian and Portlandian strata between the headlands along this coast. Typically the northern face of the ridges is formed by the structural surface of strata, which here dip northwards (inland). Opposite Lulworth Cove, the ridges are less than 1 m in height, whereas in Worbarrow Bay they attain 9 m. C = Cave; A = Arch; hanging dry valleys are shown with a bracketed arrowhead, whereas valleys draining to sea level are shown without a bracket. Locations of the profiles 1 to 6 are indicated in the plan view.

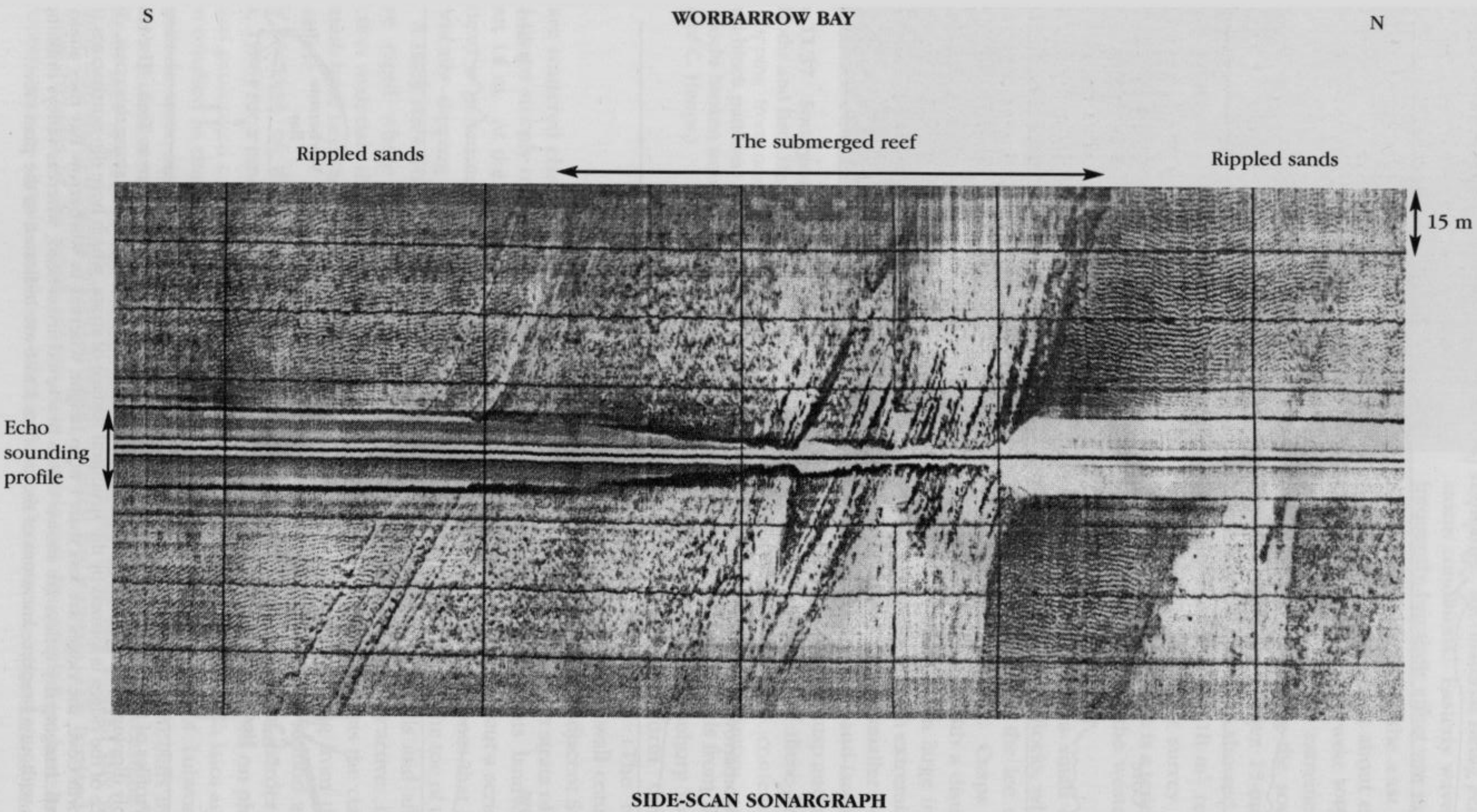


Figure 11.39 Sonargraph of the Worbarrow Bay submerged rock reef. The echo-sound profile shows the depth profile of the seabed and the distinct, steep, backwall of the ridge. Either side of the echo-sound trace, the sonar image shows the seabed patterns of the individual ridges formed by the eroded, dipping strata. The alignment of the sand ripples indicates that sand movement is alongshore. (Photo reproduced by permission of C. Heeps.)

Worbarrow Bay to re-emerge at Worbarrow Tout. The detailed form of this offshore feature has been described by Heeps (1986) as have the nature and behaviour of the cliffs and beaches in Worbarrow Bay. The submerged reef appears to describe an arc from Mupe Rocks to Worbarrow Tout with its apex opposite Arish Mell. The reef stands as a series of prominent ridges and troughs separating a flat plain both to landward and seaward. A second reef trending south-west–north-east is aligned with Gad Cliff. It is about only 1.5 m in height and is made up of a series of very jagged, parallel ridges crossed by numerous small faults. Bifurcating and sinuous sand and shell ripples cover much of the intervening floor of the bay. The main Worbarrow Bay Portland Stone reef is a substantial feature, up to 9 m in height above seafloor (Figure 11.39). It is rugged, with a crest marked by a series of parallel ridges separated by troughs that are up to 3 m deep. On its landward side the reef has an almost-vertical wall. The seaward slope is gentler. The average depth of water seaward of this feature is 23 m, whereas to landward it is only 18 m. Opposite Arish Mell it stands at 6 m high (*c.* –12 m OD) and has a gap, probably the line of the former valley through the ridge. The presence inside the reef of unbroken shells in profusion suggests that this is a low-energy environment with little sediment movement induced by wave or current action. There are large boulder accumulations to seaward of Gad Cliff and opposite the main cliff falls at Cow Gap.

The shape of Worbarrow Bay is strongly controlled by the outcrop pattern of Chalk and Upper Greensand, Wealden and the Purbeck and Portland Beds (Figures 11.32 and 11.41). The Chalk cliffs drop directly into the sea and there is no intertidal platform except at the extreme western end of the bay. A large shingle beach rests against the slumped cliffs cut in Wealden strata, which are affected by many small landslides (Allison and Brunsden, 1990). Despite this inherent instability and the development of mud fans on the upper beach, especially after prolonged rainfall (Heeps, 1986), the cliffs supply little sediment to the predominantly flint beach. Changes in the beach are mainly onshore–offshore; there is some longshore movement within the bay, but there is no dominant direction of movement. There is a well-developed upper berm at about 5.45 m OD that is affected only during major storm events and

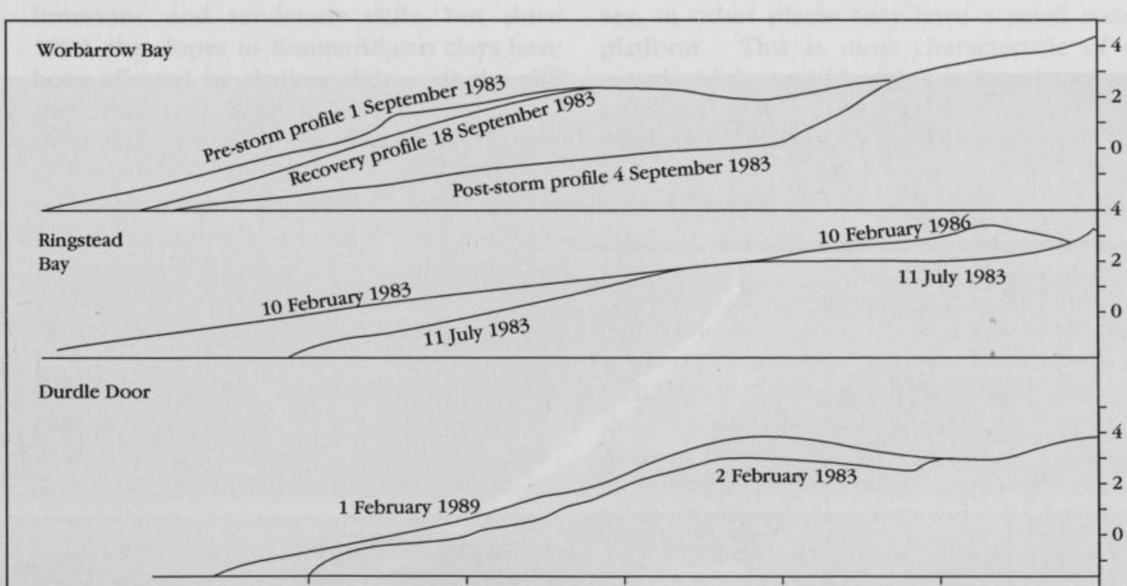


Figure 11.40 Changes in shingle beach profiles in Worbarrow Bay, Ringstead Bay and Durdle Door. Erosion and recovery of beaches can take place over very short timescales. These profiles are based upon monthly resurveys of sample transects. (After Heeps, 1986.)

can be as steep as 30°. These steep profile areas are the most exposed and are composed of the coarsest and best-sorted sediments (Arkell, 1947; Heeps, 1986).

The cliffs at Gad Cliff are very exposed (Figure 11.42), and are characterized by an upper cliff predominantly in Portland Stone and a vegetated lower slope on the Portland Sand and the Kimmeridge Clay. There are large boulder accumulations at the cliff foot that very effectively protect the cliff. The boulder fields continue offshore for several hundred metres. East of Gad Cliff, the cliffs decrease in height towards Kimmeridge Bay. Low (*c.* 15 m) steep cliffs in gently dipping clay and shale strata stand behind a very well-developed series of wide platforms of Kimmeridgian cementstone (Figure 11.43; Arkell, 1947). The form is mainly controlled by geological structure.

Between Hounstout and St Aldhelm's Head, the coast is dominated both by high (to 130 m) limestone-capped cliffs and large undercliffs. Areas of very rapid change (Figures 11.44–11.47) occur via landslides wherever the Kimmeridge Clay occurs at sea level. At Chapman's Pool, a small semi-circular cove has developed between headlands formed of large boulder accumulations resulting from the landslides. Small platforms are exposed in the intertidal zone in Chapman's Pool. The stepped profile described by Brunsden (1973) for west Dorset is found here in both active and passive landslide areas, although in the latter there has been widespread degradation of many of the clay slopes. Flat-topped ridges of Portlandian limestone and sandstone lying on Kimmeridge Clay are truncated by landslides of various (but as yet undetermined) ages. The strata dip southwards and seawards at about 2° and there is a fault to the east of St Aldhelm's Head. There are three major spatial units within this landslide region (May, 1997a).

1. An active landslide at Hounstout cliff distinguished by clay slopes, frequent rockfalls, mudslides and widespread gullying. Vegetation occurs mainly on the back-tilted, rotational slip blocks. There is much standing surface water and during rainfall, runoff is high. There are many small, frequent, mass-movements. These landslides have been particularly active since about 1970 (Jones, 1980).
2. At Emmet's Hill, the landslides are not particularly active today, although back-tilted blocks of limestone and sandstone indicate significant past movements. The hollows between these blocks are filled by debris from localized rockfalls and by downwashed sand and clay. Small trees (10 m high) grow in some of these

Figure 11.41 Looking eastwards across Worbarrow Bay, showing the outcrop of Purbeck and Portland beds at Worbarrow Tout, the Wealden cliffs undergoing erosion and the shingle storm-beach with cusp development. (Photo: V.J. May.)

Figure 11.42 Gad Cliff. The upper cliff is in Portland Stone; the debris and boulder field, well-vegetated by scrub, lies on Portland Sand and upper Kimmeridge Clay. The boulder beach has alternating ramparts and baylets related to differential erosion (associated with bedding in the Kimmeridge Clay) and debris toes. (Photo: V.J. May.)

hollows. Most movements of the 20th century have been rockfalls from the high limestone and sandstone cliffs, but since 1990, the slopes in Kimmeridgian clays have been affected by shallow slides. At the cliff foot, there has been increased marine erosion.

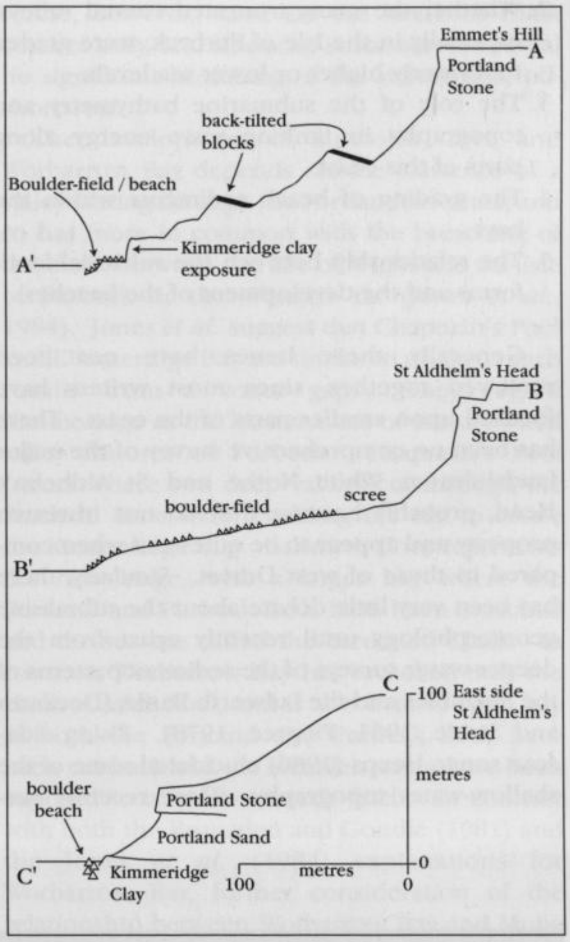
3. St Aldhelm's Head is marked by a wide undercliff cloaked by boulders. There are a number of large debris fans produced by both natural processes and quarrying, the latter during the 19th and 20th centuries. Back-tilted blocks appear to be absent. Small (1970) suggested that these slopes may have formed under frost action during the Quaternary Period, but there is as yet no firm evidence to support this view.

East of St Aldhelm's Head, the undercliff narrows rapidly and the cliffs become lower in height, but steeper. Immediately east of St Aldhelm's Head, although there is no true undercliff, a steep grassed slope on the Portland Sand lies below the steeper upper cliff of Portland Stone. Boulders protect this from erosion in a similar way to the cliffs at Gad Cliff. To the east towards Durlston Point, the cliffs are steep. Sometimes they plunge directly into the sea, in other places they have a small coastal platform. This is most characteristic of the mouths of the small hanging valleys that characterize this coastline at Winspit, Seacombe and Dancing Ledge. At the mouth of Seacombe, the cliff face truncates a former stream valley infilled by angular debris. The slope-over-wall form of much of this coastline has been modified in places by lynchets (man-made terraces). The lower part of the slope is often cloaked by angular debris, the thickness of which appears to deepen downslope. Some slope sections are well-exposed where quarrying has cut into the slope. The valleys are floored by angular debris. At Seacombe the valley is flat-floored almost to its mouth, whereas the Winspit valley is distinguished by a series of incised meanders. Although these features are not parts of the original GCR site, they are related to the origin of the coast and the extent to which it is a contemporary feature or a reworking of earlier forms.

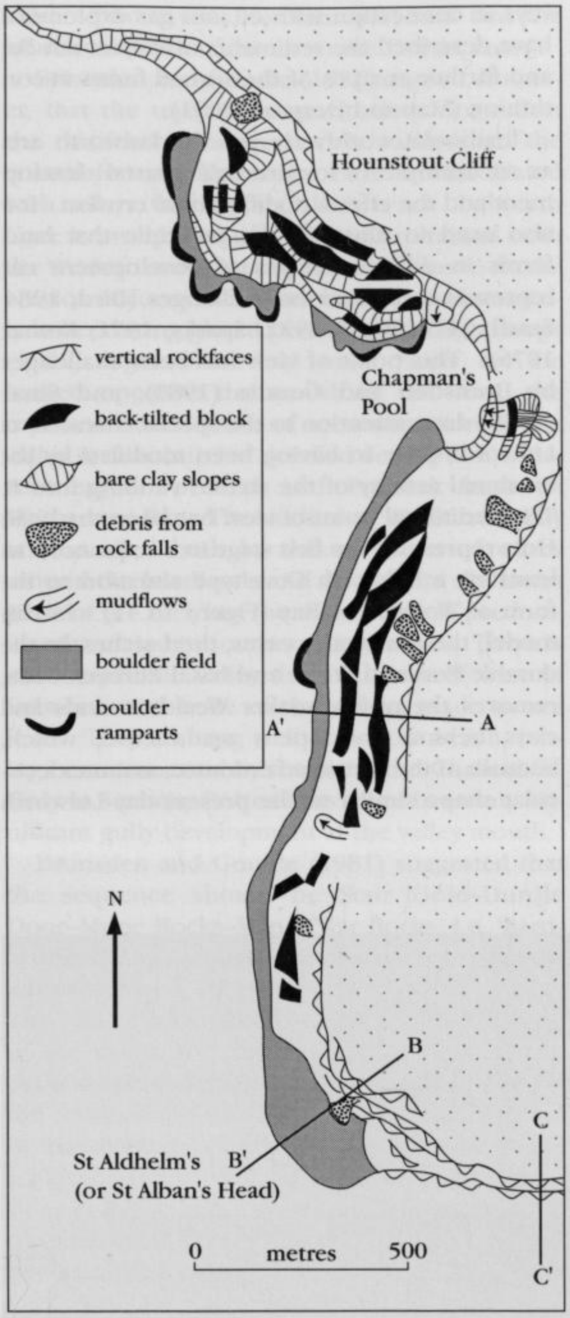
At Durlston Head, the coastline changes direction to become a transverse one. Much of the cliff has been affected by landslides; they recur

Figure 11.43 Broad Bench, a Kimmeridge shale platform, showing block removal at platform edge. (Photo: V.J. May.)

Figure 11.44 The cliffs between Hounstout and St Aldhelm's Head are characterized by large landslides of as yet undetermined age. Large Portland Stone boulder fields provide protection against wave attack, but where they are absent shoreline retreat produces steep lower cliffs. (Photo: V.J. May)



▲**Figure 11.45** Emmet's Hill and St Aldhelm's Head cross-profiles. For locations of profiles A–C, see Figure 11.47.



◂**Figure 11.46** Landslide features between Hounstout and St Aldhelm's Head. (After May, 1997a.)

sporadically. In late 1994, for example, a small slide affected the cliff to the north of Durlston Castle. Part of this cliff has now been modified by dumping of boulders in an attempt to protect cliff-top dwellings. The southern cliffs of Durlston Bay are more active than their well-vegetated characteristics imply. The northern extremity of the GCR site lies at Peveril Point, where a series of intertidal reefs reflect the synclinal tectonic structure here.

Interpretation

Five issues have been the focus of debate and research along this coastline:

1. The development of the headland–bay topography east and west of Lulworth Cove.

2. Whether the many truncated coastal valleys, especially in the Isle of Purbeck, were graded to formerly higher or lower sea levels.
3. The role of the submarine bathymetry and topography in limiting wave energy along parts of this coast.
4. The grading of beach sediments within the bays.
5. The relationship between the subaerial landforms and the development of the beaches.

Generally these issues have not been reviewed together, since most writers have focused upon smaller parts of the coast. There has been no comprehensive survey of the major landslides at White Nothe and St Aldhelm's Head, probably because they do not threaten property and appear to be quiescent when compared to those of west Dorset. Similarly, there has been very little debate about the submarine geomorphology until recently apart from the deeper-water surveys of the sediment patterns of the Shambles and the Lulworth Banks (Donovan and Stride, 1961; Pingree, 1978). Using side-scan sonar, Heeps (1986) elucidated some of the shallow-water topography. More recently surveys in connection with oil and gas exploration have described the sediments of Weymouth Bay and further analysis of the seabed forms is continuing (May and Drayson, 2001).

Textbooks worldwide use the Lulworth area as an example of longitudinal coastal development and the effects of differential erosion. It is also used to illustrate the principle that landforms in different stages of development can represent a time series of changes (Bird, 1984; Small, 1978; Ward, 1922; Sparks, 1971; Komar, 1976). This point of view has been challenged by Brunsden and Goudie (1981), and Small (1970) drew attention to the special character of Lulworth Cove in having been modified by the erosional activity of the stream running into it. The traditional point of view has been that Stair Hole represents the first stage in a sequence that leads via a Lulworth Cove-type situation to the form of Worbarrow Bay (Figure 11.41). In this model, the sea erodes caves, then arches, in the durable Portland Stone and basal Purbeck beds, removes the much weaker Wealden sands and clays behind and opens up a cove, which, because of the restricted entrance, assumes a circular shape similar to the present-day Lulworth

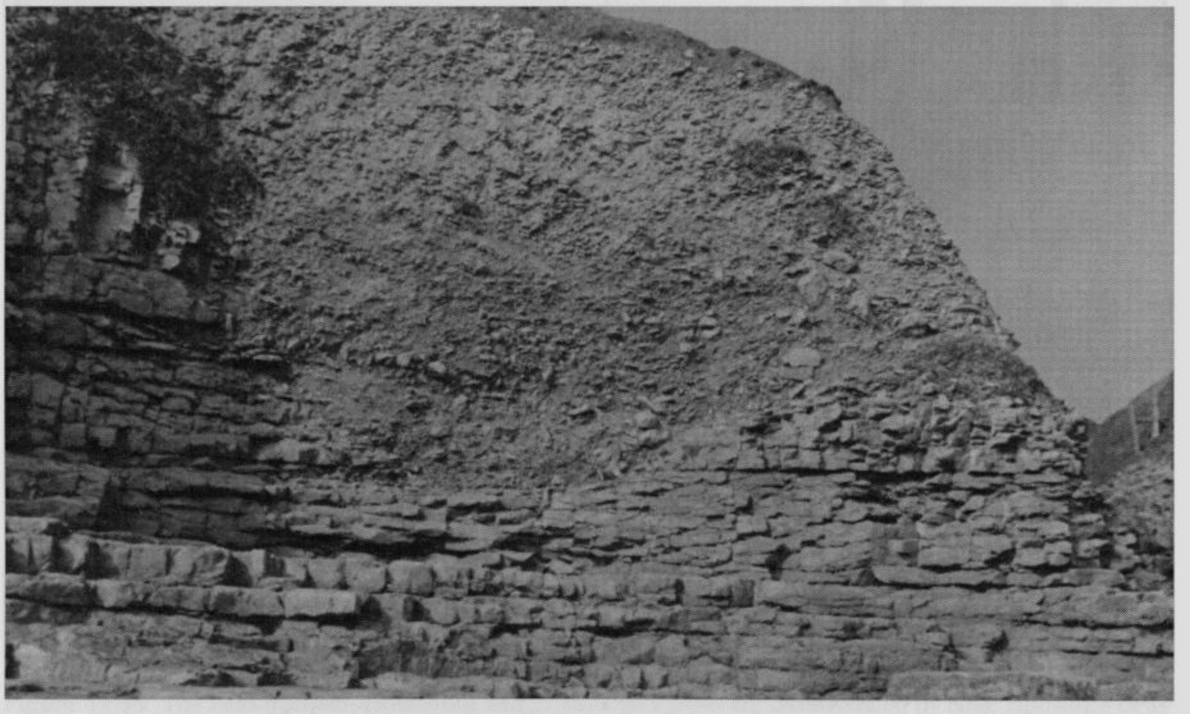


Figure 11.47 Truncated valley infill at Seacombe Valley (SY 983 785). The altitude of the valley floor is about 7 m. (Photo: V.J. May.)

Cove. Bird (1984), for example, said that the 'classic example of this is on the Dorset coast'.

Brunsden and Goudie (1981) argued, however, that the textbook scenario does not reflect the relationship between river valleys and the coastal forms. The major bays are associated with valleys, whereas Stair Hole is not. Lulworth Cove is on the line of a valley that drained both the western and eastern sides of the cove; fluvial erosion occurred when sea level was substantially lower during glacial periods. Although Heeps (1986) reported several small faults on the seabed opposite the mouth of the cove, she reported no evidence of a continuation of the valley seawards in her detailed description of the submerged Portland and Purbeck beds in Worbarrow Bay. The outline of Worbarrow Bay is controlled both by the refraction of waves around the headlands and also by the shallower parts of the reef, but the main beach is predominantly related to south-westerly waves. There is no comparable valley form in the reef west of Lulworth and none of the valleys grade to sea level. They all hang well above the beach, having been truncated by retreat of the Chalk cliffs. Only at Scratchy Bottom has there been any significant gully development at the valley mouth.

Brunsden and Goudie (1981) suggested that the sequence should be Stair Hole–Durdle Door–Mupe Rocks–Man o'War Rocks, i.e. 'barrier breaching–arch formation–stack formation as a result of arch collapse–isolated rock barriers'. The role of subaerial processes in the slumping of the sands and clays is very important, but depends on the efficiency of the sea in removing the resultant debris. The individual bays formed by the breaches merge before a true circular cove can form because their eastern and western sides collapse more rapidly than the Chalk of their backwall. Jones *et al.* (1984) consider that two small dry valleys west of Durdle Door may have formed features smaller but comparable to Lulworth as the coastline retreated. They believe that these have coalesced and are responsible for the area of water between Durdle Promontory and White Nothe. The two dry valleys between Durdle Door and Bat's Head are underlain by deeply weathered materials of periglacial origin that descend almost to present-day sea level. Gaps in the offshore reef coincide with the valleys and so it is conceivable that there were two bays here, one associated with Scratchy Bottom and the other between Swyre Head and Bat's Head. West of White Nothe, however, there are the heads of chalk combes only, and side-scan sonar surveys reveal no significant breaching of the submerged, offshore reef.

The development of Lulworth Cove and Worbarrow Bay depends on the existence of a valley cutting through the Portlandian strata, and so has more in common with the breaching of the chalk between the Isle of Wight and the Isle of Purbeck or the Western Yar (Jones *et al.*, 1984). Jones *et al.* suggest that Chapman's Pool and Kimmeridge Bay are similar in origin as each results from a water gap. They regard Kimmeridge as the least-mature of the drowned valley features of Purbeck. Chapman's Pool occurs where two deep valleys cut through the Portland Limestone, enabling the sea to erode the Kimmeridge Clay. Lulworth Cove represents the next stage, with a larger bay where the Portland and Purbeck Beds have been breached and the sea has cliffed the hardened Chalk. In contrast, Worbarrow Bay has breached only the chalk at Arish Mell, and is also a more open bay as both the Portland and Purbeck Beds have been cut back and the Wealden strata have been exposed to a south-westerly fetch. In contrast with both the Brunsden and Goudie (1981) and the Jones *et al.* (1984) explanations for Worbarrow Bay, further consideration of the relationship between Worbarrow Bay and Mupe Rocks–Mupe Bay and suggests that the origin of Worbarrow Bay is likely to be composite. The Wealden outcrop widens across the bay, exposing as Worbarrow Bay was opened up increasing lengths of weak strata to the dominant waves from the south-west. In the same way as Mupe Rocks were penetrated in the Brunsden and Goudie sequence, the reef was already breached to the east and had attained the Man o'War Bay configuration, allowing a bay to develop into Mupe Bay that would merge with the expanding Worbarrow Bay (Figure 11.48). Retreat of the coast of the Isle of Purbeck is thus controlled by four barriers to marine erosion (Jones *et al.*, 1984), the Kimmeridge shales forming the Ledges, Portland Limestone boulder beaches, in-situ Portland Limestone and tectonically hardened Chalk. The resistance of the Portland Limestone to erosion is affected by the angle of dip, with erosion and then breaching taking place more effectively with steeper dips (Jones *et al.*, 1984).

The relationship between the many truncated valleys and the cliffs and their changes has

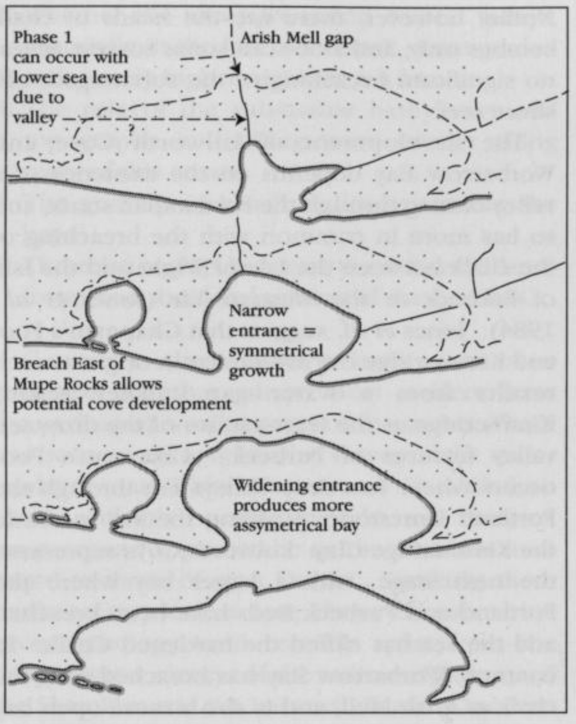


Figure 11.48 Development of Worbarrow Bay from initial flooding of former valley along line of Arish Mell gap. The breakthrough in the vicinity of Mupe Rocks develops in early stages in similar way to that at Stair Hole. Subsequently, both Worbarrow and Mupe bays merge with increasing asymmetry as the eastern shoreline of Worbarrow Bay becomes more exposed to waves from English Channel.

attracted attention. Between Durlston Point and Furzy Cliff, 23 valleys are cut by the coastline. Of these, 11 have been truncated by the sea, four having permanent or occasional waterfalls and six valleys reach the coast by a gorge or deeply incised valley. At Lulworth and Arish Mell, partially drowned valleys are cut in the Portland beds. Four occur in the Portland and Purbeck beds, seven in the Kimmeridge Clay, and eight in the Chalk. Three are in the clays of the Wealden or Oxford Clay. The rates of present-day cliff retreat in the clays are such that the lack of incision of streams could be attributed to their inability to keep pace in their downcutting with the retreating cliffline. In the Chalk, the dry valleys are truncated by the sea in a similar way to those in other Chalk sites at the Seven Sisters (Sussex) and between Kingsdown and Dover (Kent; see GCR site reports). In the Isle of Purbeck, the valleys at Winspit and Seacombe both have floors that are not graded to present-day sea level. Both have deeply incised rock valleys that are filled by angular debris. At Seacombe a cross-section of this infilled valley is exposed in the cliff face (Figure 11.47), whereas at Winspit it has mostly been excavated by a series of incised meanders. The coastal slopes around these valleys have a slope-over-wall form. The lower cliff cuts across the lower part of the 'slope', which is characteristically cloaked by angular debris.

There are several possible interpretations for this combination of forms. The first is that the truncated valleys are a result of the varying ability of coastal streams to keep pace with cliff retreat in different lithologies. A second possibility is that the present-day cliffs are being reworked, having been cloaked by angular slope deposits during the last glacial period. The last 6000 years have been a time during which debris has been removed, with some erosion of the cliffs and some removal of the valley infill, especially in the Winspit valley where the stream has a higher discharge. This is comparable to present-day retreat rates of about 0.03 m a^{-1}. Both to the west of Winspit and at Gad Cliff, there are high cliffs that have a vegetated slope below a vertical face. Both show very little sign of retreat and owe their present stability largely to the protection afforded by boulder accumulations at the foot of the slope. In the absence of specific dating of the slopes it is possible to only speculate on the period over which they have had this form beyond the last couple of centuries. Offshore from Gad Cliff, there are large accumulations of boulders that can be interpreted as resulting from cliff retreat during a lower or rising sea level and which would reduce the energy of waves approaching this coastline. The large landslide at St Aldhelm's Head appears to be covered in parts by angular debris, which Small (1978) suggested may have a periglacial origin. Most of the evidence for reworking of an earlier coastline is circumstantial (Mottram, 1972), in the absence of dated sediment. However, it is difficult to explain many of the forms of the hard-rock coastline without considering this possibility.

Heeps' (1986) study of the submarine topography and the additional interpretation of later side-scan sonar records reveal an intricate morphology in which boulder accumulations, submerged platforms, ridges and troughs are cloaked by a veneer of sand, shell and coarser sediments (May and Drayson, 2001). There is some evidence from repeated seabed surveys that the veneer is subject to slight changes, rather than major changes. Some of the larger boulder fields are associated with cliffs where collapse carries boulders of sufficient size to the shoreline. That these areas of boulders continue offshore argues that they have been active over much of the period of Holocene sea-level rise and of present-day sea level. Much more work needs to be done on this part of the site, but there are few other areas where the nature of a cliffed coastal zone has been investigated from the cliff top to the usual seaward limit of wave action.

Concerning the question of the grading of sediments within the bays, Arkell (1947) commented on the tendency towards coarser sediment in the centres of the bays. Heeps (1986) confirmed that this is generally the case and put forward reasons for the wave-sorting that occurs. She also demonstrated that most of these bays are closed sediment-cells, in that the enclosing headlands and the offshore barriers prevent outward sediment transfers of particles other than clays in suspension. Inward transfers also appear very limited because of the nature of the barriers and their height. The beaches, therefore, depend solely upon the addition of shingle from the erosion of the cliffs and the longevity of flint already within them. Measurement of the sedimentary product of rockfalls from the Chalk (May and Heeps, 1985; Heeps, 1986) shows that most chalk is broken down into pebbles, and then shelly fragments and fines within a few months of the original cliff collapse. Boulders of limestone and sandstone that are upwards in size of 0.5 m may survive for longer in the intertidal and shallow water zone on the seabed if they are large and resistant enough.

The relationship between subaerial processes and the development of the beaches has attracted attention in the literature. Although Bray *et al.* (1992) indicate that the net direction of sediment transport in Weymouth Bay is from east to west, this is true only of the offshore transport routes where the sediments become finer westwards. Along the shoreline itself, transport is largely confined within the bays, where reversals of drift as well as localized onshore–offshore movements occur regularly. Of the shingle beaches, only one, east of White Nothe, appears to be formed mainly of contemporary material. All the others contain substantial quantities of well-rounded, oxidized flint clasts together with varying volumes of angular and subangular, grey flint. Davies' (1972) view that flint nodules are readily quarried from the Chalk platforms and so provide an 'abundant source of pebbles' (p. 118) is not borne out in the short term by Heeps' (1986) examination of the beaches in this area.

In summary, strike-aligned coasts are comparatively unusual in Britain. Most wave attack here is from the south-west, obliquely to the coastline, with a potential fetch of several thousand kilometres at the eastern end of the site. However, because the location is microtidal, much wave energy is concentrated in a narrow band at the base of the cliffs. A submerged rock reef along part of the coastline reduces wave energy inputs to the beaches, and sediment is conserved within each bay.

Conclusions

The Dorset Coast GCR site contains some of the most visually appealing coastal landforms in Britain. It is a world-renowned example of a longitudinal coastline, includes such classic landforms as Worbarrow Bay and Lulworth Cove, and provides an excellent field observatory for studies of cliff, beach and nearshore geomorphology. Lulworth Cove and Durdle Door are also known worldwide for their scenic value. The scientific importance of this site comes from the variety of erosional features, the debate about the sequence of their development, the linked submarine forms, the closed sediment systems of the bays, and the very large number of truncated (hanging) valleys.

This coast is a complex one, whose interpretation ranges from the analysis of the present-day processes to the unravelling of the longer geomorphological history of the site. The classic landforms have been studied at scales that often ignore the detail of smaller features and localized processes but these combine with the larger forms to suggest a complex and lengthy history for this coastline.

It is an unusual coast in having been the focus of both traditional geological and geomorphological study and submarine survey that now allows the whole coastal system to be described and analysed.

This coast is also important in containing the largest set of closed sediment-cells to have been described anywhere in the British Isles. There remain a large number of sub-sites within this site that warrant more detailed examination. It is also an most important rocky coastline on account of the assemblage of forms that occur within it, from the scale of the longitudinal coast to the individual features of the seabed, beaches and cliffs. In this totality of interest, it is of international importance to coastal geomorphology.

The Purbeck coast is also the location of Britain's first Voluntary Marine Reserve at Kimmeridge, is designated as a Special Area of Conservation under the European Union Habitats Directive and includes Jurassic stratotypes. Indeed, so important is the geology and geomorphology of this coast, that this site forms part of the Dorset and East Devon Coast World Heritage Site, which was declared on account of its Earth science features of interest in December 2001.