Coastal Geomorphology of Great Britain

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Chapter 8

Sand spits and tombolos – GCR site reports

INTRODUCTION

V.J. May

Sand spits and tombolos in Britain are associated with

1. areas of wide intertidal sandflats
2. estuary mouths
3. intensive erosion of cliffs that provide copious longshore sand supplies, and
4. comparatively sheltered locations.

Typically, they are low in height: even when dunes occur on them, the main structures are only a few metres in height. They are dynamic features of the British coast, for although sandy structures have been in their present sites for many centuries, they have changed in detail, undergoing erosion, breaching and accretion. Although some are still extending, they are also often marked by narrowing and breaching of their proximal (landward) ends. The term 'sand spit' is typically used for any low ridge of sand extending from the shore across an embayment, estuary or indentation in the coast and they have a number of forms (Figure 8.1), ranging from those that cross the mouths of estuaries or bays, such as at Forvie, Aberdeenshire, or to those that form barrier islands. Some sand structures, in contrast, link hard-rock features to the mainland or to islands (for example St Ninian's Tombolo, Shetland, and parts of the Isles of Scilly). Small bay-head beaches often form as ridges deflecting small streams alongshore. Although these have been described as spits, they are often the result of shore-parallel beach ridge construction (e.g. Pwll-ddu) rather than longshore transport that

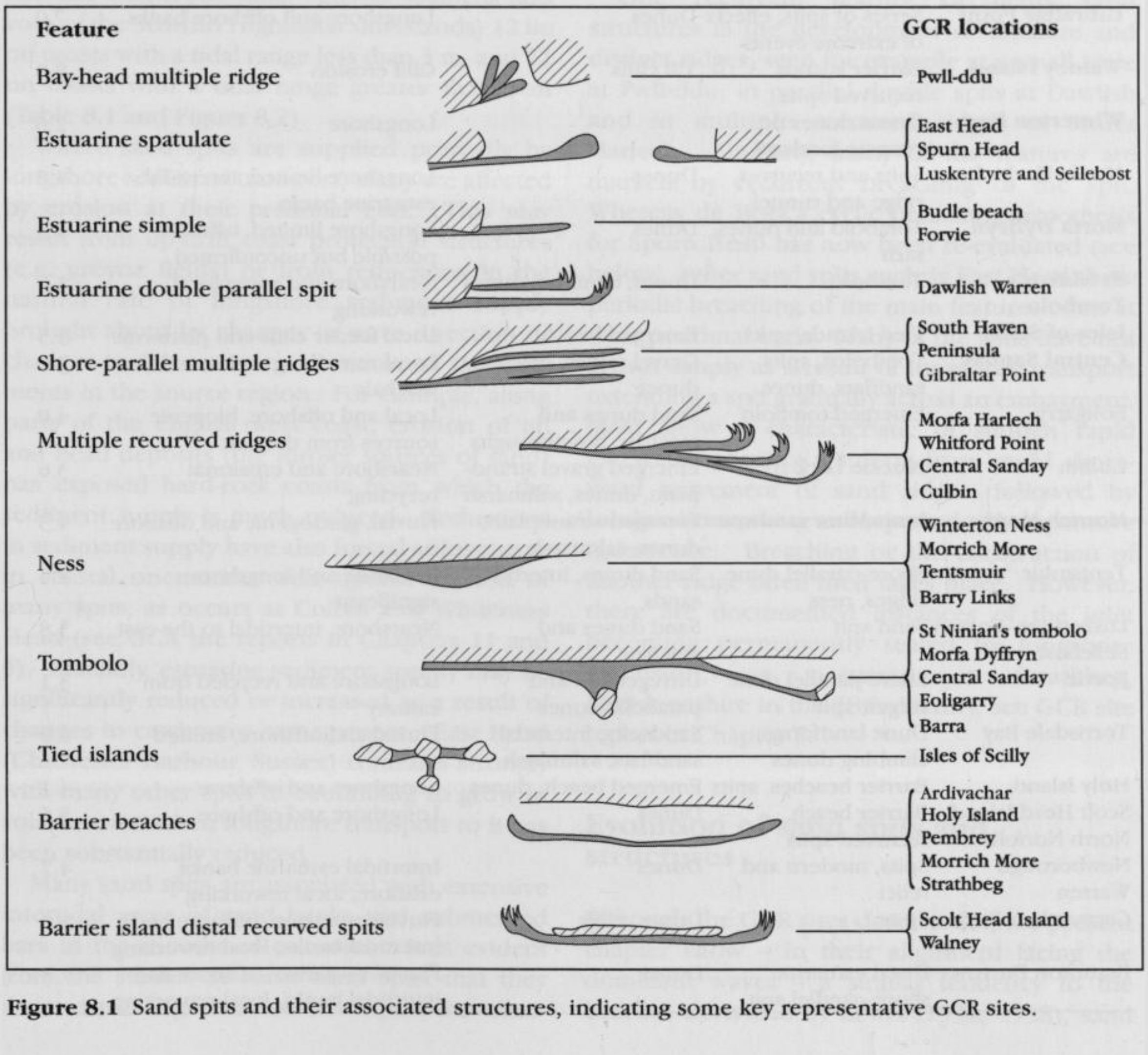

Figure 8.1 Sand spits and their associated structures, indicating some key representative GCR sites.

has extended a spit across an estuary. Some sand spits have a distal 'spatulate' form that does not display individual recurve ridges. Typically, these occur where there is a base on which the sand transported to the distal end can accumulate over a wide area. This base may be salt-marsh or mud-flats. Many spits have been built upon gravel ridges, or, in Scotland, emerged beaches as their foundation, and in some cases the presence of morainic gravels provides a basis for the distal parts of these spits (for example Spurn Head, Yorkshire and Whitford Spit,

Table 8.1 The main features of sediment sources and tidal ranges of sand spit GCR sites, including coastal geomorphology GCR sites described in other chapters of the present volume that contain important sand spit structures in the assemblage of features. Many machair sites have small sandspits – see Chapter 9. (Sites described in the present chapter are in **bold** typeface.)

Site	Main features	Other features	Present-day natural sources of sediment	Tidal range (m)
Pwll-ddu	Sand spits		Local fluvial and shallow nearshore	8.2
Ynyslas	Sand spit	Dunes	Estuarine, longshore (reduced)	4.1
East Head	Sand spit, distal dunes		Restricted alongshore: mainly from offshore banks	3.4
Spurn Head	Major spit in macro-tidal environment	Dunes	Longshore and offshore	6.4
Dawlish Warren	Sub-parallel double spit	Dunes	Intertidal banks	4.1
Gibraltar Point	Series of spits, effects of extreme events	Dunes	Longshore and offshore banks	7.0
Walney Island	Barrier islands recurved spits	Till cliffs	Cliff erosion	9.0
Winterton Ness	Linear dunes on cuspate foreland		Longshore	2.6
Morfa Harlech	Spits and recurves, ridge and runnel	Dunes	Longshore limited, intertidal estuarine banks	4.5
Morfa Dyffryn	Tombolo and dunes, sarn	Dunes	Longshore limited, offshore possible but unconfirmed	4.3
St Ninian's Tombolo	Tombolo	Dunes, climbing dunes	Nearshore and some local reworking	1.1
Isles of Scilly	Tied islands, spits	Emerged beach	Local feeder cliffs and platforms	5.5
Central Sanday	Tombolos, spits, sandflats, dunes	Gravel ridges, machair, dunes	Local reworking and nearshore machair	3.0
Eoligarry	Emerged tombolo	sand dunes and machair, bowthroughs	Local and offshore, biogenic sources from the east	4.0
Culbin	Bluckie Lock spit	Emerged gravel strand-plain, dunes, saltmarsh	Nearshore and erosional recycling	3.6
Morrich More	Innis Mhor sand spit	Emerged strandplain, dunes, saltmarsh	Fluvial, glaciogenic and offshore	4.3
Tentsmuir	Shore-parallel dune ridges, ness	Sand dunes, intertidal sands	Estuarine and longshore, significant	4.4
Luskentyre–Corran Seilebost	Sand spit	Sand dunes and machair	Nearshore, intertidal to the east	3.8
Forvie	Shore-parallel dune ridges, spit	Unvegetated and parabolic dunes	Longshore and recycled from estuary	3.1
Torrisdale Bay	Dune landforms, climbing dunes	Sandspits, intertidal sandflats, saltmarsh	Fluvial and offshore, limited	4.0
Holy Island	Barrier beaches, spits	Emerged beach, dunes	Longshore and offshore	4.1
Scolt Head Island, North Norfolk	Barrier beach, recurved spits	Dunes	Longshore and offshore	5.6
Newborough Warren	Spits, modern and relict	Dunes	Intertidal estuarine banks offshore, local reworking	4.7
Carmarthen Bay	Spits	Dunes, cliffs	Fluvial/estuarine, offshore and intertidal banks, local reworking	8.0
Braunton Burrows	Distal estuarine shore-parallel spit	Dunes	Fluvial/estuarine, offshore and intertidal banks, local reworking	7.3

Carmarthen Bay). In some cases, the spits also form the base upon which important dune systems have developed, such as in Central Sanday, Orkney or at Luskentyre, Seilebost and Gualan in the Western Isles (see GCR site reports).

According to Pethick (1984), British coastlines with a tidal range of less than 3 m are noted for their spit development. However, sand spits are not restricted to areas with low tidal ranges: spits both in sand and gravel are a common feature of the high tidal ranges of the eastern English Channel and also occur on the Scottish coast. Pethick (1984), Goudie (1990) and Goudie and Brunsden (1994) provided incomplete maps of British major spits, defining a 'major' spit as being longer than 1.5 km (Pagham Harbour being the smallest mapped). Of 34 sand spits on the British coast south of a line between the Solway Firth and Fraserburgh, (thus omitting all the machair sites with spits and the numerous small spits in sealochs and voes of the Scottish Highlands and islands) 12 lie on coasts with a tidal range less than 3 m, and 22 on coasts with a tidal range greater than 3 m (Table 8.1 and Figure 8.2).

Where sand spits are supplied primarily by longshore sediment transport, many are affected by erosion at their proximal end. This may result from up-drift coast protection structures (e.g. groyne fields) or from reductions in the natural rate of longshore sediment supply brought about by changes in wave direction or changes in the amount and nature of the sediments in the source region. For example, along parts of the English west coast, erosion of till and head deposits (the former sources of sand) has exposed hard-rock coasts from which the sediment supply is much reduced. Reductions in sediment supply have also forced adjustments in coastal orientation with updrift erosion of many spits, as occurs at Culbin and Whiteness Head (see GCR site reports in Chapters 11 and 6). Similarly, estuarine sediment supply may be significantly reduced or increased as a result of changes in catchment management. East Head (Chichester Harbour, Sussex) contrasts strongly with many other spits in continuing to grow in volume even when longshore transport to it has been substantially reduced.

Many sand spits are associated with extensive intertidal areas of sand banks and submerged bars at the mouths of estuaries. It is evident from the studies of some sand spits that they depend to a significant extent upon the transport of sediment from these areas. Sand nesses (e.g. Winterton Ness), although less common than the gravel forms, are associated with offshore shoals, but the directions and quantities of sand moving between them are uncertain.

The problem of breaching of the proximal end of spits, and the potential demise of the feature, besets the management of many other sites (e.g. Spurn Head, Hurst Castle Spit, Dawlish Warren). Although it has been argued by de Boer (1964) in relation to Spurn Head that this can be shown to be part of a natural cycle of events, at other spits it is attributable to the reduction of longshore transport resulting from cliff or beach protection works. Kidson (1963), however, suggested that many spits were dominated by erosion and were well into a final stage of development leading to their extinction. The geomorphological interest of spits thus lies partly in their potential for self-destruction.

One recurrent feature of many sand structures is the development of separate and distinct ridges, seen for example at a small scale at Pwll-ddu, in parallel double spits at Dawlish and in multiple recurved ridges at Morfa Harlech. Similarly, many of the features are marked by recurrent breaching of the spit. Whereas de Boer's cyclic breaching hypothesis for Spurn Head has now been re-evaluated (see below), other sand spits such as East Head show periodic breaching of the main features often at their proximal ends. Many of the spits have not grown simply as a result of longshore transport extending a spit gradually across an embayment. Most show a characteristic of sudden rapid extension possibly resulting from rapid shoreward movement of sand ridges, followed by localized reworking and a period of comparative quiescence. Breaching or the construction of another ridge often then takes place. However, there are documented instances of the inlet becoming permanently sealed by longshore extension, as occurred at Strathbeg, Aberdeenshire in the 18th century, see GCR site report in Chapter 7.

Evolution of sand spits and structures

Although the GCR sites described in the present chapter show – in their alignment facing the dominant waves – a similar tendency to the beaches described by Lewis (1932, 1938), sand

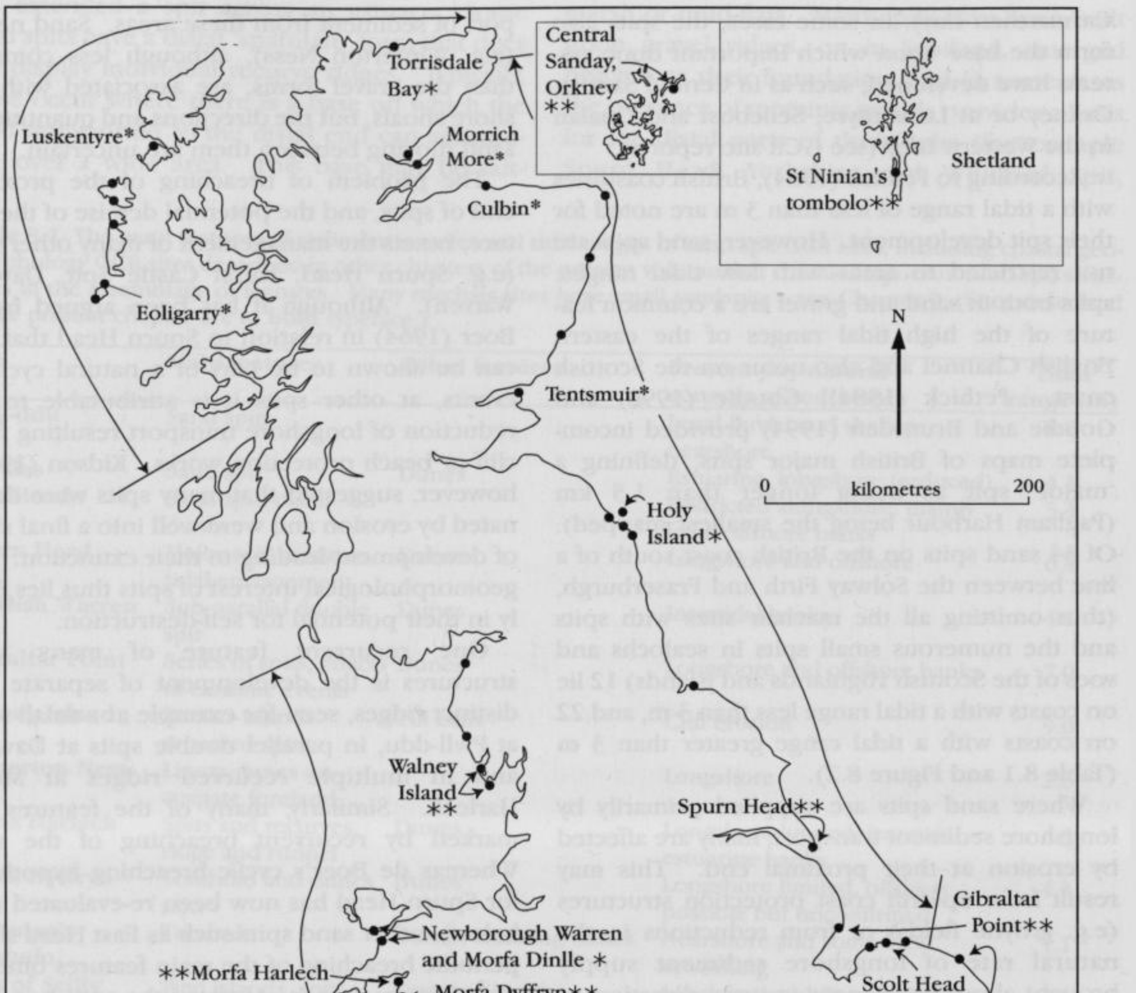

Figure 8.2 The location of sand spits in Great Britain, also indicating other coastal geomorphology GCR sites that contain sand spits in the assemblage. (Modified after Pethick, 1984).

spits are much more dependent upon the foundations provided by lag deposits from erosion of rocky coasts and in particular glacial deposits. For example, Spurn Head, Morfa Dyffryn and Whitford Burrows depend in part upon the presence of remnant Devensian moraines. Similarly, the development of transgressive gravel ridges and the erosion of coastal platforms on low-lying coasts have provided the foundations for both transgressive sand ridges and for the extension of sandy beaches across estuaries. Roy *et al.* (1994) distinguish between the flux of sediment on wave-dominated sandy coasts and the movements of barrier sand masses during sea-level changes (which include phases of transgression, stillstand and regression). Many of the sand structures described here may result from a combination of these processes. Some features, which have been regarded in the past as the result of longshore transport, appear in fact to result from the transgression of barriers. These became restricted in further onshore movement by the pre-existing topography and have been re-shaped by subsequent wave conditions. The debate in Robinson's 1955 paper about the formation of double spits at the mouths of estuaries in southern England focused on two separate processes: longshore spit development and subsequent breaching as opposed to 'frontal accretion' (as Robinson called it, which can be regarded as a form of barrier development). Sites such as East Head and Spurn Head, although of different scale, have developed as the result both of longshore sediment transport and transgression, and such origins need to be considered for other similar structures.

Carter (1988) considered the concept of the coastal cell as a framework for the long-term development of spits. In his view, spits, like all beaches, depend upon the balance between the flux of wave energy (total shoreline wave energy per unit wave crest per unit time *ECn*) towards the shore (shore-normal P_N) and along the shore (shore-parallel P_L). The angle made with the shore by the breaking wave (α_b) affects the magnitude of P_L whose spatial distribution alongshore can be mapped. Where waves break parallel to the shore, $\alpha_b = 0$ and sediment is simply transported up and down the beach. However, on a spit, the breaking angle increases rapidly around the recurve, although at the same time wave height decreases due to wave refraction. As a result, P_L remains constant except at the farthest distal curve. This implies that the spit will only survive as a long-term feature as long as there is a sufficient longshore supply of sand to maintain the longshore component of sediment transport. Few British sand spits fit this model exactly. For many, the longshore supply of sediment is interrupted either by periods of weaker, or longer-term reduction in, longshore supply and transport or by direct interruptions as a result of the construction of structures such as groynes. For example, in parts Scotland, sediment reduction and sea-level rise has led to smaller coastal cells than before, and has forced internal re-organisation of sediments, manifested by updrift erosion and downdrift accretion of spits at Culbin and Spey (Hansom, 2001). Furthermore, where spits enclose large open bodies of water, waves also affect the behaviour of the spit on its landward side and can bring about significant changes in the overall development of the spit (e.g. Spurn Head). This model also largely ignores the role of the intertidal and offshore routes by which sand is transported often with different values of P_L. For example, both Dawlish Warren and Morfa Harlech (see GCR site reports in this chapter) display different patterns of wave breaking at low water from those affecting the upper beach and the main spit form. The effects of very long-period swell, high-energy events, surges and short periods of waves from opposite directions from the prevailing waves may each provide explanations for some of the sand structures around the British coast. Once developed, many of these features are very persistent forms. Although some features have developed in their present locations during the last 1000 years, many others are built upon a foundation that is considerably older: the spits at Culbin have ancestors that span most of mid–late Holocene times.

The conservation value of sand spits and associated structures

The conservation value of sand spits and structures arises from:

1. their historical role as areas of accumulation of sediment, so providing the basis for pioneer plant species to colonize the area,
2. their links with intertidal and offshore banks and bars as part of the sediment transport system,
3. their association with dunes and ecology,

4. their role in narrowing the entrances to estuaries and providing protection for the development of extensive mud flats and saltmarshes in the resulting shelter,
5. their place in coastal education and research. Three of the longest-running continuous coastal university research programmes are based on major sandy structures at Spurn Head (University of Hull), Gibraltar Point (University of Nottingham) and Scolt Head Island (University of Cambridge) since the 1920s, and
6. the fact that many remain largely undisturbed by artificial structures and development.

Sand spits are also very important:

1. in providing sheltering structures at the mouths of navigable estuaries,
2. in their role as natural coast protection structures providing low-cost protection to low-lying coastal land.

Despite their dynamism, many of these structures are of considerable age, with documentary and archaeological evidence for their existence and growth reaching back over many centuries. Some of the structures have built up during the historical period and so it is possible to assess the ways in which these features have resulted from environmental changes within their coastal and river settings. Some of the sand structures are important assemblages of many geomorphological forms that demonstrate the different ways in which sandy coasts adjust to differences in sediment availability and changes in climate and oceanic conditions. Their conservation value derives from their present-day features and in demonstrating the ways in which the coastal environment adjusts to change can be observed and their persistence understood.

In this chapter the site reports are ordered so that the more simple forms precede the more-complex ones: Pwll-ddu, Ynyslas and Spurn Head are simple spits with spatulate form, lacking recurves; Dawlish Warren, Gibraltar Point and Walney Island are double/subparallel spits with some recurves; Winterton Ness has a cuspate form; Morfa Harlech is a large cuspate form with extensive recurves, Morfa Dyffryn a simpler cuspate-like spit, more accurately described as a tombolo; St Ninan's Isle displays classic tombolo forms, and the Isles of Scilly tied islands; and Central Sanday has an assemblage of features.

PWLL-DDU, GLAMORGAN (SS 580 970–SS 570 963)

V.J. May

Introduction

The coastline of south Wales is characterized by dramatic cliff scenery and some nineteen beach and dune systems between Merthyr Mawr Warren at the mouth of the Ogmore River in the east, and Broomhill Burrows near the mouth of Milford Haven in the west. They fall into three broad categories:

1. large spit and beach systems extending across the mouths of estuaries (for example Laugharne Burrows, Carmarthen Bay)
2. extensive low hindshore dunes that rest upon bedrock (e.g. Broughton Burrows, Carmarthen Bay)
3. small bay-head beaches and dunes, usually with an easterly aspect (e.g. Oxwich Bay, Glamorgan).

Pwll-ddu is the smallest and least well-developed representative of the final category. Its importance arises from its place within this group of sites. It contains a wide variety of coastal forms within a very small area: shore platforms, slope-over-wall cliffs, other cliff forms, and sand and shingle beaches. In addition to this important assemblage of features, the site includes a series of small shingle and sand ridges on the west side of Pwll-ddu Bay that have diverted a small stream to the east (Strahan, 1907; Ward, 1922; George, 1933; Steers, 1946a; Guilcher, 1958; Potts, 1968).

Description

Pwll-ddu (see Figure 8.2 for general location) is among the smallest of the coastal sand accumulations along the Welsh coastline, and, unusually, has not developed any significant dunes (Potts, 1968). There are three main morpho-sedimentological units within the site:

1. former and present-day sea cliffs on the eastern side of the bay,
2. sand and shingle beach and ridges, and
3. slope-over-wall cliffs and shore platforms at several levels on the western side of Pwll-ddu Bay.

The cliffs within this site appear to be receding

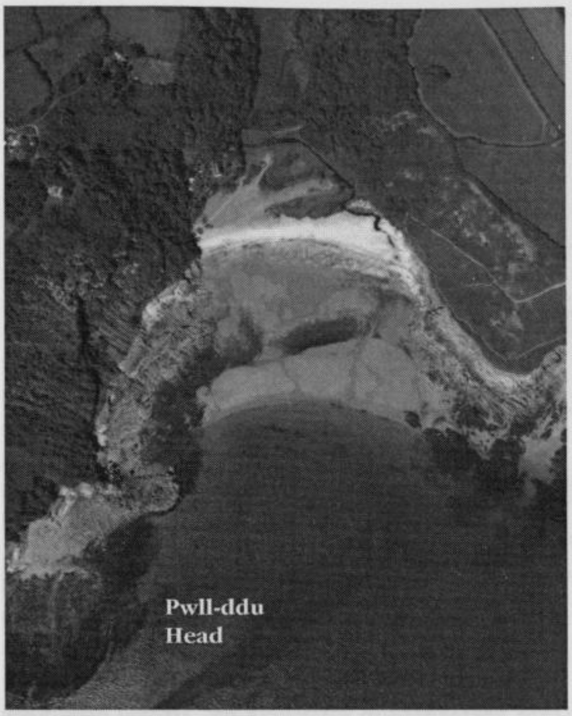

Figure 8.3 Pwll-ddu Bay. See Figure 8.4 for explanation. (Photo: Cambridge University Collection of Aerial Photographs © Countryside Council for Wales.)

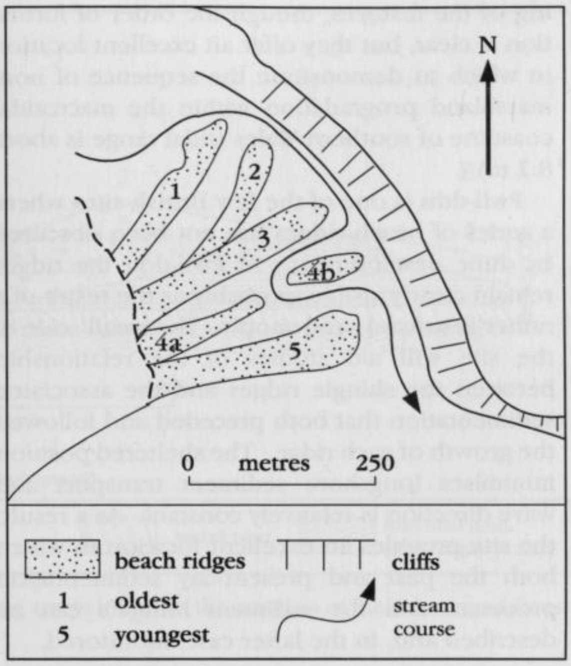

Figure 8.4 The succession of beaches at Pwll-ddu Bay: (1) oldest, (5) youngest (as yet undated). 1, 3 and 5 are the higher ridges that dominate the site.

very slowly, as there are well-preserved remnants of former platforms and slopes that are cloaked with periglacial scree material. On the eastern side of the bay, the foot of the slope has been trimmed, probably by a combination of marine and fluvial erosion. The small stream that flows along the eastern side of the valley appears to have occupied this position throughout the period of progradation that led to the growth of the beach ridges. The most landward (oldest) ridge is aligned SW–NE and successive ridges swing progressively to an alignment closer to the present-day position of the shoreline. The fourth ridge (4a,b on Figure 8.4) is formed of two separate features, the eastern one diverting the stream across the valley. Ridges 1,3 and 5 are the highest and longest ridges (Figures 8.3 and 8.4). They have changed little in appearance since the early part of the 20th century (Strahan, 1907).

Interpretation

Guilcher (1958) suggested that when a beach is prograding, several successive ridges may be left, and he described Pwll-ddu as a very fine example of this. Many dune sites rest upon sand and shingle ridges (e.g. Oxwich Bay and Morfa Harlech GCR sites), but the very limited development of dunes at Pwll-ddu means that this early stage of growth in bay-head beach–dune systems has not been buried by dunes. The site is sheltered from storm waves approaching from the south-west, and is aligned towards the SSE. Apart from waves generated from the south-east or south within the restricted fetch of the Bristol Channel, all other waves are refracted around Pwll-ddu Head. Sediment sources are limited. The stream entering the bay generally carries only fine-grained materials, longshore transport of sand is restricted by both Pwll-ddu Head and the headland to the east, and little is known about possible seabed sources.

The Pwll-ddu valley is possibly an advanced stage of a ria in which the rock floor, which lies below sea level, has been cloaked by infilling assisted by the blocking action of the growing beach ridges. As sand and shingle was deposited in the bay, the ridges appear to have migrated into the valley and aligned more towards the north-east as a result of refraction (Figure 8.4). Later ridges have protected the older ridges, overriding them in some cases. There is no dating of the features, though the order of formation is clear, but they offer an excellent location in which to demonstrate the sequence of non-marshland progradation within the macrotidal coastline of southern Wales (tidal range is about 8.2 m).

Pwll-ddu is one of the few British sites where a series of beach ridges has not been obscured by dune development. At Pwll-ddu the ridges remain clearly visible, probably as the result of a rather restricted sand supply. The small scale of the site will aid studies of the relationship between the shingle ridges and the associated sedimentation that both preceded and followed the growth of each ridge. The sheltered position minimises longshore sediment transport and wave direction is relatively constant. As a result, the site provides an excellent location in which both the past and present-day sedimentation processes and the sediment budgets can be described and, in the latter case, monitored.

Conclusions

Pwll-ddu is important because of its generally unmodified series of small beach ridges. Seen in the context of bay-head beach and dune development on western coasts, it is valuable for comparative purposes, because it represents an early phase in the development of these features. The site, although small, contains a wide range of coastal forms: shore platforms, slope-over-wall cliffs, sand and shingle spits.

YNYSLAS, CEREDIGION (SN 605 919)

V.J. May

Introduction

The spit at Ynyslas, north of Borth (see Figure 8.2 for general location), forms part of the Dyfi National Nature Reserve. (Watkin, 1976). It is a good example of a sand spit built upon a gravel base, but it is also important because it is possible to show that a similar feature has been in existence here since about 6500 BP (Wilks, 1977, 1979). The southern part of the spit is dominated by a shingle ridge upon which there has been some accumulation of sand. The central part of the spit is dominated by vegetated dunes, whereas the northern, dista, end forms a low sandy flat upon which there are some small vegetated dunes. The behaviour of the spit seems to be related not only to the general tendency in Cardigan Bay for sediment to move northwards, but also to the patterns of water movement within the lower Dyfi estuary (Dobson, 1967; Chesnutt and Galvin, 1974; Williams *et al.*, 1981).

Description

The spit extends about 3 km from the southern side of the Dyfi estuary. The main line of the spit is formed by gravels that are exposed at high-water level along the southern part of the spit. They are veneered with sand on the northern part of the spit, but re-appear north of the distal end of the spit at Cerrigypenrhyn (SN 611 953). The dunes form a narrow fringing ridge about 100 m in width that extends northwards (from SN 606 927 to SN 605 938) whence it swings more and more south-eastwards towards a former distal end at SN 615 936. Gravel and shingle are exposed both as a fringing high-water deposit and as a large ridge extending into the estuary (Figure 8.5). Former recurve and swale topography is exposed in this area. The northern part of the spit also extends further into the estuary as an area of dunes up to 9 m OD. Parts of the dunes have been eroded by recreational trampling. Extensive sandflats east of the dunes, parts of which are used for car parking, provide a reservoir of sand for the dunes and the estuarine sandbanks. The Afon Leri flows into the estuary today through a canalized course. However, in the past, before drainage works were carried out in this area, the Afon Leri entered the sea at Ynyslas Turn. This may indicate that there was insufficient sediment transport alongshore to divert the stream mouth farther north.

Offshore from the distal end of the spit, there are intertidal banks, including the South Banks, which cause reflection and refraction of waves approaching the spit from most directions. Tidal range at springs is about 4 m and tidal streams can reach 0.5 m s^{-1} near the shore (Williams *et al.*, 1981). Under storm-wave conditions from the south-west, wave energy is focused at the distal end of the spit, whereas with north-westerlies the distal end is less affected and wave energy is concentrated on the shingle ridge farther south (Williams *et al.*, 1981).

Submerged forest beds (best observed

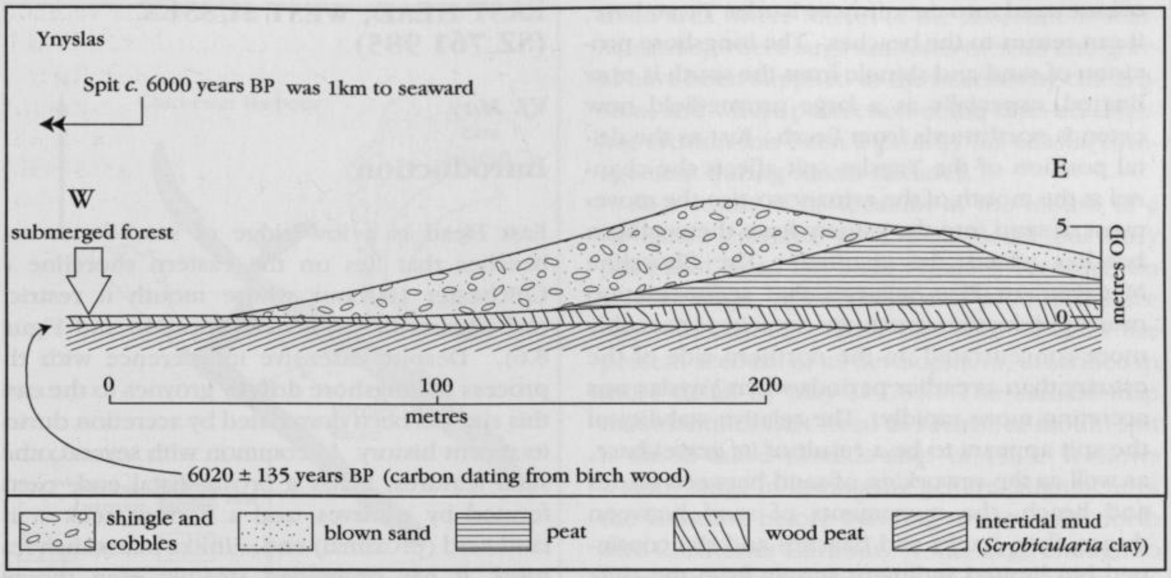

Figure 8.5 A east–west beach section at Ynyslas. The large arrow indicates the position of the submerged forest beds. (After Campbell and Bowen, 1989.)

between about SN 604 924 and SN 604 933) have been exposed on the foreshore as the spit gradually moved about 150 m landwards during the 19th century (Campbell and Bowen, 1989). The basal peat was dated at 5898 ± 135 BP (Godwin and Willis, 1961) and birch *Betula* wood *in situ* near the base of the forest bed was dated at 6026 ± 135 BP (Godwin and Willis, 1961). Borth Bog, a very important Quaternary site, lies to the east of the spit and owes its development largely to the protection afforded by the spit and its predecessors.

Interpretation

The earliest investigations of the Dyfi estuary focused on the estuary itself and its saltmarshes (Yapp et al., 1917; Richards, 1934; Burd, 1989). The sedimentary history of the estuary, including the behaviour of the area around the spit have demonstrated the longevity of the sedimentation within a sheltered microtidal estuary (Shih, 1991, 1992).

The shingle ridge was established during the Holocene transgression (Williams *et al.*, 1981), when coastal conditions stabilized sufficiently about 6500 BP to allow the creation of a sand and shingle spit that extended northwards from the cliffs at Borth (Wilks, 1979). This earliest position of the spit is thought to have been about 1 km seawards of its present position (Campbell and Bowen, 1989). Interpretation of the stratigraphical, radiocarbon and pollen data from the submerged forest beds and Borth Bog suggests that since about 4000 years BP the spit has been maintained by shingle supplied by the eroded material from the cliffs at Borth and has moved landwards across the submerged forest and peat at about 0.25 m a^{-1}. Churchill (1965), however, suggested that this coast had been elevated by about 3 m since 6500 years BP by isostatic uplift. This could have the effect of increasing the positional stability of the spit by reducing the effects of wave energy inputs.

Detailed analysis of wave and tidal conditions and the associated changes in its form have shown the feature to be relatively stable in recent years (Williams *et al.*, 1981). Although storm conditions are destructive, the spit recovers quickly, with the dunes acting as a sand reservoir. On this site, as elsewhere (for example Hurst Castle Spit, Hampshire and Ainsdale, Lancashire), surges at high springs play a particularly important role in modifying the form of the coast. The storm of 11 November 1977, for example, saw a surge of 1.1 m that co-incided with high spring tides. Unlike Ainsdale (see GCR site report), Ynyslas rests on a relatively permeable base and so there is a greater chance of the intertidal sands drying and being blown onto the dunes. In contrast, sand blows around the northern end of the dunes over the wide, distal sandflats, where current action across the intertidal and shallow submerged banks may re-distribute sand into the offshore banks. From here, it can return to the beaches. The longshore provision of sand and shingle from the south is now limited, especially as a large groyne-field now extends northwards from Borth. Just as the distal position of the Ynyslas spit affects the channel at the mouth of the estuary, so also the movement of sand into the estuary from the northern beaches affects the channel. The Shoreline Management Plan suggests that sedimentation causing reduction in estuary capacity is probably more concentrated on the northern side of the estuary than at earlier periods when Ynyslas was accreting more rapidly. The relative stability of the spit appears to be a result of its gravel base, as well as the reworking of sand between dunes and beach, the movements of sand between dunes, flats, banks and beaches and the continued but limited sediment supply from the cliffs to the south, although this is now restricted by groynes at Borth. The role of the estuarine water movements and their interaction with waves need to be investigated more fully.

There are similarities with the cobble ridge at Westward Ho! (see GCR site report in Chapter 6) where the ridge has also moved landwards and exposed older sediments in the intertidal area, but Westward Ho! lacks the critical evidence of the age of the feature, which is provided by dates from Borth Bog and the submerged forest. Ynyslas is especially important because of the links between local coastal processes and other aspects of Quaternary geomorphology.

Conclusions

This shingle and gravel ridge – or a similar feature – may have existed here or slightly offshore since about 6500 BP and has become the base for dunes at the mouth of the Afon Dyfi. It is of particular interest because of its age and effects on other features of the local landscape. It is not always possible to demonstrate that a beach has maintained much the same position at the mouth of an estuary while migrating landwards. Although dates for the origin of the spit have been suggested they allow only a limited estimate of the average rate of migration (between 0.15 and 0.25 m a^{-1}). The probable age of the Ynyslas spit, and its similarities with the feature at Westward Ho!, make it important for our understanding of the timescale over which many features of the British coast have developed.

EAST HEAD, WEST SUSSEX (SZ 761 985)

V.J. May

Introduction

East Head is a low ridge of sand-dunes and beaches that lies on the eastern shoreline of Chichester Harbour whose mouth it restricts (see Figure 8.2 for general location and Figure 8.6). Despite extensive interference with the process of longshore drift by groynes to the east, this site has been dominated by accretion during its recent history. In common with several other such features, it has a broad distal end, partly formed by recurves, and a narrow neck at its landward (proximal) end. Unlike many such features, it has prograded steadily even though there has been breaching of its neck. Today its volume is probably greater than at any previous period. Its development appears to be associated with changes in the intertidal 'delta' at the mouth of Chichester Harbour. Shingle ridges, which successively change orientation from NNW–SSE towards NE–SW, form the base of the dunes, which attain about 3.5 m in height. The area of the spit, which declined steadily during the 19th and early 20th centuries, has increased since 1972. Cartographic evidence suggests that a comparable period of progradation after progressive lateral migration of the spit also occurred during the 18th century. Like many of the shingle spits of the central south coast of England, East Head is paired with a spit on the opposite side of the estuary, but it has received less attention until recently. Searle (1975) outlined its key features and particularly the effects of occasional recent breaches in its form. Examination of the cartographic evidence during the last 200 years coupled with more recent aerial photography suggests some unusual features about the development of the spit, not least because what has appeared to be an erosional phase is in reality a depositional one.

Description

East Head is narrow (under 100 m) at its landward end but widens at its distal end to over 400 m. It is backed by saltmarsh onto which it has encroached. To seaward the beaches extend into intertidal areas known as 'The Winner' and 'East and West Pole Sands'. The coastline of

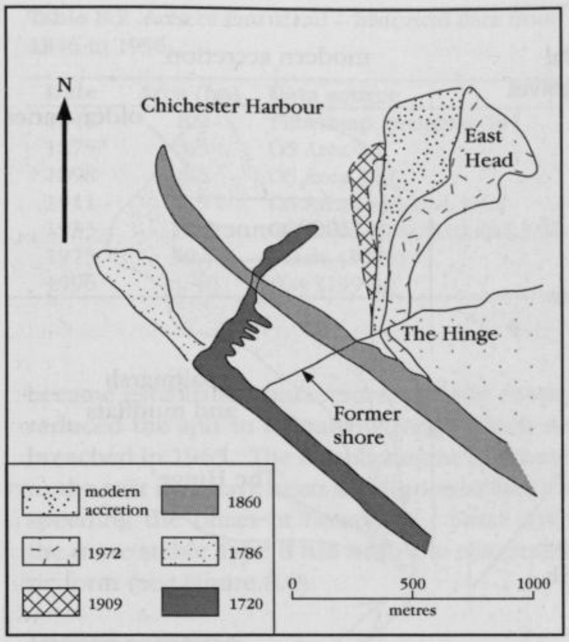

Figure 8.6 Historical changes at East Head. (After May, 1975.)

which East Head in part is low-lying with occasional low cliffs cut into drift deposits, including substantial quantities of gravel and sand. The shoreline is characterized by a flat and wide sand beach resting on a clay platform. Narrow banks of shingle mark the boundary between land and sea. The relatively weak Tertiary and Quaternary sediments offer little resistance to marine erosion, and consequently much of the eroding shoreline has been protected by walls. There is almost no part of the coastline of this site from which groynes are absent. Selsey can claim to have had one of the most rapidly eroding coastlines in the British Isles: over 9 m a^{-1} between 1932 and 1951 (Duvivier, 1961). At all points between East Head and Pagham, the shoreline during the past century was dominated by erosion. This erosion provided a major source of shingle feed to the beaches to east and west, until it was gradually cut off by coast protection works (Duvivier, 1961; May, 1964). In contrast to this pattern of continuous erosion to the east of East Head, the shoreline of Hayling Island on the western side of the mouth of Chichester harbour was much more stable and between 1875 and 1960 its beaches on Hayling Island grew seawards in direct contrast to those on East Head. The rate of change was not as great between 1933 and 1960 (May, 1966). Thus East Head lies in an area where retreat of the shoreline is characteristic, where large amounts of sand and gravel have been supplied to the beaches by cliff erosion, and where protection of the cliffs undergoing erosion has been a priority for coastal management during recent decades.

As a result of its location at the mouth of a navigable entrance to a once small but busy port, East Head has been regularly recorded on various maps, plans and charts produced since the 16th century. These form the basis for the present account of its development, described in more detail by May (1975). The earliest map that identifies East Head as a harbour mouth spit is the so-called 'Armada map' of 1587. It shows a stony ridge following the general alignment of the coastline before bending towards the north into Chichester Harbour. It was large enough to form the base for a small defensive battery. By the time of Avery's 1721 chart, the spit had a complex distal end and several recurves. The probable position of the spit in about 1720 is shown in Figure 8.6. The northward-trending part of the spit was breached sometime between 1720 and 1759 when the recurve is shown as broken. Between 1759 and 1846, the spit retained a similar shape with a wide distal end connected to the mainland by a narrower neck from which the remnants of the main recurve project northwards. Comparison of the surveys of the 18th century with the Tithe Map of 1846 suggests erosion of the whole shoreline except for the distal end of the spit. By 1875, all evidence of the earlier spits had disappeared except for a low ridge that projected from the northern side of the shingle ridge below high-water mark. This probably represents the remnants of the most northerly part of the 1721 recurve. From 1875 onwards, the spit swung towards the position now occupied by vegetated dunes. Vegetation was first mapped on the plans of 1911. The present alignment was first recorded in the OS 1:2500 survey of 1933, and has altered little since then.

Breaches have been frequent; the latest occurred in 1963. The 18th century maps reveal a breach in a north-trending ridge, and Ramsey (1934) reported several breaches during the early part of the 20th century. In 1963 a breach separated the two distinctive parts of the spit.

1. The proximal ridge, which has a similar alignment and dimensions to all the spits mapped since 1887. Although the ridge has moved

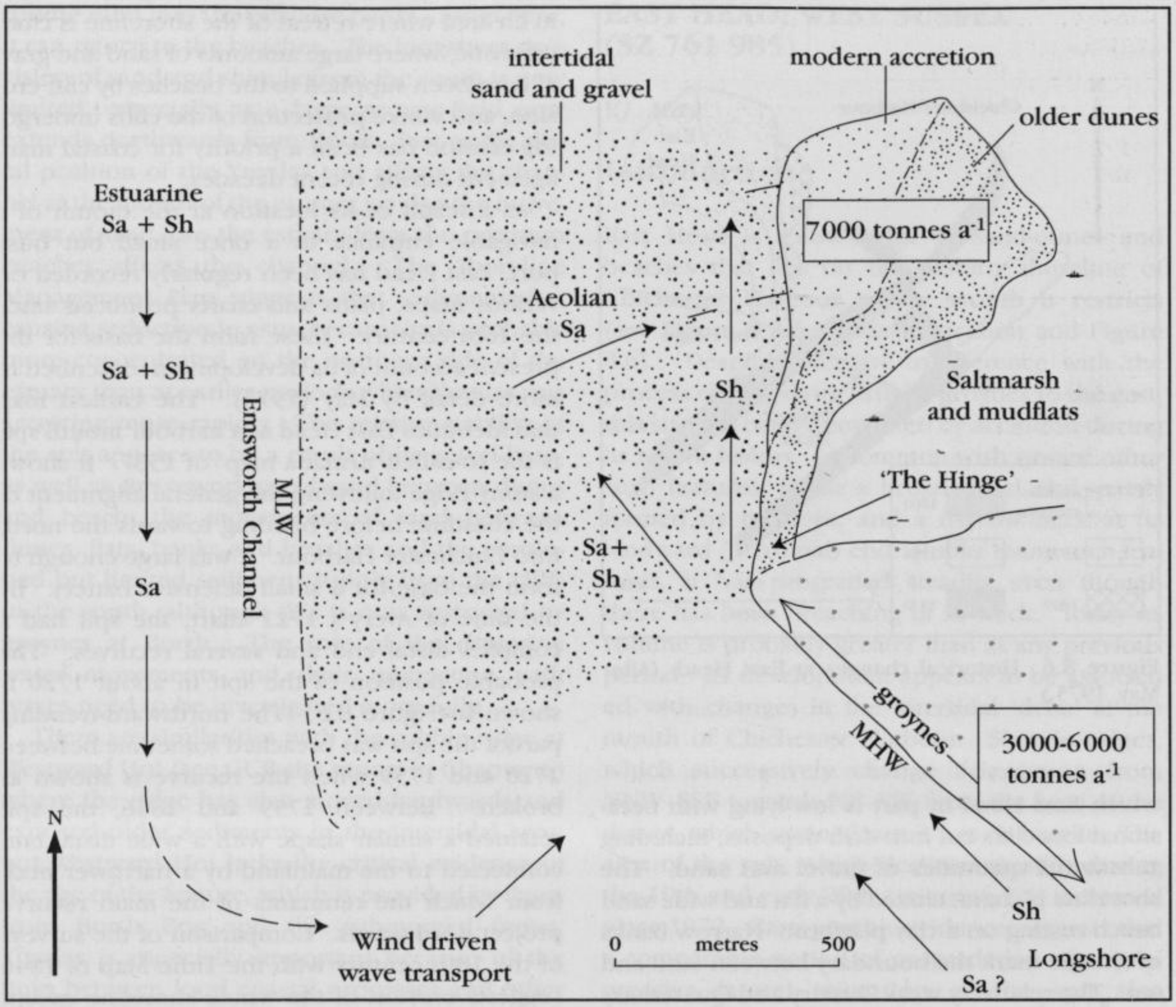

Figure 8.8 Schematic diagram showing the key features including sediment transfers at East Head. (Sa = sand; Sh = shingle). Sand and shingle transported out of Chichester Harbour may be added by wave and aeolian action to longshore transport from the south-east. This may account for the excess of sediment reaching the spit over longshore transport. (After Harlow, 1982.)

landwards, it has retained much the same plan and has rotated only slightly towards the north.

2. The distal end, which is roughly triangular in shape. In contrast to the proximal ridge, the outer spit swung rapidly towards the north-east during the early 20th century.

The differential movements of the two main parts of the spit have produced a 'dog-legged' feature in which the distal end is set back from the shoreline of the landward end. There appear to be two 'hinge points' on the spit, one at its junction with the mainland and known locally as 'the Hinge', the other about halfway along the spit. Interpretation of aerial photographs taken since 1963 shows that there has been a steady growth of sand ridges in front of the older vegetated ridge. The spit has a larger area now than at any previous time since the mid-18th century (Table 8.2). The Hinge has moved landwards with erosion of the cliffs to its east, but it has not moved alongshore.

The form of the spit appears to have been been of two types that appear to alternate. The first (Type A) is a long narrow ridge, the second (Type B) a narrow ridge turning landwards leading to a broadly triangular distal end. Thus Type B appeared first and was replaced by Type A by the mid-18th century. This was subsequently breached. From about 1760 to about 1850, Type B predominated, whereas Type A was the dominant form until 1933 and was breached several times (Ramsay, 1934). Type B then

Table 8.2 Area of East Head – historical data from 1846 to 1996

Date	Area (ha)	Data source
1846	8.9	Tithe map: property 541
1875	5.3	OS Area 83
1898	6.5	OS Area 310
1911	2.3	OS Areas 310 and 310a
1933	17.5	OS Areas 309a, 310 and 310a
1975	30.7	Searle (1975)
1996	*c.* 40	May (1997b)

became established once more. Steady erosion reduced the spit to its narrow form, which was breached in 1963. The establishment of groynes to the east may have been an important factor in speeding the onset of breaching. Since 1963, the more stable Type B has been the characteristic form (see Figure 8.6).

Interpretation

East Head owes some of its present-day form to the coast protection activities that have taken place both within and beyond the boundaries of the site. The National Trust has taken steps to ensure that the dune system is stabilized and that the vegetation, in particular, is not seriously disturbed. After the 1963 breach, brushwood and small scrub windbreaks were constructed to aid sand deposition (Searle, 1975). Harlow (1982) outlined the more substantial coast protection works that have been undertaken to the east of the site, at Medmerry and Bracklesham, and their effects upon sedimentary processes. Both activities have been intended to retain sediment within specific parts of the coastline. Whereas the National Trust action has been concerned with the retention of sand and shingle within the site, the action of coast protection authorities to the east has been designed to prevent (or at least retard) movement of sediment away from other sites towards East Head (Hooke *et al.*, 1996). Shingle has tended to move northwards along the spit at East Head, but has not been replaced by shingle arriving from the east as happened in the past. Harlow (1982) estimated that about 7000 $m^3 a^{-1}$ of shingle was added naturally to the front of East Head between 1975 and 1978.

After 1965, there was a marked increase in sand seaward of the old vegetated ridge of the dunes (Figure 8.6) and there was also considerable intertidal accretion that provided a source of windblown sand for the dunes. Harlow's (1982) sediment budget analysis for this coastline confirmed that this sand supply and the changes in intertidal areas of East Pole, West Pole and The Winner are related.

This site is unusual among small estuary-mouth spits in that it continues to grow even though the main longshore sediment source has been curtailed by extensive groyne-fields. It has been viewed as an erosional site by its managers, although the overall volume of sand and shingle has increased. The reason for this is that much of the sediment added to it has so far accumulated on the intertidal banks at the mouth of Chichester Harbour. Recent changes in the position of the spit have tended to assist progradation by making both wave and wind transport from the intertidal area perpendicular to the shore and dunes.

This site is also important because of the juxtaposition of shingle beach, spit, dunes and saltmarsh. A similar assemblage is found at Gibraltar Point, Lincolnshire, but East Head is smaller and in a different tidal and current environment. It has undergone considerable anthropogenic modification, as measures have been sought to manage and preserve the dune system. The shingle beach processes seem to have been independent of the management activities. The site is an excellent example of beach dynamics in circumstances where, despite interference with longshore transport, the planform of the sediment cell is adjusting towards a new dynamic equilibrium with changes in sediment availability and alterations in wave direction. As a result, the shoreline has swung back towards its earlier north-west–south-east alignment. The intertidal area is a mobile sediment store and forms part of a transport system by which sediment crosses the mouth of an estuary (Harlow, 1982). Progradation of the intertidal area provides a source of sediment for the beach and thence the dunes.

At a regional level, the contrast between East Head and the shingle spit at the mouth of Pagham Harbour, West Sussex, is an important one. The Pagham site lacks sand and dunes and has well-developed shingle ridges and fulls. The lack of sand is mainly a result of the limited volume in the intertidal area seaward of the spit. East Head has a shingle base, but its dunes owe their development very largely to the presence of intertidal sources of sand. In addition, East Head is on a windward shore in contrast to the lee position of the Pagham site. Together, the two features are important sites that help to elucidate the way in which spits have developed at the entrance to shallow-water estuaries.

East Head contrasts strongly with many other spits in continuing to grow in volume even when longshore transport to it has been substantially reduced. The problem of breaching of the proximal end of spits, and the potential demise of the feature, besets the management of many other sites (e.g. Spurn Head, Hurst Castle Spit, Dawlish Warren, see GCR site reports). Although breaching can be shown at some spits to be part of a natural cycle of events, in many other cases it is attributable to the recent reduction of longshore transport resulting from cliff or beach protection works. East Head is a rare example of continued progradation and a total increase in volume in an area of rising sea level and an increasing frequency of storm surges. This appears to arise from two related effects: the re-alignment of the spit to the dominant waves, that is, to face more towards the south, and a substantial local supply of intertidal sediment.

Conclusions

East Head is a small, growing, mixed sand and shingle spit upon which low dunes have developed. Unlike many such features, it has increased in size over recent decades, despite the reduction of longshore movements of beach material towards it from the cliffs undergoing erosion in Bracklesham Bay. Maps made during the past five centuries show considerable variation in its growth and decay with an important exchange of sediment between the spit and intertidal areas and the spit itself. Nourishment from the intertidal banks at the mouth of Chichester Harbour has been very important in the continued growth of East Head. It demonstrates well the need to conserve both the shoreline and the intertidal zones that are linked to it.

SPURN HEAD, YORKSHIRE (TA 420 130)

V.J. May

Introduction

The sand and shingle spit of Spurn Point or Head lies on the north side of the mouth of the River Humber (see Figure 8.2 for general location), together with an area of till and alluvium to the north. The northern part of the site is formed by low till cliffs that are being eroded at rates in excess of 2.5 m a^{-1} and which feed sediment to the spit. The spit extends for about 5.5 km south-westwards across the Humber estuary, mainly as a narrow feature about 150 m in width but widening at its distal end to over 350 m. Its maximum altitude reaches about 9 m OD, but for much of its length it rarely exceeds 6 m.

De Boer (1963, 1964, 1967, 1968, 1981) argued that the spit has been characterized by recurring 250-year cycles of partial washing away and re-growth (Figure 8.8a). The Institute of Estuarine and Coastal Studies (IECS, 1992) challenged this, suggesting that the present-day morphology of the spit results from 19th century construction work that followed a number of breaches of the spit in the 1840s (Figure 8.8b). The comprehensive documented history of the site arises both from the recorded losses of land and villages and the regular need to relocate lighthouses marking the entrance to the Humber (e.g. Smeaton, 1791). There is no spit of comparable form and length to Spurn Head in a macrotidal environment in the British Isles or probably in Europe. The tidal range in the lower Humber estuary reaches 6.4 m.

Description

The GCR site includes both the spit itself and a cliffed area of till and alluvium to the north-east of Kilnsea. Along the seaward side, the very low cliffs expose sections of Devensian till and alluvium and occasional patches of peat and tree remains. Kilnsea Warren, which forms the northern end of the spit proper and extends a little over 1 km southwards to the narrow neck, is a flattish area between 5 m and 6 m OD, mostly covered by marram *Ammophila arenaria* and sea buckthorn *Hippophae rhamnoides*. The coast changes its alignment from NNE–SSE off How Hill to north–south at the southern end of Kilnsea Warren. At the southern end of High Bents at the curving neck of the spit, a further 0.8 km farther south, the sea coast faces almost south-east. At this point, the narrow neck, only about 30 m wide between high-water marks yet rising to 9 m OD, has been greatly modified by management activities. The remainder of the peninsula is very nearly straight for over 3 km,

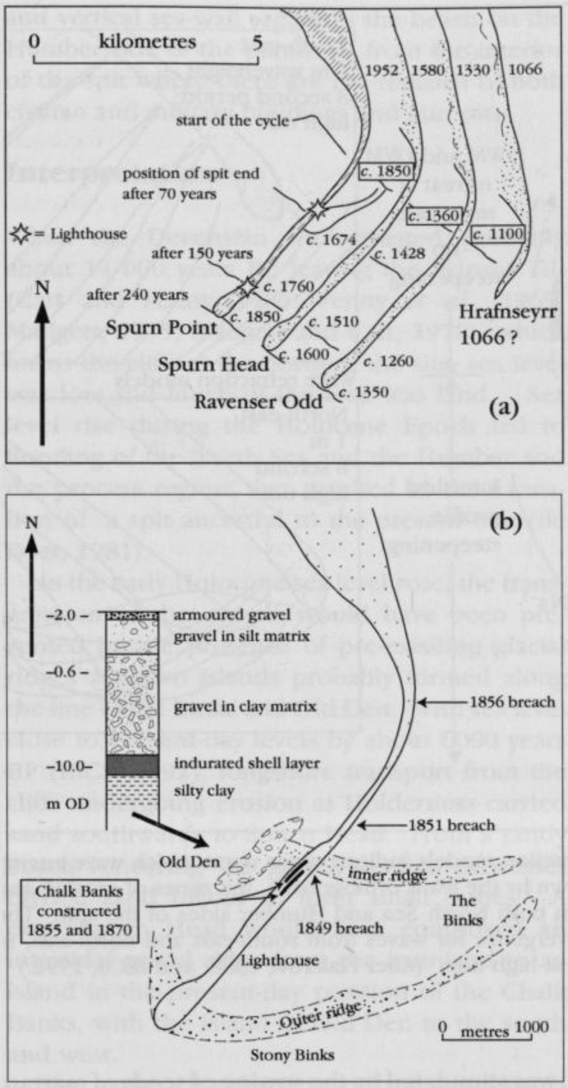

Figure 8.8 (a) The cyclical evolution of Spurn Head as envisaged by de Boer (1964). Over a period of about 240 years, the spit extends, beginning to develop a spatulate distal end after about 150 years. The neck of the spit is breached and a new cycle of spit growth begins. (b) The key features and 19th century development of Spurn Head. The log shows the sediments underlying Old Den. (After IECS, 1992.)

and is aligned approximately north-east–south-west. It consists of irregular ridges of sand dunes, usually highest on the North Sea coast, and intervening hollows. The foreshore on the Humber side of the peninsula consists of mudflats with patchy cord-grass *Spartina anglica* as far south as the Chalk Banks (Figure 8.8b). Farther south, the muddy shingle of Old Den contrasts with a wide beach of fine-grained sand that extends almost to the tip, commonly built into a ridge and runnel beach, with the ridges curving across the beach. Four hundred metres offshore in the Humber, beyond a shallow muddy channel ('Greedy Gut'), lies 'Old Den', now a shoal of muddy shingle submerged by every tide. In the 17th century it was an island with dunes and vegetation. The area of most vigorous dune growth lies near a shorter jetty, where the prevalent south-westerly wind carries sand from the wide beaches on the Humber side. These dunes increased in height by about 6 m between 1960 and 1974.

Near the tip of the peninsula is an arcuate system of shoals, the Stony Binks, which branch off seawards at a tangent. This complex appeared to de Boer (1964, 1968) to be a shoal system related to the ebb tidal stream running past the point where it has scoured a deep hollow (depth at least 24 m) immediately off the tip. IECS (1992) show that the Binks lie along the line of an arcuate ridge of glacial till (about 15 m below present HWMOST), which extends seawards of Spurn Head north-eastwards along the line of the Binks (Figure 8.8b). A second till ridge about 2.5 km to the north follows a similar curved path running beneath Spurn Head (at about 6 m below HWMOST) near the Chalk Banks and co-incides with the position of the Old Den. During the breach of 1849 this ridge was exposed as a basal sill to the breach. The glacial ridge at the Point is overlain by 15 m of sand, gravel and cobbles. The gravels are exposed along the line of the Binks and the Old Den.

Three cores in the area of Kilnsea Warren to the north of the spit passed through sand and gravel, or through silt and clay with silt bands: all ended in clay at depths of 18 m below the surface (IECS, 1992). Whereas as far south as the Chalk Banks, cores passed from sand and gravel into clay at depths of 10 m to 12 m from the surface, i.e. –4 m to –6 m OD, cores to depths of 18 m in Spurn Warren ended in sand, gravel and boulders. A core taken in 1971 on the foreshore near the lifeboat station near the spatulate tip (TA 398 110) passed from sand and gravel into a firm sandy, silty clay, possibly the Skipsea Till, at between 10.5 m and 12 m from the surface (–12.5 m to –14 m OD) and into Chalk at about 28.5 m from the surface (–30.5 m OD) (IECS, 1992).

During the 17th, 18th and 19th centuries, the low ground between Kilnsea and How Hill at the narrow northern neck of Spurn Head was a part-

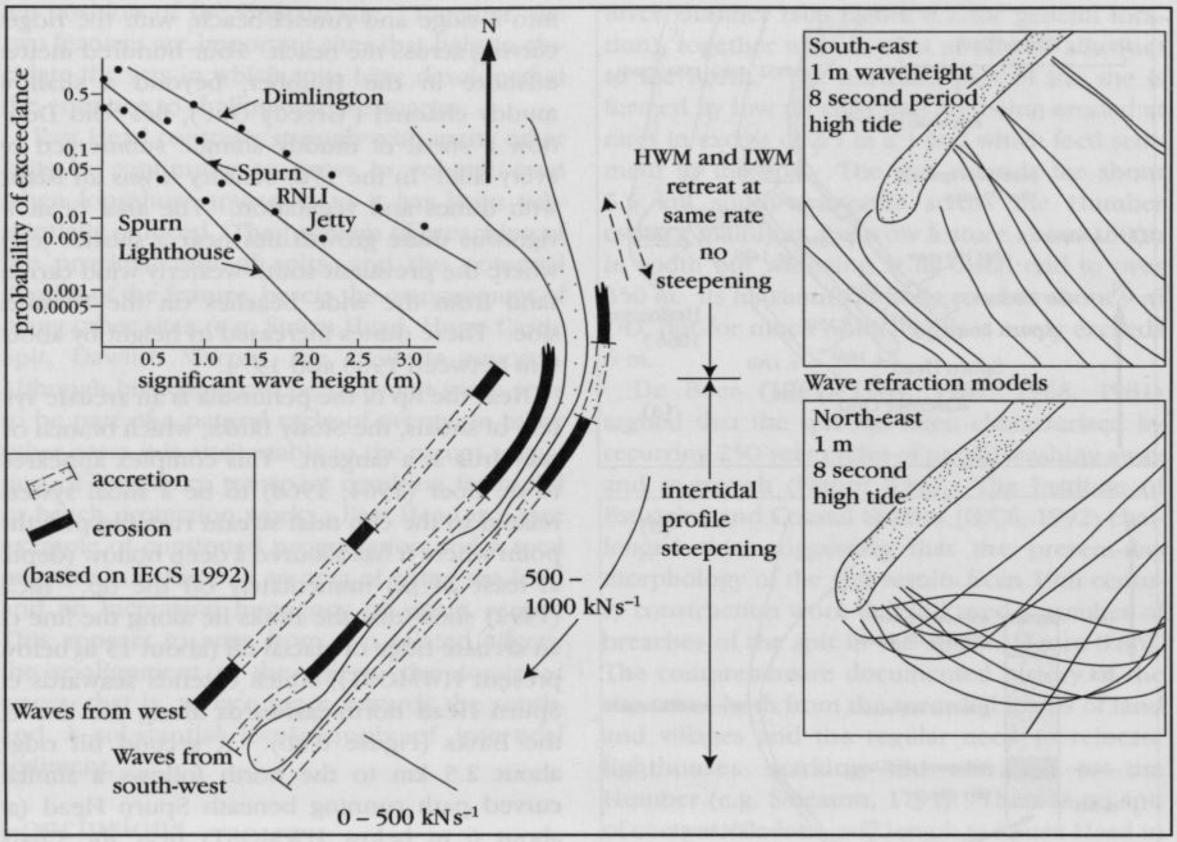

Figure 8.9 Active processes at Spurn Head. Wave-refraction models indicate areas upon which wave energy concentrates. With waves from different directions (shown by the wave orthogonals), the zones of erosion and accretion change, giving rise to possible breaching from both North Sea and Humber sides of the spit. The wave-refraction models show wave convergence and divergence for waves from south-east and north-east, in both cases for waves 1 m-high, of period 8 seconds and at high tide. (After Halcrow, 1988; and IECS, 1992.)

ly vegetated wave-swept bank of sand and shingle. During the 18th century ballast-diggers removed gravel and cobbles mostly from this area of the neck. Up to 50 000 tons (*c.* 51 000 tonnes) per year were removed, exceeding the natural rate of removal by up to seven times (IECS, 1992). The selective removal of the larger material greatly reduced the natural gravel foundation of the neck of the spit, weakening it substantially.

The Chalk Bank lies across the site of the great breach that opened in December 1849, which attained a width of 460 m and a depth of 5 m at high water before it was closed in 1855. The dunes in this section remain lower than elsewhere. A series of groynes at 250 m intervals were constructed between 1864 and 1926 and revetments were added about 1884: stakes and wattling were placed along the Humber (west) side, and blocks of chalk dumped. Dune growth was stimulated by the sowing of seeds of marram *Ammophila arenaria* and by thatching, and the surface may have been raised even higher and graded when the Spurn–Kilnsea railway was built around 1915. The neck widened by almost 40 m between 1846 and 1878 (IECS, 1992). The irregular river margin consists of the remains of the bank by which the breach was first closed in 1855: the straighter Chalk Bank was built in 1870. An area of saltmarsh between these banks is connected to the Humber by a tidal creek at the north-eastern end. The seaward side was strengthened by concrete revetments from 1942 onwards: these are now collapsing in places.

Spurn Head, from the lighthouse south-westwards, has been much affected by the establishment of the lifeboat station, by lighthouse construction, and by military fortification. The effects of fortifications are most concentrated within the spatulate tip of Spurn Head. A high and vertical sea-wall separates the beach on the Humber side of the peninsula from the interior of the spit where there are the remains of both civilian and military buildings and gun pits.

Interpretation

When the Devensian ice retreated probably about 14 000 years BP, leaving the Skipsea Till (Catt and Penny, 1966; Penny *et al.*, 1969; Madgett, 1975; Madgett and Catt, 1978), which forms the cliffs at the north of the site, sea level was low and much of the area was land. Sea level rise during the Holocene Epoch led to flooding of the North Sea and the Humber and the process regime that resulted in the formation of a spit ancestral to the present one (de Boer, 1981).

As the early Holocene sea level rose, the transgression of the gravels would have been prevented by the presence of pre-exisiting glacial ridges and two islands probably formed along the line of the Binks and Old Den. With sea level close to present-day levels by about 6000 years BP (IECS, 1992), longshore transport from the cliffs undergoing erosion at Holderness carried sand southwards to Spurn Head. From a sandy beach veneering the gravel, aeolian processes carried sand inland to form small dunes. A proto-Spurn Head would have comprised an intertidal gravel ridge from the mainland to an island in the present-day position of the Chalk Banks, with the island of Old Den to the south and west.

The earliest historical record of a peninsula occurs in the 7th century AD and four predecessors of the present-day feature may have succeeded each other at the mouth of the Humber (de Boer, 1964). Hydrographical conditions at the mouth of the Humber in the 16th century were probably similar to those of the present time (de Boer and Carr, 1969; de Boer, 1973; de Boer and Skelton, 1969). A series of breaches reduced Spurn Head in the 1850s to a string of small islands according to the Admiralty Chart of 1852. Thereafter, the peninsula was maintained by artificial defences against erosion and thus differs from its predecessors (de Boer, 1981).

The earlier development of Spurn Head, as described by de Boer (1964), combined extension of the peninsula by growth at the tip and a westwards retreat of the spit as a whole. The breaches on which de Boer based his 250-year cycle occurred in 1360, 1600 and 1849. The first 'breach' occurred when Ravenser Odd (in the vicinity of the present-day Chalk Banks) was abandoned after 60 years of continued erosion. IECS (1992) noted the co-incidence of the erosion of Spurn Head with the flooding of the Broads, attributing both to the 12th and 13th century sea-level rise, and speculated that it is this rather than the over-lengthening hypothesized by de Boer that accounts for the abandoning of Ravenser Odd. According to de Boer, the present-day peninsula developed after its predecessor had been breached about 1608 (de Boer, 1963, 1964, 1967; de Boer and Carr, 1969). The evidence for the 'breach' of 1600 is disputed by IECS (1992), which contradicts the view that the island, Old Den, came into existence when the predecessor of the present-day spit was breached around 1600 (de Boer, 1963, 1964, 1968, 1981; de Boer and Carr, 1969). The Old Den is clearly portrayed on maps of 1540 and so the view that it originated as a result of the breach must be questioned. Subsequently, the spit grew rapidly southwards to reach the position of the present-day lighthouse by about 1750. Since at least 1290, it had ended at the Chalk Banks. IECS considers that this rapid extension may co-incide with fall in sea level from the mid-17th to mid-19th centuries, which may have resulted from the 'Little Ice Age'. The intertidal gravel beaches between the two till ridges would have been exposed, allowing sand accumulation and dune building. As a result the sand supply to the Old Den dunes was reduced. They gradually eroded during the 17th and early 18th centuries and, by 1750, Old Den had been reduced to an intertidal gravel mound.

Remarkably, the 1953 storm surge failed to breach the peninsula, though causing some damage, and a comparison of the peninsula's condition in 1849 and 1953 is instructive. Before 1849, little if anything had been done to keep erosion in check. The neck of the peninsula was bare of dunes and wave-swept at high spring tides. This condition had become more pronounced since the beginning of the 19th century, and it appears that waves broke across the neck of the peninsula and carried with them beach material that would otherwise have been moved south. The spatulate tip of the peninsula was attacked by waves from both the sea and the river side, and reduced to a strip little wider than the rest of the peninsula. The broader tip at present is the result of accretion on the Humber (west) side of beach material carried round the tip, and when this supply is cut off the tip becomes attenuated.

A combination of several factors appears to have caused the 'breach' of 1849, including the selective removal of gravel and cobbles from the neck, and the loss of intertidal and aeolian sand supplied on the western side of the spit. Before 1808, when the North Channel was finally closed, it carried sand and fine-grained gravels during the flood tide into the channel and beyond. Aeolian transport carried sand from the banks not only to the western side of the spit but also along the entire estuarine shoreline of the Bight. Aeolian transfer is of the utmost importance to the western shoreline sediment budget, especially in the vicinity of the Old Den (IECS, 1992). The 1849 breach (de Boer, 1964) occurred sufficiently far south for the effects of wave erosion on the seaward side to be added to wave erosion of the river side, and far enough along the spit to be exposed to wave erosion in the lower Humber produced by north-westerly gales. The residual effects of riverside accretion farther south prevented the whole of the distal end of the spit from being swept away in such conditions: the results of the storm surge were thus limited to the opening of the breach across the neck.

The 1849 breach, once formed, developed into a tidal channel with streams of possibly 3–3.5 m s^{-1} running through it. It rapidly enlarged to a width of about 60 m and a depth of 5 m at high-water spring tides. Small ships began to use it instead of going round the point. The Old Den was enlarged at that time by the deposition of material swept through and scoured from the breach by the flood tide (de Boer, 1964). The development of the spit was very considerably changed by the closing of the breaches in the 1850s by the erection and maintenance of groynes and revetments and by the encouragement of dune-colonizing plants, especially marram *Ammophila arenaria* (de Boer, 1981).

Up to the present time, the distal part of the spit has been held in its mid-19th century position. However, over the past 6000 years the spit has migrated westwards at an average rate of about 0.2 m a^{-1} . Comparison of the shoreline on 19th century maps showing Smeaton's lighthouse and the present-day shoreline shows that Spurn Head has been retreating more recently at about 0.5 m a^{-1}. In contrast, the mainland Holderness coast has been retreating at about 2.0 m a^{-1} (IECS, 1992). As a result, Spurn Head now has three parts, a proximal section responding to the high retreat rates of the Holderness coast and a distal spatulate area largely fixed by coast protection activities, separated by a central section which is increasingly exposed to destructive waves coming from northerly and even west of northerly directions. These waves, generated by the strong to gale force winds that accompany the barometric pressure conditions associated with storm surges, are especially destructive. They occurred during both the 1953 storm surge, and the 1849 breach.

The relationship of Spurn Head to the Holderness coast is therefore different now from that in 1849. Erosion has continued unchecked north of Kilnsea: the destruction by the sea of the defences at Kilnsea has also caused rapid retreat of the coast. Relative to the Holderness coast, therefore, Spurn Head as a whole stands in a position more to seaward than it did in 1849, and this may be the primary cause of the present-day rapid erosion, from the northern boundary towards the Narrow Neck.

The wave and tidal processes operating along the shores at Spurn Head have been discussed by Phillips (1962, 1963, 1964), Robinson (1964, 1968) and Hardisty (1982). Along the seaward side, particularly after periods of constructive wave activity, the beach is built into a high, relatively steeply sloping upper beach zone of sand and shingle, and a lower flatter zone of finer-grained sand, sometimes with an intervening runnel. The lower edge of the upper beach is often a sharply demarcated line of seepage, locally called the 'grope'. The height of the beach varies along its length and lower sections, known locally as 'ords' or 'hords' (Phillips, 1964; Scott, 1976; Pringle, 1981), migrate slowly towards the tip of the spit. Erosion is often particularly severe where they occur.

The waves around the spit are responsible for

1. washover processes that transport sand from the eastern shore across the spit to its western shore,
2. longshore transport in the nearshore zone by wave-driven currents southwards to the southern extremity of the spit, and
3. transport by waves in combination with tidal currents onto the western shore (IECS, 1992).

As a result, most sand accumulates along the southern part of the south-western shore.

The predicted 1-year wave height return periods of 4.75 m at Dimlington (15 km to the north), 2.25 m at Spurn Lighthouse and 3.25 at the RNLI jetty show that the Binks have a crucial role in reducing wave energy inputs to Spurn Point (IECS, 1992; Figure 8.9). Modelling wave refraction patterns IECS show that between Kilnsea and the Warden's cottage, with the greatest exposure to the north, wave energy and, as a result, sediment transport increases. Erosion of both the tills and beach sediments follows. As the shoreline swings towards the south-west, however, wave-energy potential decreases and sediment transport is reduced. Deposition increases towards the lighthouse and decreases towards the Point where it is zero (IECS, 1992). This is contrary to the view of de Boer (1964) who described deposition as occurring at the Point. IECS further suggest that there is sufficient sediment reaching the spit to maintain a positive sediment budget. The transport processes do not, however, carry the sediment to the areas with the greatest sediment deficits and that are therefore most likely to undergo erosion.

Conclusions

Spurn Head is an outstanding example of a dynamic spit system and is very unusual, if not unique, in that it extends well across the mouth of a macrotidal estuary. Unusually also, there is an exceptionally long historical record extending back to the 7th century AD. Though there are many spits of sand or shingle along the British coast, there are some features of Spurn Head that are exceptional and give it international importance. These features are as follows.

1. It derives its character as an outstanding example of a dynamic spit system from the coastline undergoing rapid erosion of Holderness whence it grows, where the mean annual rate of retreat over the century 1852–1952 rises in places to 2.75 m, an extreme figure that is among the highest over a comparable period of time anywhere in the world (Valentin, 1954, 1961). Its length and volume reflect the massive longshore transport from the Holderness coast.
2. It is exceptional, nationally and internationally, in that it extends across the mouth of a macrotidal estuary. Few spits are able to maintain comparable size and length in a setting with such a large tidal range.
3. It has an unusually long recorded history of more than 1000 years, exceptional for Great Britain and probably internationally. The comparable length of record for Dungeness offers considerable scope for unrivalled comparative studies.
4. The cyclic pattern of development proposed by de Boer is disputed by a view that the spit has a much more stable position due to Holocene gravel ridges and wave energy distribution.
5. The breaches in the spit are explained by different circumstances: in 1360 by sea-level rise, in 1650 by sea-level fall and in 1849 by gravel extraction and changes in longshore sediment transport.

DAWLISH WARREN, DEVON (SX 985 795)

V.J. May

Introduction

The coastal spit at Dawlish Warren is a classic landform that extends from the western side of the Exe estuary (see Figure 8.2 for general location) and diverts the main channel towards Exmouth. This complex sand spit at the mouth of the estuary is dominated by two parallel ridges, the more seaward of which has a broad distal end. Extensive sandbanks to seaward affect the low-tide and intertidal wave-energy distribution, but the beach form is largely the product of a combination of wave patterns at high tide levels and the discharge of the estuary, so that currents may control the sediment distribution more than waves (Figure 8.10). The site is now partly modified by gabions buried beneath the shoreline dunes and by a wall at its proximal end. Erosion has become acute here in recent years following protection of the cliffs to the south-west that had formerly provided at least part of the former sediment supply.

Description

The spit (Figure 8.10) extends for about 2 km north-eastwards across the Exe estuary from cliffs originally cut into Permian breccia and conglomerate, but now entirely formed by a artificial shoreline of boulders, timber structures

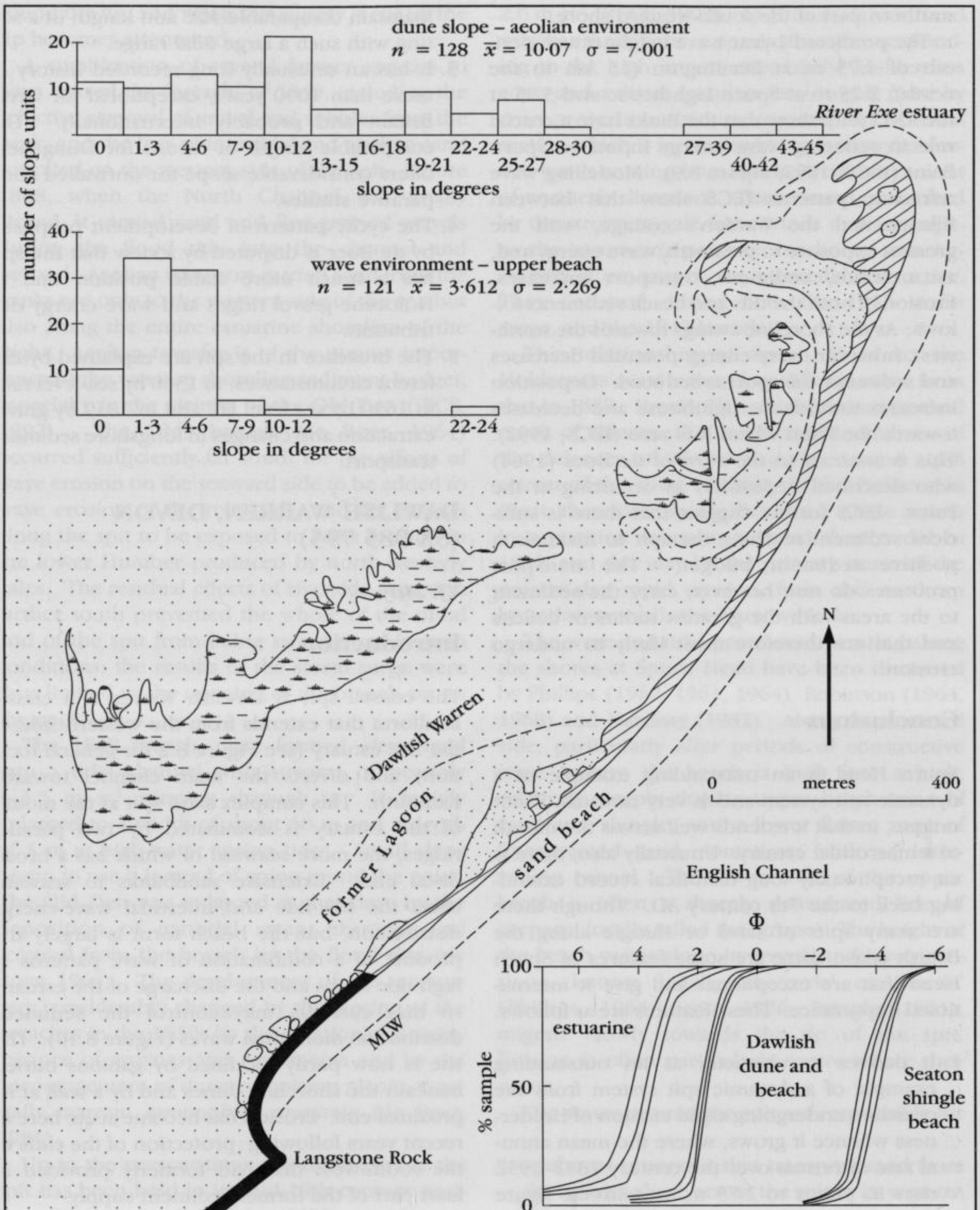

Figure 8.10 Key geomorphological features of Dawlish Warren, showing differences in slope on dunes and the upper beach, and differences in sediment sizes. n = number of observations of slope angle; $\bar{x}$ = mean slope angle; σ = standard deviation. $\Phi = -\log_2$ (grain diameter in mm); the grain-size profile for estuarine material and for Seaton, Devon, are shown for comparison.

and a concrete sea-wall. This area is mostly excluded from the GCR site. The spit is about 500 m wide throughout its length, but is made up of several distinct units. The landward side of the spit supports an area of saltmarsh that has developed in its shelter. To seaward, the Inner Warren, is a low hummocky area of former sand hillocks resting upon clay, probably of estuarine origin, and 0.6 m to 0.8 m-thick shingle layers (Kidson, 1964b). The Outer Warren comprises a line of semi-fixed dunes of varying width behind a discontinuous line of sand hills between 25 m and 50 m in width and rising to a maximum of about 6 m in height. The distal part of this ridge widens into a triangular area that preserves several former shoreline ridges (Figure 8.11). There is a wide intertidal beach, which is connected at low tide to a large sandbank, the Pole Sand. Within the estuary, another large sandbank, Bull Hill Sands, is separated from the distal end of the spit by the channel of the Exe. Both sandbanks include substantial quantities of gravel at depths of –1.3 m to –1.6 m OD. The sand of the spit itself is as much as 20 m in thickness and rests upon Devensian gravels (Durrance, 1969), which in turn rest upon and fill deep channels cut into Triassic breccia. The bedrock slopes from about 0 m OD at the inner end of the spit to about –20 m OD beneath the distal end. A series of NW–SE-trending palaeochannels that have been cut by fluvial processes to below –40 m OD meander across it. Kidson (1964b) reported that the bedrock of Checkstone Reef, which underlies part of the Pole Sand, is occasionally exposed.

The spit appears to have existed in its present-day position on the western side of the Exe estuary since at least the 16th century. Martin (1893) was unable to confirm local reports that at one time it extended across the estuary from the eastern shore at Exmouth. Throughout its documented history (i.e. since 1869) Dawlish Warren has been undergoing erosion. The Outer Warren has been breached frequently and the shape of Warren Point changed considerably. When high spring tides are accompanied by south-easterly gales driving high onshore waves, the lowest part of the ridge is overtopped and breached. The breach is subsequently rebuilt as waves from the south and south-west move sand along the spit and extend it. At the same time the face of the beach and dunes is eroded and so the spit retreats. Sand is also blown from the dune ridge towards the distal end. Sand eroded from Warren Point may be transported into the estuary or may travel towards the Pole Sands. Kidson (1964b) pointed out that erosional phases at Warren Point were not associated with any increase in the volume of sediment in the Pole Sands. The interplay of different wave directions has produced a highly dynamic form.

Interpretation

The nature and behaviour of the sand spit at the mouth of the Exe has been a focus of geomorphological attention since the 1860s (Peacock, 1869; Martin, 1872, 1876, 1893; Kidson, 1950, 1964a,b; Mottershead, 1986). Steers (1946a) commented that an unusual feature was the formation of two spits – an inner and an outer – which was then unexplained. Pethick (1984) described it as a detached beach and Bird (1984) identified it as an example of a spit that has been artificially armoured. Most attention has been given, however, to the erosion and expected demise of the spit. Kidson (1964b, p. 178) described it as the 'outstanding example of a depositional feature which has passed through this period of stability and is now well advanced in the final stage leading to ultimate extinction'. Peacock (1869) had already forecast its ultimate extinction.

Some authors in discussing the dominance of erosion (Martin, 1893; Clayden, 1906; Steers, 1946a) have suggested that the construction of the railway towards Teignmouth in 1849 reduced cliff erosion and cut off the supply of sediment to the spit. Kidson (1950) has shown, however, that the rate of retreat of the face of the spit over the 100 years before and after the construction of the railway was comparable, and concluded that its impact was negligible. Comparison of the shorelines mapped by Kidson (1950) suggests that the spit has migrated landwards as a unit rather than suffering greater erosion at its proximal end, as might be expected if the reduction in longshore transport were the key factor in its retreat. Interestingly, however, Kidson suggested that much of the sand forming the spit was derived from erosion of the cliffs to the west. Rapid erosion of the cliffs at the end of the Holocene rise in sea level would probably have supplied most of the sand for the spit. Even if erosion was already active on the spit by the mid-19th century, the reduction of sand supply from the west cannot be ruled out as one factor in the continuing decline

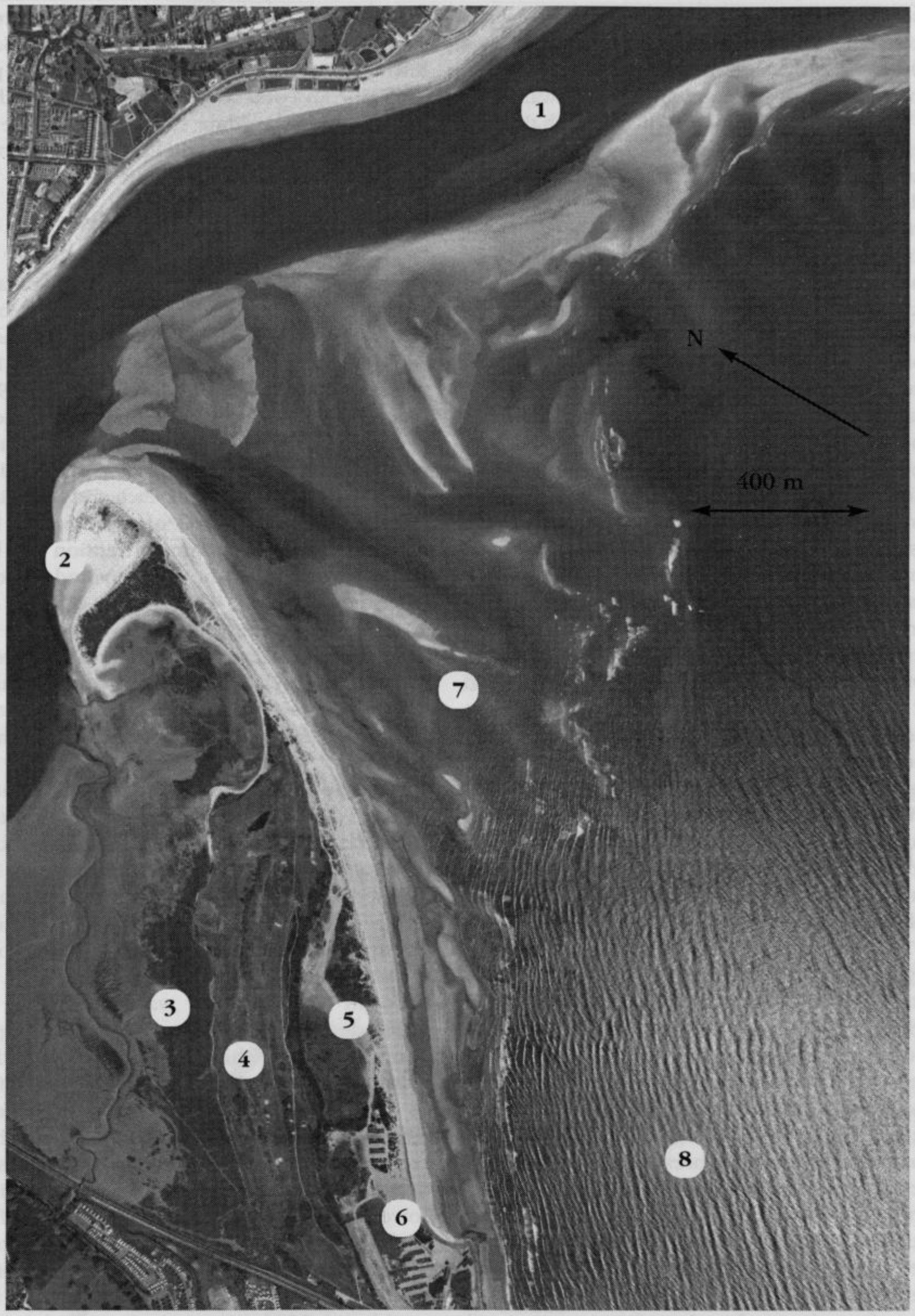

Figure 8.11 Aerial photograph of Dawlish Warren with the main geomorphological features numbered. 1 = Exe estuary, main channel; 2 = active recurved distal end (Warren Point); 3 = saltmarsh; 4 = inner spit (largely modified); 5 = outer spit; 6 = proximal end coastal protection works; 7 = intertidal sandbanks; 8 = prevailing and dominant wave direction (from the south-east). (Photo: courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

of the spit.

The Warren is sandy, unlike other beaches in the region, which are shingle (Mottershead, 1986). Mottershead noted that the River Exe has a drainage basin an order of magnitude larger than any other rivers flowing to this coastline. As a result it would have been able to deliver a much larger volume of sediment. As sea level rose during the Holocene Epoch these sediments could have been driven landwards to form the spit. This was, therefore, a 'once-only' mechanism according to Mottershead, who saw this as a realistic hypothesis in the absence of any published analysis of the mineralogy of the sands forming the Warren. This would suggest that sediment is no longer being supplied to the spit.

A second issue, which was noted by Steers (1946a), concerns the double (parallel) nature of the spit. Mottershead (1986) suggested that Kidson (1963) believed that the Inner Warren was probably an accumulation of windblown sand derived from the Outer Warren. Kidson, however, saw the area around Warren Point as the receiving area for sand blown from the Outer Warren. He suggested that the Inner Warren was a normal spit that built across the estuary with both wave-borne and windblown sand built into dunes on a shingle base. Neither author examined the reasons for the development of two separate spits.

The cartographic and documentary evidence points to the Warren as being developed from two spits. The Inner Warren could have developed as a spit across the estuary, but set well back from its mouth. During a period of reduced sediment supply, it might have migrated into the estuary. The intercalation of clay and sand layers suggest that this spit, like most others, migrated on to the marshland behind it, but that more rapid marshland sedimentation transgressed the landward sandy beaches before the present-day pattern developed. With the older spit pushed back into the estuary and sand supply to it cut off because of the presence of Langstone Rock, it would have been possible for a new spit or beach ridge to develop. The effect upon wave energy distributions of the underlying gravel and bedrock could produce sedimentation and longshore transport, which would initiate a new spit in much the same original position as the earlier one. The new one would then migrate up the estuary, overlapping the older feature.

The spit has now been armoured to reduce the chances of breaching and to ensure its survival as part of the sea defences in the lower Exe. As Kidson pointed out this may well be a futile exercise, as the long-term pattern here has been an erosional one. There is a need to understand much better the sedimentary pathways around the spit especially in the intertidal area.

Conclusions

Dawlish Warren is an important site for four reasons. First, it is a good example of a spit in the later stages of development. In this, it complements such features as Hurst Castle Spit, Hampshire, and Orfordness, Suffolk. If sea-level rise becomes more rapid, it can be expected that many more coastal features will show the changes that have occurred at Dawlish Warren. The efficacy of coastal engineering works in similar situations needs to be carefully evaluated and so this site offers a natural test-bed for measures to adjust to the rise of sea level over the next century. Second, it is unusual in having a double parallel form, for there are few such features in Britain. The nearest analogous site is at South Haven Peninsula, Dorset, and Gibraltar Point, Lincolnshire, has some similarities. Neither, however, has developed across a major estuary. Third, its predominantly sandy sediments make it unusual on the south coast of England where most beaches are of shingle and sandy spits are rare. Finally, the intertidal banks both within the estuary and to seaward form an integral part of this beach system, with the result that, unusually for the coastline of southern England, fluvial as well as marine sediments are a sediment source.

GIBRALTAR POINT, LINCOLNSHIRE (TF 568 562)

C.A.M King and V.J. May

Introduction

The Gibraltar Point area covers a wide range of types of accretion on a coast of low topography. It is one of the few stretches of relatively natural coastline on the east coast of England between the Humber and the Wash (see Figure 8.2 for general location). It has been studied in detail over several decades, the initial surveys being carried out over 50 years ago (Barnes and King, 1951). It illustrates very clearly the interaction of tidal and other coastal processes in a complex and actively developing environment. It provides a very important contrasting site in similar tidal and wave conditions farther north at Spurn Head, Yorkshire. The features include intertidal sandbanks offshore, a well-developed ridge and runnel foreshore, a spit, sand dunes and saltmarshes (see Figure 10.4) in various stages of evolution (Barnes and King, 1953, 1955, 1961; King and Barnes, 1964).

Description

The nearshore zone in this macrotidal environment, where the spring tidal range is over 7 m, is dominated by intertidal sandbanks, including tidal stream ridges and tidal deltas (Davies, 1963). These features are connected with the movement of sediment to the foreshore, which is characterized by a well-developed ridge-and-runnel beach. The ridges and runnels, which are built by waves, lie at a slight angle to the shore, diverging from it southwards. The ridges are composed of sand, but mud can accumulate in the sheltered runnels. Towards the top of the foreshore, the ridges become stabilized and are converted into foredunes by the addition of windblown sand accumulating around sand-loving vegetation. The growing dune ridges are separated by marsh slacks. Saltmarsh vegetation plays an important part in the development of the slacks. Farther inland, beyond the reach of the high spring tides, mature dunes form the backshore zone.

At Gibraltar Point, the coastline turns sharply south-westwards into the Wash and the upper foreshore ridge prolongs the beach line as a short spit. This spit has provided shelter behind which a new saltmarsh is forming (Figure 8.12). This demonstrates clearly the stages of marsh development in a macrotidal area with a good supply of fine sediment available. The New Marsh is separated from a mature marsh by a storm beach, a feature that illustrates well the importance of the occasional extreme event in the development of a low coastline of this type. It was the result of a storm surge in 1922 that truncated the mature dunes at their southern end and the mature marsh that had grown in their shelter.

Tidal streams have been measured in the marsh creeks and in the nearshore zone by specially devised current meters. Wave action and

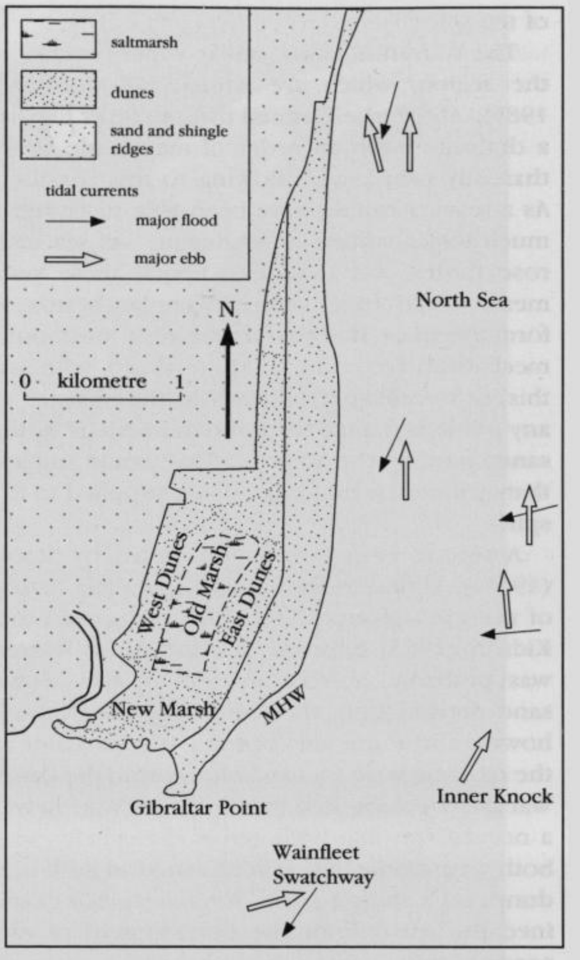

Figure 8.12 The key features of Gibraltar Point. Tidal currents based on Dugdale (1977). The West Dunes developed during the 19th century and the sandy ridge of Gibraltar Point since the 1920s.

longshore movement have been studied by means of fluorescent tracer experiments (Fox, 1978). Beach profiles can also be related less directly to the processes operating on the foreshore. Tidal sediment movement has been studied by drifter releases in the nearshore zone and by samplers in the New Marsh creeks. Windblown sand movement has also been recorded in sand traps on the dunes. There is considerable scope for further development of these process studies.

Interpretation

Since medieval times, most of the Lincolnshire coast has retreated between 400 and 800 m, the main agent of erosion being storm waves as well as storm surges, which breach the coastal defences and flood the land-claimed marsh behind them (Owen, 1952; 1974–1975). The worst of the recent surges occurred in 1953, when flooding was very serious and caused extensive damage. Since this storm, the sea defences have been rebuilt more strongly and they mostly withstood the 1978 surge, which destroyed Skegness pier. Erosion is now confined to the area between Skegness and Mablethorpe. In the last 150 years, the Gibraltar Point area has been accreting naturally (Fraser, 1979) to produce a wide range of features (e.g. Psilovikos, 1974, 1979). The offshore banks have been studied (Dugdale, 1977; Russell, 1978), using a variety of techniques. Current-meter studies show that northerly ebb residuals are dominant seaward of the Inner Knock, whereas southerly flood residuals occur close to the shore between the Skegness Middle Bank and the shore, and along the Wainfleet Swatchway between the Inner Knock and Gibraltar Point. These paths by which sediment reaches the foreshore have been confirmed by drifter experiments. Dugdale (1977) suggests that there is a closed circulation of sand between the offshore sandbanks and the beaches. Sediment size is related to tidal current and coarse sediments are found where currents are strongest, and the finest in the most sheltered positions, such as in the lee of the flood shield near the north end of the Inner Dog's Head. The minor bed forms, which include ripples, mega-ripples, sand waves, large sand waves and a flood tidal shield, also reflect the pattern of tidal streams, mega-ripples indicating high-energy environments.

One of the qualities that makes Gibraltar Point an area of special importance is the wide range of features that develop together to form a system that demonstrates clearly the processes of accretion in a relatively sheltered environment on a low-lying macrotidal coast. Tides, waves, wind and vegetation all play an important part in the rapid evolution of the morphology of the area. Nearshore banks and channels are formed wherever strong rectilinear tidal streams have access to a supply of sand-sized sediment. The southern North Sea and the Irish Sea, with a supply of glacially derived sediment, have excellent examples of these forms (e.g. Ainsdale, Lancashire, see GCR site report). They have been extensively studied, particularly along the east coast of England, with special emphasis on East Anglia, where several different interpretations of their relationship to coastal changes have been put forward. Thus the studies made of the nearshore tidal banks off Gibraltar Point are of considerable interest and importance.

The foreshore is wide and sandy with well-developed ridges and runnels. These features are characteristic of a coast locally supplied with an excess of sand in an area where waves are usually short, and therefore, require a fairly steep equilibrium gradient. Wave action produces the ridges in order to create an equilibrium slope on a foreshore whose overall gradient is too flat. Such ridges occur, for example, on the Lancashire coast and in areas of accretion with a low overall gradient in the North Sea where the average waves have a period of about five seconds. Because the longest and most constructive waves approach Gibraltar Point from the north, the southward ridges diverge slightly from the coastline. Thus on any one profile the ridges move inland. This occurs at a rate of up to 100 m a^{-1} until the ridge reaches the upper foreshore, when the growing ridge to seaward protects it from further wave action. It then becomes the foundation of a foredune. The operation of this process has been recorded in detail just south of Skegness, where, between 1955 and 1972, six ridges successively became stabilized during the period of most rapid accretion following the storm surge of 1953 (Barnes and King, 1953, 1955).

Series of profiles surveyed at several points between Gibraltar Point and Skegness (King, 1964, 1968a, 1973) show clearly the rapid accretion just south of Skegness, where the Skegness Middle Bank approaches very close to the lower foreshore. This took place mainly during the late 1950s, 1960s and early 1970s. More recently, accretion has been greater farther to the south at Gibraltar Point, and erosion has spread south from the north towards central Skegness. The height of the ridges is related to the rate of accretion, as the greater the accretion rate the lower the overall gradient of the foreshore becomes. The ridges are highest in the centre of the foreshore, and thus the sweep zone is widest here. It is narrowest at the top of the foreshore, where the banks are stabilized, and at the bottom, where drying nearshore banks prevent effective wave action at low tide. The gradual shift southwards of the zone of most accretion has been due to the slow southward migration of the Skegness Middle Bank. The accretion causes shallow nesses of accumulation, with a generally convex plan curvature to the sea, to form. The nesses gradually migrate south causing the variation of accretion at different profiles over time, as recorded in the repeated surveys. This longshore drift is responsible for the formation of the spit at Gibraltar Point.

The development of the spit has been studied by annual surveys, which provide evidence of its change in length, height, volume, and vegetation cover (Barnes and King, 1957; King, 1970). The new saltmarsh that developed in its shelter has been studied in detail (Harper, 1976, 1979; Hartnall, 1982), using stakes to measure accretion rates, as well as measuring currents, sediment concentration and details of vegetation (to assess their roles in the growth of the marsh and its creeks). The spit prolongs the upper foreshore where the coast turns abruptly into the Wash. It is a small spit of sand with a little shingle, derived from the glacial deposits and is the latest of a series of spits, each of which has been built farther to seaward than its predecessor. Armstrong's map of 1779 shows a spit prolonging the mature western dune line, which then formed the frontal system. During the 19th century this spit was preserved as the newer dunes developed east of the old system, a new spit prolonging these eastern dunes at the end of the 19th century. The end of this second spit was destroyed by the 1922 storm surge, which created the storm beach and truncated the end of the eastern dunes. The present-day spit has developed since this date.

Until about 1965, the spit continued to grow in length, height and volume, and it moved landwards by about 70 m. Since the spit became stabilized, vegetation has become established on its crest. During the 1980s this vegetation became denser, thus helping to preserve the feature despite a reduction in volume caused by the growth of a ness to the north. It will probably be starved of material as another spit develops seawards of it. This will continue the type of development recorded for former spits, and helps explain the small size of this spit compared with others on the east coast, such as Spurn Head and Orfordness. The spit at Gibraltar Point has formed by stabilization of a ridge on the upper foreshore, in a similar position to the sand dunes, which form one of the distinctive elements of this coastal system.

Sand dunes can be seen in a wide range of stages of development. The foredunes form from the uppermost beach ridges as they become stabilized by the growth of ridges to seaward. They become arcuate in form as their southern end is driven landwards once the northern end is stabilized. Once they are stable, windblown sand adds to their height, and this is trapped by vegetation. Grasses are the earliest colonizers: Lyme-grass *Elymus juncea* is followed by *Leymus arenarius* and marram *Ammophila arenaria* when the height is further increased and the frequency of tidal inundation reduced. As the dunes become more mature, sea buckthorn *Hippophae rhamnoides* becomes dominant, covering the stabilized eastern dunes. *Hippophae rhamnoides* also covers the dune slacks when they are blocked from the sea by the formation of the storm beach. The western dunes, which are about 100 years older, show a much more mature and mixed vegetation, including elder *Sambucus nigra*.

Saltmarshes of various types and in various stages of development occur at Gibraltar Point. Marsh slacks are elongated strips of marsh between the foredunes. They represent the runnels that have accreted owing to the deposition of silt in the shelter of the stabilized ridge to seaward. Vegetation again plays an important part in the accumulation of silt in the runnels. All stages of development are visible at Gibraltar Point, including the changes from initiation of a slack to the stage when only the highest tides can inundate it. Wider areas of marsh occur in the area. One lies between the main western and eastern lines of dunes. This is now mature, the inner part being a freshwater marsh, whereas the outer part between the old and the new spits is still covered by the high spring tides that flow up and spread out from the creek systems. The marsh exhibits a typical east coast mature marsh vegetation at the salting stage (see Figure 10.4). Sea purslane *Atriplex portulacoides* dominates the lower interfluves while the slightly higher creek levees are covered by sea couch *Elymus atherica*, sea lavender *Limonium vulgare*, sea aster *Aster tripolium*; other mature salting plants are present locally. The most northerly British presence of shrubby seablite *Suaeda vera* occurs in the marsh. This shingle plant indicates former shingle and sand ridges in the marsh, outlining their curved form. The marsh also provides examples of various types of pans. The drainage of the outer edge of the marsh was reversed by the building of the storm beach across its seaward end during the storm surge of 1922, which blocked one of the main creeks.

The New Marsh has developed since the 1922 storm surge when the new spit started to develop and provide the shelter necessary for deposition of fine-grained sediment. An aerial photograph taken in 1946 (the earliest evidence of new marsh development) shows mudflats devoid of vegetation apart from a narrow strip near the western end of the storm beach. Up to about 1960 the marsh was dominated by cord-grass *Spartina* spp. and creek development was also taking place (Barnes and King, 1961). By 1970, vegetation covered most of the marsh, including large stands of glasswort *Salicornia* spp., annual sea-blite *Suaeda maritima* and common saltmarsh-grass *Puccinellia maritima*, and the creek pattern was well developed. The marsh sediments include medium silt to sand, the latter being washed through the low proximal end of the spit in stormy high tide conditions, or blown from the spit by easterly winds. Since 1922, 1.4 m to 1.6 m of marsh sediments have accumulated. The mean annual rate of accretion, as measured in detail in the 1970s, is in excess of 40 mm a^{-1} in the centre of the marsh, falling to less than 20 mm a^{-1} in the upper part of the marsh. The mean rate over the marsh as a whole was 17.8 mm a^{-1}. The winter rate of accretion was found to be three times the summer rate, despite the die-back of some annual species of vegetation. The increase can probably be explained by the greater silt content of the incoming tidal waters during the winter owing to increased storminess. A strong correlation was found between data for wind speed, wave height and monthly suspended sediment. Some parts of the marsh are changing more than others, the central area showing the greatest changes and the strongest seasonality of deposition. Changes are most erratic in the lowest part of the marsh; there the River Steeping is gradually changing course, causing rapid erosion in places and equally rapid deposition elsewhere as its meanders shift. The New Marsh thus provides a dynamic environment in which saltmarsh processes and vegetation development are well displayed.

Conclusions

Gibraltar Point is one of a small number of sites around the British coast that have been the focus of more than 50 years of continuous geomorphological research. It includes intertidal sandbanks offshore, well-developed ridge-and-runnel forms on the foreshore, a spit, sand dunes and saltmarshes. The interaction between tidal and other coastal processes has been a key focus of research. One of the main reasons for its importance from the geomorphological point of view is the dynamism of the environment. Changes can be measured over short time spans. For example, seasonal variation of accretion on the New Marsh, annual movements of the beach ridges, and changes of the spit can be recorded relatively simply. The vegetation of the foredunes, marsh slacks and New Marsh also repays close study, since variations and development are rapid.

Gibraltar Point consists of many different subsystems, which include the nearshore tidal ridges, the ridge and runnel foreshore, the backshore with its arcuate foreshore dune ridges and dune slacks. The spit prolongs the upper beach ridge and shelters the New Marsh. The mature marsh (Old Marsh) is separated from New Marsh by the storm beach, a feature that illustrates the importance of the occasional extreme event in the area's development, when more change may occur in a few hours than years of normal sedimentation.

WALNEY ISLAND, LANCASHIRE (SD 194 646–SD 236 624 AND SD 167 715–SD 175 727)

V.J. May

Introduction

Walney Island (see Figure 8.2 for general location) is one of the largest islands around the coastline of England and Wales, exceeded in size only by the Isle of Sheppey, the Isle of Wight and Anglesey. The GCR site at Walney Island has two parts, which represent the main features of the island, in particular the distal features of an island erosion-deposition system. Walney Island itself is the product of erosion and reworking of glacial sediments rather than of coastal deposition (Steers, 1981), but the spits at North End Haws and South End Haws result from transport and deposition of eroded sedments. The spits are important in several respects:

1. They represent the distal features of the island and occur in a macrotidal environment.

2. They differ both in form and sediments. North End Haws is fed by sandy sediments in the intertidal zone and has small dunes on its surface, whereas South End Haws comprises mainly shingle with only limited dune development.
3. They are associated with 'scars' (boulder- and cobble-dominated areas of the intertidal zone) that are a characteristic form on this coast.

Research has concentrated mainly upon the changes in the distal features (Kendall, 1907; Whalley, 1977; Phillips, 1969; Phillips and Rollinson, 1971; Steers, 1981).

Description

The southern part of this GCR site extends from Hillock Whins (SD 194 646) in the north to Haws Hole (SD 236 624) in the south. The beach is set back about 150 m from the low cliffs to the north of Hillock Whins and runs in an almost straight line for 3.5 km (to SD 209 620), swings through 40° and runs for another 1000 m (Figure 8.13), beyond which it changes direction and forms a broadening beach for about 1.3 km. At South East Point, it turns abruptly northwards. Between Hillock Whins and South End, a beach of shingle and boulders rests against remnants of a series of low hills composed of till. The beach is about 50 m wide, fronts low bouldery till cliffs and separates a wide intertidal area up to 750 m wide from low-lying pasture, marshland and dunes. Much of the area behind the present-day distal area has been commercially exploited for its gravel and is now characterized by long shallow lakes. Steers (1981) comments that between 1895 and 1905 about 1.2 million tonnes of gravel and cobbles were removed from the Haws Point area.

Changes in the position of the Haws Point Spit were investigated by Whalley (1977, reported in Steers, 1981) and show that between 1907 and 1976 the spit grew by about 565 m. There were annual growth rates of 3.7 m a^{-1} between 1907 and 1919 and also between 1964 and 1976. These rates were far exceeded by almost three times between 1919 and 1946 (9.5 m a^{-1}) and 1946 and 1964 (10.0 m a^{-1}). Kendall (1907) estimated that between 1737 and 1889 the rate of growth had been about 4.4 m a^{-1}. The drift of material is mainly southwards from the till cliffs that are undergoing erosion, which form most of

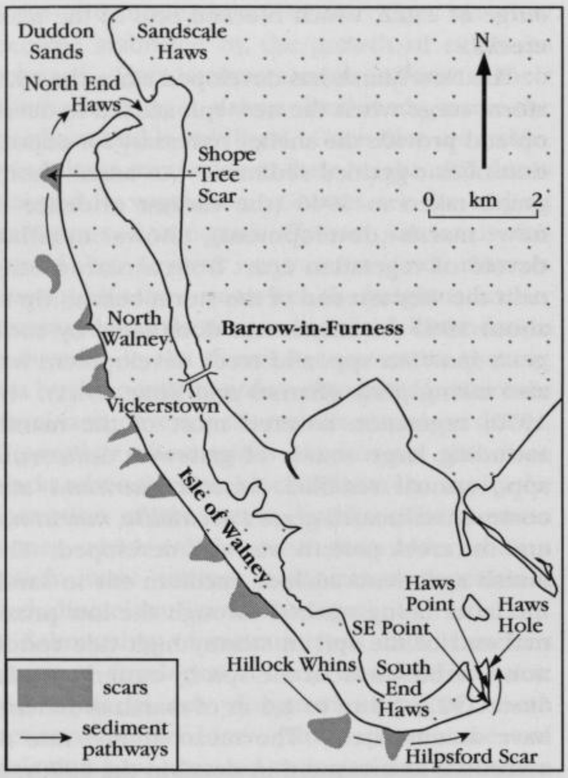

Figure 8.13 Location of scars along the coast of Walney Island, Lancashire.

the western side of Walney Island. With a tidal range of 3 m at neaps and 9 m at springs, sufficiently rapid currents develop in the channel beyond the distal end of the spit to move finer grades of sediment in suspension.

The northern part of the site (from SD 167 715 to SD 175 727), in contrast, is much sandier with a low fringing dune ridge resting on a shingle base. The dunes form a broad distal feature about 250 m in width fringed by a narrow shingle beach. The intertidal area is very wide, forming the southern part of Duddon Sands. The northern end of the site is separated from a further area of dunes, Sandscale Haws, by a 400 m-wide tidal channel.

Interpretation

Steers (1946a) described Walney Island as having several features characteristic of an offshore bar. However, the western shoreline of the island appears to have formed as a series of spits and tombolos linking several islands formed of till and related glacial sediments, for example, between Hillock Whins and South End. Erosion in the recent past has been rapid, up to

0.3 m a^{-1}, and variable. Steers suggested that the pattern of tidal streams gave rise to a predominantly southward drift of beach material. He was uncertain about a possible counter-movement to feed the northern spit. This is not unusual on comparable features with similar wave refraction in the mouths of estuaries (e.g. the North Norfolk Coast, East Head, South Haven Peninsula, and Dawlish Warren).

The presence of extensive deposits of gravel and boulders, sometimes known locally as 'scars', within the intertidal zone may reflect earlier positions of the retreating shoreline, probably related to high points on the eroded glacial sediments. The 'scars' also influence the distribution of wave energy by causing local refraction and offering more resistance to intertidal erosion. Each of the sharp changes of direction in the southern beach is associated with an extensive boulder covered area. The right-angle turn at South East Point may be partly a result of the effects of the deep water channel, but also of the change in wave direction to which this part of the beach is exposed.

Experiments using seabed drifters (Phillips, 1969) suggest that accretion on the southern spit results from transport from the seabed. This is important because it means that management of this feature and changes in its form are likely to be affected by offshore conditions, including the effects of gravel or sand extraction. According to Phillips, tidal streams assisted by the stronger waves that accompany the prevailing and dominant westerly winds bring about transport from the seabed. Drifters released on the ebb moved to the outer part of Morecambe Bay, whence they could reach Walney Island. On the flood, in contrast, they moved farther into the bay. Within the bay, movement was mainly to the north and north-east, but at the mouth of the bay, movement is in an anti-clockwise direction towards the north-west corner of the bay. In both cases, sediment would be transported into intertidal areas, whence it could be supplied to the spit at the southern end of Walney Island.

Walney Island has been the focus of several studies, mainly of coastal changes, but as Steers (1981) pointed out, they say little about the changes to North End Hawes or about its relationship with Sandscale Haws across the estuary. Future investigations should consider the evolution of this point and its relation to Sandscale Haws. There remains a need to consider the whole system, although in this volume much of the western cliffed coastline has been excluded from the GCR site because of the coastal defences and its urbanized nature. The spits at either end of the island exemplify well the unique nature of their sources of sediment and their development at opposite ends of this substantial barrier island.

The origins of Walney Island are the subject of some debate. Tooley (1978a) regarded the island as having been separated from the mainland during Lytham II (8390 to 7800 years BP) or possibly even earlier during Lytham I (9270 to 8575 years BP). Steers (1981, p. 132) was unconvinced that a single long island was separated from the mainland as suggested by Tooley, arguing that the island is a 'series of hillocks joined by beach drifting'. Walney Island is not a barrier island in the traditional sense of an entirely depositional feature, because much of its length is not composed of recent beach sediments, but rather of older glacial materials that are being reworked by marine erosion. This is consistent, however, with barrier development in higher latitudes where sediment is largely derived from the erosion of adjacent cliffs cut in glacial materials (Bird, 1984). Similar features were described in New England by Johnson (1925) and Sakhalin by Vladimirov (1961). Walney Island thus provides an unusual contrast with the other barrier sites along the coastline of England and Wales.

Conclusions

The Walney Island GCR site has two parts, both containing the distal features of a barrier island. Walney Island, however, differs from the usual characteristics of barrier beaches in being mainly the result of erosion and the reworking of glacial sediments rather than the result of coastal deposition. The spits at the northern and southern extremities of Walney Island form the distal features of an unusual barrier island. They are of considerable interest because of their sediment sources and the changes that have taken place within the spits themselves. Walney Island is a unique feature of the English coast, in that small eroded hillocks have been joined by a series of sand, gravel and cobble beaches to produce a single island. It warrants more research, for better understanding of its development will facilitate a better interpretation of the recent evolution of the coastline of north-west England.

WINTERTON NESS, NORFOLK (TG 489 216–TG 506 181)

V.J. May

Introduction

The term 'ness' (an Old Norse word) is commonly used, particularly in south-east England, to describe either a headland, for example White Ness (Thanet), or a low-lying foreland or promontory, for example Dungeness. Derived local terms include 'nothe' (Dorset) and 'naze' (Essex). Technically it has been applied most usually where a narrow cuspate foreland occurs with a high obtuse angle between its two shorelines. Such features occur on the East Anglian coast at Winterton Ness, Benacre Ness and Orfordness. Winterton Ness is unusual because of its modern dynamism, its predominantly sandy beach and its migration, often in an opposite direction to that of the longshore drift.

Description

Winterton Ness (see Figure 8.2 for general location) is significant both for the well-formed dunes, which are its most characteristic landform, and for the processes that affect its continuing development. At Winterton Ness, there appears to be a slight sediment budget surplus and some growth in the volume of sediment retained in the ness. There is both erosion and deposition within the site and an important aspect of the interest of the site is its dynamism, a feature that has been the focus of much of the research here (Cambers, 1975; Craig-Smith, 1971a,b, 1973; Green *et al*., 1953; McCave, 1978b; Onyett and Simmons, 1983; Robinson, 1966; 1980a; Steers, 1927, 1939a, 1964a; Steers and Jensen, 1953; Ward, 1922; Williams, 1956). It is one of a small number of such features cited in the wider coastal literature (Bird, 1984, 1985; Bird and Schwartz, 1985).

The site extends from TG 489 216 in the north to TG 506 181 in the south. From a narrow dune ridge at its northern end, the ness widens to over 500 m in its central section around the ness itself before narrowing again southwards. North-east of the village of Winterton-on-Sea, the site is formed of linear dunes and slacks. Much of the dune landscape was greatly altered during the 1953 floods, and many of the blowthroughs and other features that existed before 1953 were modified or eliminated (Steers, 1964a). Ridges of shingle also occur, albeit occasionally. Towards the ness, low dunes rest upon parallel sand and shingle ridges about 1.0 to 1.3 m in

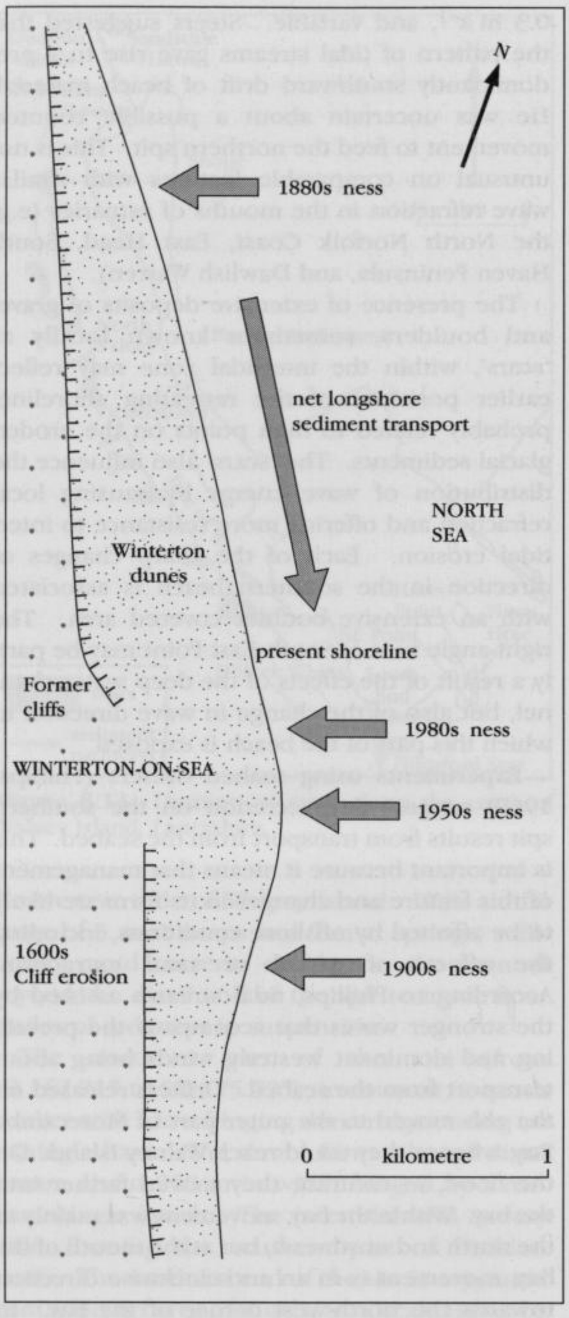

Figure 8.14 Former positions of the ness at Winterton, indicating a rapid southwards change in position between the 1880s and 1900s, but a subsequent movement northwards to the 1980s, and then a return southwards in the 1990s.

height. South of the village, the old cliffline (which is up to 15 m in height) is separated from a line of dunes by a valley, the origins of which remain obscure.

Cambers (1975) reported that there was some slight accretion around the Ness. Onyett and Simmons (1983) indicated that accretion at Winterton had passed its peak with the area of positive growth moving north to the Horsey area. Halcrow (1988) described the coast as retreating at rates up to 2 m a^{-1} on both sides of the ness, whereas at the ness the coast had advanced at about 0.5 m a^{-1} (Figure 8.15). The foreshore was steepening. They confirmed that the ness was migrating towards the north. The Shoreline Management Plan (North Norfolk District Council *et al.*, 1996) reports beach retreat on the northern side of Winterton Ness of up to 1 m a^{-1}, in contrast to general accretion on its southern side. Sediment transport is towards the south. This suggests a return to the patterns described by the earliest descriptions of the Ness. It also accords with Cambers' view that the Ness results from a change in the rate of littoral drift resulting from the change in beach alignment. The northern edge of the site lies just south of a point where there have been breaches of the dune line (Steers, 1964b), as in 1938 and 1953, but the main dune area remains unscathed. There are several ebb-flood channels offshore from the Ness.

Interpretation

The development of nesses along the East Anglian coast has been the subject of some debate, but it is difficult to develop a general hypothesis for their formation as a group because their individual sedimentary characteristics are not similar. The beach at Winterton Ness, for example, is mixed sand and shingle, whereas Benacre Ness to the south is usually veneered by shingle. Both the movements of sand and shingle and the forms associated with them differ. Benacre Ness shows a strong tendency to migrate northwards, but the movements and history of Winterton Ness are less certain. Robinson (1966) demonstrated that ness features are associated with offshore ebb-flood channel systems and suggested that material reaches the nesses via these systems. The process thus involves a complex interaction of offshore tidal streams and wave action. Cambers (1975), however, suggested an alternative hypothesis. His sediment transport calculations show that in the vicinity of Happisburgh 1 000 000 m^3 of sediment could move annually towards Winterton. To the south of Winterton at Hemsby 390 000 m^3 could move southwards. Cambers interpreted this to mean that Winterton Ness could be an area where part of the balance is added to the ness, whereas the remainder moves offshore via the ebb-flood channel system. This is completely the reverse of Robinson's hypothesis. Despite some conflicting and inconclusive evidence from the analysis of drifter releases between Winterton Ness and Benacre Ness (Craig-Smith, 1973), Cambers proposed a simple hypothetical model for the sediment budget of Winterton Ness. Allowing for an accretion rate of 1 m^3 per metre length of coastline per year, 2000 m^3 would accumulate annually at the Ness. In practice such rates are unlikely to be achieved today with much of the cliffed coast now artificially protected to the north.

Ward (1922) linked the changes in the offshore banks to the intermittent pattern of erosion along the East Anglian coast. This view had been expressed earlier by the Royal Commission on Coastal Erosion and Afforestation (1907–1911), which attributed periods of increased erosion to the lowering of offshore banks. The relationship between the offshore banks and ness maintenance may therefore be a very complex one. Steers (1964b) put forward the possibility that the contrast between the northern and southern parts of Winterton Ness might result from the presence of a sandy spit or bank, or even a shingle bank, on which the dunes south of Winterton could form. If this were the case, the ness would form at a point where following the trend of the coastline would cause the beach to extend into deeper water and for refraction around it to assist the rate of transport of sediment southwards. What is of particular interest at Winterton is that, unlike other nesses, it does not appear to have been a gradually growing feature, but may be more akin to features such as Orfordness, Suffolk, where a ness is accompanied by a spit at its down-drift end.

The significance of this site lies in the contrast between its northern (erosional) and southern (aggrading) parts and the processes that affect its continuing growth. It has been suggested that Winterton Ness, like other similar forms, marks a location where there is net offshore transport of sediment. As far as the longshore

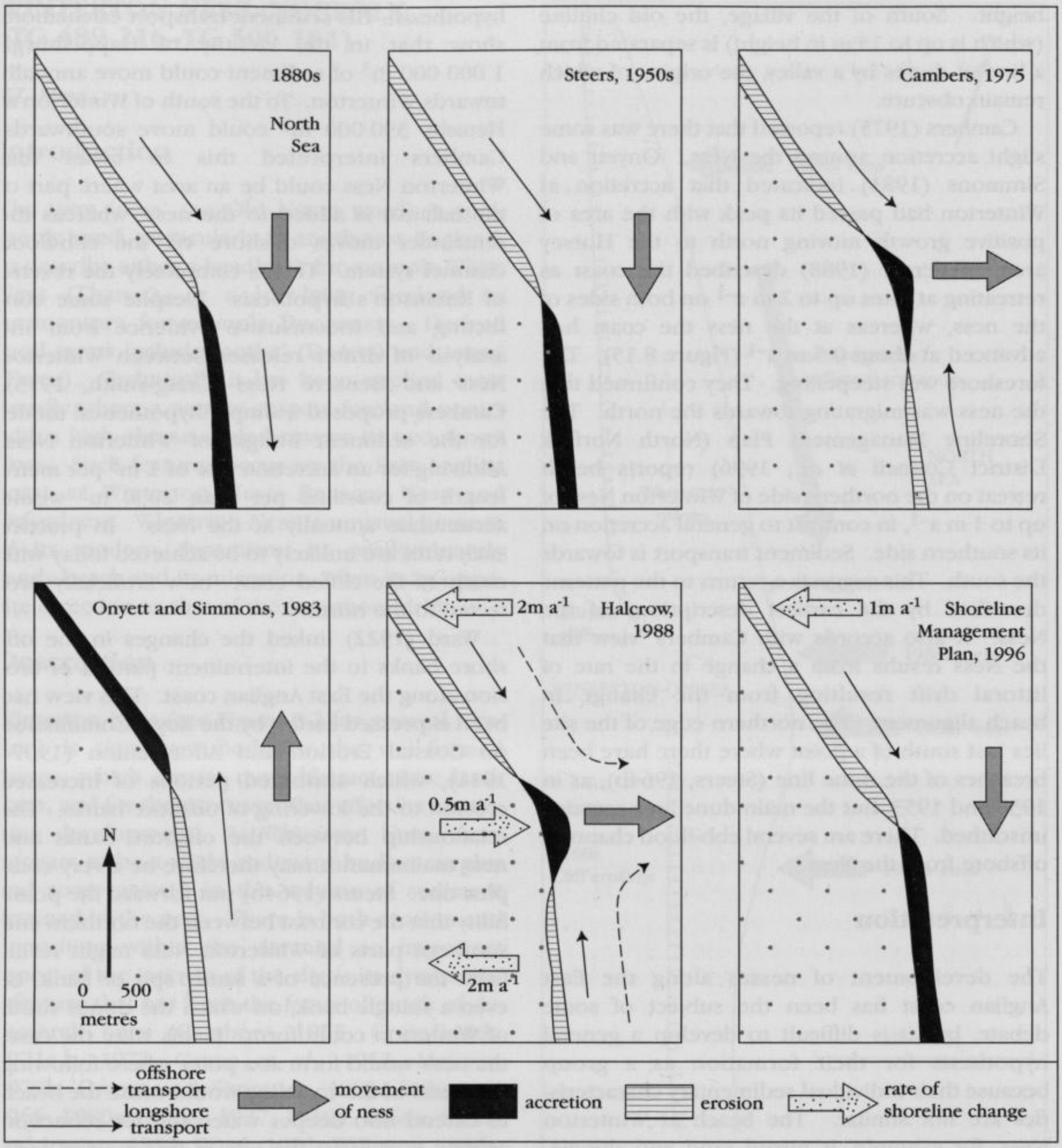

Figure 8.15 Different interpretations of the sediment transfers at Winterton Ness. In the 1880s, according to Steers (1964a) and the Shoreline Management Plan (North Norfolk District Council *et al.*, 1996), net sediment transport was southwards and the ness moved in the same direction. Others have suggested that transport is from the south, and Cambers (1975) and Halcrow (1988) agree on transport from both south and north with a transfer offshore and the ness extending seawards.

sediment budget is concerned, it is a sediment sink. However, the role played by offshore banks may be such that sediment returns elsewhere to the shore via ebb-flood channels.

The dynamism of the feature and its place within a continuum of longshore sediment transport makes the definition of its northern and southern extremities difficult. They have, however, been set, for GCR purposes, so as to include the processes maintaining the ness as well as the form itself. The offshore limit of the site should be related to the processes in the ebb-flood channels and on the offshore banks, but since the evidence of their precise role is conflicting they have not been included in the site. If sediment reaches the ness from offshore, as in Robinson's (1966) hypothesis, then it is essential that the offshore is offered the same protection as the ness itself for without the former the latter will remain at risk. If, however, Cambers' (1975) hypothesis is correct, designation of the offshore zone is not critical for the Ness. In the early 1980s the evidence seemed to favour the latter position, but Halcrow (1988) suggest that the ness is the result of littoral sediment supply from the north-west associated with converging tidal residual currents. There is a need for further investigation to determine not only the relationship of the Ness and the offshore area, but also the relationship of the probable offshore transfer of sediment to the sediment budget farther south.

Conclusions

Winterton Ness is a narrow cuspate foreland dominated by well-developed dunes and a sandy beach. It has been identified as an area with a sediment budget surplus and of considerable sediment transfer offshore. Winterton Ness differs from the other similar features of the East Anglian coast in being predominantly sandy and in having a slight sediment budget surplus. It also differs from other nesses because it has not had a consistent pattern of growth. Although there has been an historical pattern of movement towards the south, this has not been maintained in recent decades. The shoreline dunes are very geomorphologically active at the site, since they migrate inland on shorelines undergoing erosion or build seawards where accretion takes place. Winterton Ness has been cited by a number of writers (e.g. Ranwell, 1972; Goudie, 1990) as a key example of a prograding ness dune system. Behind the linear coastal dunes, the dunes of the central part of the ness are of considerable ecological importance because of their relative stability and alkalinity, and much of the GCR site co-incides with the Winterton Dunes National Nature Reserve. It is an important member of a group of narrow cuspate forelands that play an important role in the longshore sediment transport of the East Anglian coast.

MORFA HARLECH, GWYNEDD (SH 574 303–SH 550348)

V.J. May

Introduction

Morfa Harlech forms a large triangular area of sandflats, beaches and dunes, and claimed land between an abandoned cliff north of Harlech and the estuary of the Afon Glaslyn and Afon Dwyryd (see Figure 8.2 for general location and Figure 8.16). The present-day beach and dunes form a narrow fringing system in the south of the site, but widen northwards into several subparallel ridges. The alignment of a sand beach and dunes at an acute angle to the former cliffs has encouraged extensive sedimentation. Inland there are several recurved zones of former shoreline and dunes. Morfa Harlech is significant for the relationship of the ridges to sediment inputs from local rivers and the seabed. Though progradation is prevalent, there is also some localized erosion, both at the proximal end, near Harlech, and at the distal end of the spit. Morfa Harlech is little-affected by anthropogenic intervention into littoral sediment transport, and is part of a suite of beaches that are aligned to Atlantic swell in the Irish Sea. The first description of the site was by Steers (1939b). This was developed further by Steers (1946a) and King (1972b), but much of the description that follows is based on more recent examination of the site both in the field and on aerial photography taken at various dates since the late 1940s.

Description

The sandy beach at Morfa Harlech extends about 7 km NNW from the coastline at Llanfair towards the estuary of the Afon Glaslyn. The landward edge of Morfa Harlech is formed by a line of former cliffs upon which the 13th century castle at Harlech was built. Between the old cliffline and the beach there is a triangular area of reclaimed marshland, saltmarsh and both geomorphologically active and relict dunes. Within this area there are several rocky outcrops, such as Ynys Llanfihangel-y-traethau, former islands enclosed within the marsh. The main geomorphological interest lies in the beach and dunes that form the seaward part of Morfa Harlech (Figures 8.17 and 8.18).

Steers (1939b, 1946a) described the development of the Morfa from its earliest days as a small spit of shingle and sand providing some shelter for vessels arriving at the castle water-gate. As the spit grew northwards, sedimentation and the development of saltmarsh was accompanied by land-claim. This was not well documented until the early 19th century when embankments were constructed between the north-east corner of the high ground at Llanfihangel and the coast road at Glyn Cywarch. An Act passed in 1806 allowed embankment, and Steers (1939b) recorded that banks were constructed at both Morfa Harlech and farther up the estuary at Talsarnau soon afterwards. The 1808 embankment from Llanfihangel to Glyn Cywarch finally closed the creeks. Steers considered the relationship of the castle and its port to the growth of the spit and the marshland behind it. He concluded that the spit grew northwards and that small boats were able to reach the castle for several centuries after it was built.

Steers used a number of maps to interpret the historical development of the spit up to 1939. Since the 1950s, maps and aerial photographs have augmented his description of the development of the spit, but there has been little other work on its geomorphology. The beach and dunes fall broadly into three main parts: a southern section, about 3.25 km in length, formed mainly by sub-parallel dune ridges; a central section, formed mainly of recurved vegetated and generally low-lying dunes, and a northern area of mobile sand, also characterized by recurved sandy ridges. There are frequently several curving ridge and runnel forms in the intertidal area at the northern end of the spit. The north-eastern part of the site is formed by saltmarsh (Figure 8.17). These zones are well depicted on the aerial photo-mosaic (Figure 8.18). Although movements of sand along the spit towards its distal end have contributed in part to its extension across the Afon Glaslyn, changes in the position of the river channel have contributed also to the growth and erosion of the spit.

Bird and Schwartz (1985) included Morfa Harlech as one of several important British depositional structures in their review of the world's coastlines, and it is one of several beaches in Cardigan Bay that were reported by King (1972a) as being swash-aligned. It was also noted by Guilcher (1958) as one of the many beaches along this coastline where the larger

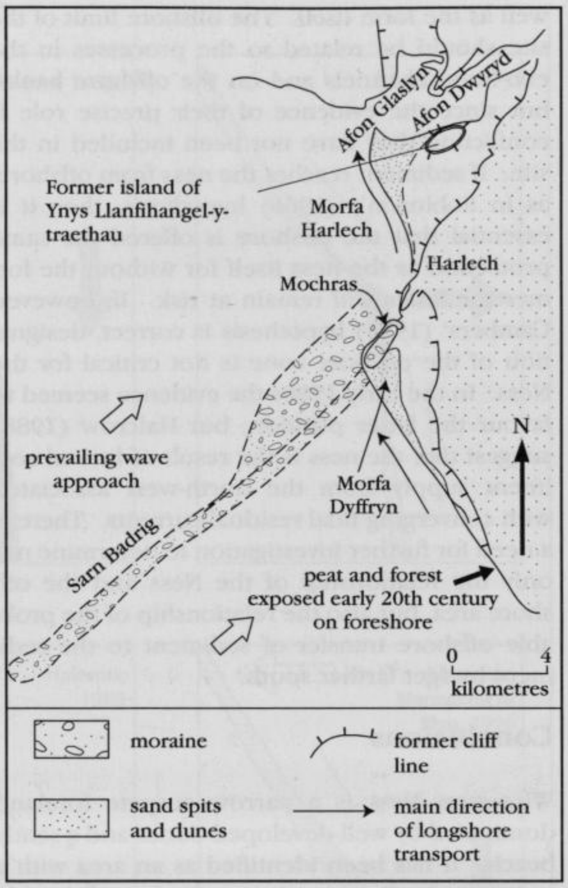

Figure 8.16 Context of Morfa Harlech and Morfa Dyffryn – key geomorphological features.

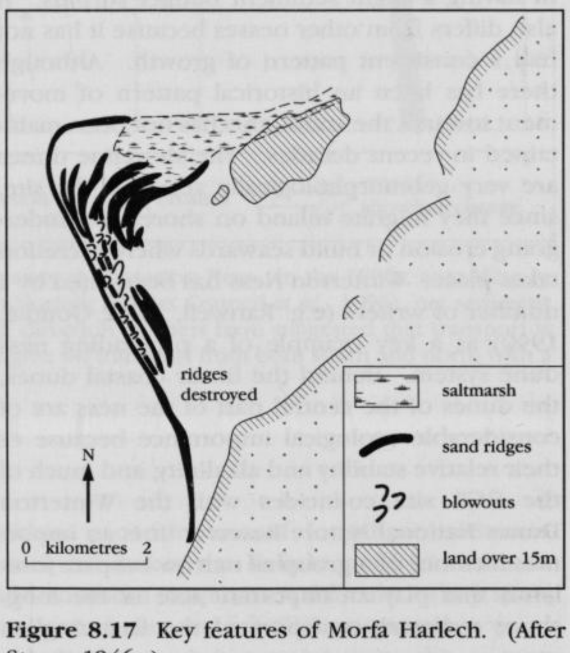

Figure 8.17 Key features of Morfa Harlech. (After Steers, 1946a.)

Figure 8.18 Aerial photograph of Morfa Harlech with the main geomorphological features numbered. 1 = former mainland; 2 = linear stable dunes ('grey dunes'); 3 = active 'yellow' dunes; 4 = zone of active blowthroughs; 5 = relict blowthroughs with SW–NE-aligned linear dunes; 6 = dune and slack topography; 7 = recurved linear dunes; 8 = former distal spits; 9 = 19th century distal features; 10 = modern distal dunes; 11 = intertidal sandflats. (Photo: courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

clasts are mainly slate and shale. As a result its sediments are characteristically platy in form rather than rounded, and this is reflected in the detailed structures of the beach ridges. Steers (1946a) described the southern part of the spit as a dune area bordered by a belt of coarse cobbles. In the 1940s, this was the only shingle visible in the whole area, and Steers estimated that it had moved north about 450 m since 1901. He considered that, prior to the construction of the railway embankment, the erosion of the till cliffs to the south would have provided a source for these cobbles. He also discussed the possibility that the dunes were underlain by shingle or in-situ till, but acknowledged that there was little evidence to resolve the issue. The way in which the sand dunes recurve in the northern part of the spit, decrease in height and fan out, led Steers to believe that they were not underlain by shingle. The northern end of the spit had grown an estimated 200 m in the previous 100 years, and Steers did not expect it to grow much further. In fact, since then the spit has grown much farther to the north-west and then retreated to about its present position. There is now a large area forming the distal end that is made up of a series of curved low ridges. They are overwashed at spring tides or during periods of high wave energy and have not become vegetated. The outer part of the distal area is formed by several ridges and runnels, features that have been discussed elsewhere by Orme and Orme (1988) and may provide a mechanism by which sediment is transferred from the intertidal zone to the beach (Figure 8.19). The changing position of the north-western part of the spit appears to be related to movements in the position of the ebb and flood channels of the Glaslyn estuary. This area has extensive sandy intertidal flats that receive sediment from the rivers of the Vale of Ffestiniog, but sources from Snowdonia via the Afon Glaslyn, north of Porthmadog, were restricted greatly during the 19th century when much of Glaslyn Valley was reclaimed. There are nevertheless extensive intertidal areas that could serve as sources for the spit.

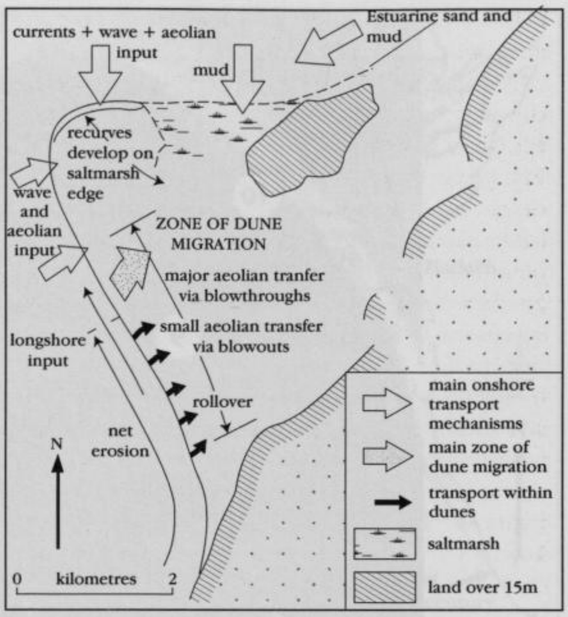

Figure 8.19 The main processes and sediment transfers at Morfa Harlech.

The vegetated dunes are affected by shoreline erosion at their southern end, but this has not been a major problem within the site. There is some damage to the dunes as a result of recreational trampling, and blowthroughs occur along the dunes south of the main public access and at several separate locations farther north, both on the foredunes and on the older inner ridges. Steers (1946a) noted that parts of the inner dunes north of the Cefn mine were affected by blowthroughs, and described the outer seaward line of dunes as wind-eroded. The inner edge of the dunes was migrating at about 4 m a^{-1} on to the pasture behind the dunes. Following afforestation of part of the inner dunes, these dunes appear to have stabilized.

Interpretation

The changes in the area of the spit both during the last 150 years and during the last four decades indicate that Morfa Harlech as a whole is in a state of progradation. The amount of erosion at its southern end is small. The spit appears to be very close to equilibrium with the dominant and prevailing south-west waves, with very little net movement of sediment alongshore. Despite the substantial growth of the distal features, the general line of the southern beach and its position have remained similar for several decades. Its alignment depends to a considerable degree on its relationship to the Glaslyn estuary and the rocky shoreline on the northern side of Cardigan Bay, both of which affect the direction of waves approaching the spit. The source of sand for the spit is probably mainly from the substantial submarine glacial deposits that floor the bay, with some exchange also taking place between the estuarine sands and the distal end of the spit.

Morfa Harlech is a fine example of a sand spit developing across an infilling estuary. Most of its growth appears to have occurred during the last 700 years, but, unlike many other such forms, it does not appear to have been seriously affected by the worldwide tendency for such features to be affected by erosion (Bird, 1985). This is attributed to a large probable source of seabed sediment in Cardigan Bay and the large quantities of sandy sediment in the Glaslyn estuary that may have increased due to mining inland. The spit has been little affected by coast-protection works, although there is some confined damage resulting from recreational trampling. The processes that are geomorphologically active on Morfa Harlech have not been investigated in detail, but its largely pristine character makes it particularly important as a site for coastal geomorphological studies. There has not been a detailed investigation of the stratigraphy landward of the beach, especially in the Harlech area, which would allow the early history of the beaches to be described. Nevertheless, the historical evidence suggests that most of the beach is a much later development than Ynyslas to the south. It contrasts also with rock-based dune systems at Newborough Warren.

Morfa Harlech is the result of several phases of as yet undated spit growth, and the progressive sedimentation and land-claim of the area between the beach and the former rocky sea cliff upon which Harlech Castle stands. Unlike the other major depositional features of the coastline of Cardigan Bay, it appears to depend upon sediment supplies from the sandy estuary to its north. Morfa Harlech displays several phases of growth, a similar characteristic to several other beach systems (for example Pwll-Ddu, South Haven Peninsula and Gibraltar Point).

Conclusions

The Morfa Harlech GCR site comprises a well-developed spit across a major estuary whose sediment load may contribute significantly to the coastal sediment budget; it has several distinctive recurved zones that relate to its development during the last 150 years. It is a fine example of a multi-phase, gravel-based, sand spit that has gradually built across a major infilling estuary. Much of its growth has taken place during the last 700 years, and continues to show a positive sediment budget, largely as result of the large quantities of sand available on the shallow sea floor and in the Glaslyn estuary. Its almost totally unspoilt character makes it especially important for coastal studies.

MORFA DYFFRYN, GWYNEDD (SH 557 271–SH 579 213)

V.J. May

Introduction

Wave conditions in Cardigan Bay are dominated by Atlantic swell from the south-west, but locally generated waves may approach from the west or north-west. Cardigan Bay is bounded by the Lleyn Peninsula in the north and St David's Peninsula in the south; the bed of the bay is marked by three major SW-trending cobble and boulder banks, known as the 'Sarns', which are believed to be of glacial origin (Foster, 1970; Bowen, 1974) and thought to confirm an extensive westward flow of Late Devensian Welsh ice from the uplands (Campbell and Bowen, 1989). These sarns affect both wave behaviour and sediment movement in the bay. Morfa Dyffryn is linked geomorphologically to Sarn Badrig (see Figures 8.16).

The beach and dunes at Morfa Dyffryn front a cuspate foreland, which is about 3 km wide at Llanbedr. The beaches developed as a spit extending across the mouth of the Afon Artro, but today they link the morainic hill of Mochras to the mainland, following diversion of the river by an embankment in 1819. Near its southern end, Morfa Dyffryn comprises a narrow fringing beach of shingle, cobbles and sand upon which there are low dunes. Northwards, the dunes are wider and higher enclosing large slacks. At Mochras, the shoreline is formed of low cliffs of glacial material and the beach is dominated by cobbles and boulders. To seaward, Sarn Badrig extends from Mochras as a shallow, submerged ridge for about 17 km. Like many of the spits and cuspate forelands of England and Wales, Morfa Dyffryn was first described by Lewis (1938) and Steers (1939b; 1946a), but has subsequently received little detailed attention. Guilcher (1958) regarded it as a good example of a cuspate foreland, although this ignores the position and role of Sarn Badrig and the historical development of the feature.

Description

Morfa Dyffryn (see Figure 8.2 for general location) is a broadly triangular area extending from Llanaber in the south to Llandanwg in the north. It is widest at Llanbedr where it extends westwards about 3 km from a probable former cliffline to its apex at Mochras. At its northern end, it encloses the much-modified estuary of the Afon Artro. Much of Morfa Dyffryn is excluded from the GCR site because it is agricultural land or forms part of RAE Llanbedr, whose construction in the 1940s destroyed much of the area of inland dunes.

The beach is virtually straight, faces southwest and extends for about 5 km from its southern boundary (at SH 579 214) to about 0.5 km south of Mochras (SH 552 255). At this point, it is aligned towards WSW before a sharp change of direction (at SH 550 262) so that the northern side of Mochras faces north-west. The southernmost part of the site is formed by a spit of sand and shingle that diverts the mouth of the Afon Ysgethin northwards. The spit is progressively extending northwards (Figure 8.20). North of the Ysgethin's outlet, the dunes gradually widen from a narrow fringing ridge about 120 m to over 1.2 km wide in the north. The dunes were described by Steers (1939b) as gradually extending inland.

The geomorphologically active dunes attain heights in excess of 20 m, with semi-parabolic ridges enclosing large slacks. Once the dunes reach a critical height (Ranwell, 1972), they tend to migrate inland and blowthroughs become dominant (Figure 8.21). The lowered areas are gradually replaced by new dunes (Ranwell, 1972). The northern area of the dunes first began to accumulate after the mouth of the Afon Artro was diverted in 1819. The 1838 first edition of the Ordnance Survey One Inch map shows Mochras as an island. With the opening of the present-day river mouth, the sand beach extended northwards to the low cliffs at Mochras. Apart from some changes in direction around the mouth of the Artro, the low-water line followed a very similar alignment to the present-day shoreline. The dunes have continued to migrate inland, but the beach is now stable in position. Sufficient sand is reaching the beaches to maintain their position and to continue to supply the landward-moving dunes.

Interpretation

Large cuspate features are rare on the British coast. Standard texts on coastal geomorphology from Johnson (1919) to Pethick (1984) refer to three such features: Benacre Ness, Dungeness and Morfa Dyffryn. Lewis (1931) regarded this beach as a good example of orientation towards the dominant waves. Others, such as Morfa Harlech to the north, show less well-developed orientation towards the dominant waves, as these other sites are more affected by the refracted waves and currents at the mouths of the estuaries. Other examples of similarly orientated beaches occur in Carmarthen Bay. King (1964) considered that this beach was controlled by dominant waves related to the coastal outline, but that Sarn Badrig also played a part in affecting wave alignment and energy. Morfa Dyffryn is one of several beaches in Cardigan Bay in which the coarse sediments are dominantly made up of slate and shale derived from local sources (Guilcher, 1965). The beach at Morfa Dyffryn is, nevertheless, predominantly sandy, particularly towards its northern end. Moore (1968) described the patterns of sedimentation in Cardigan Bay between Aberystwyth and Mochras. Sand was transported northwards along Morfa Dyffryn, but also entered the sand-floored area south of Sarn Badrig at both its shoaling and seaward ends. Moore regarded tidal streams as the most important agents of sediment dispersal in Cardigan Bay. Geochemical and mineralogical analyses suggested that the estuaries of both the Afon Mawddach and the Afon Dyfi were being filled by sediments from the sea rather than from the rivers.

The relative stability of the shoreline, despite a strong tendency for the dunes to migrate inland and a limited supply from littoral drift, poses questions about the sediment supply to Morfa Dyffryn. There is no longshore source of any volume to the south and the southern part of the beach shows signs of being generally in deficit. There is little evidence to support the hypothesis that sand may be transported from the north into this site. Moore (1968) supported the possibility of offshore sources. Sediment movements across Sarn Badrig from the northern part of Cardigan Bay would provide one mechanism for maintenance of the sediment supply to Morfa Dyffryn. Sarn Badrig and its landward expression at Mochras have

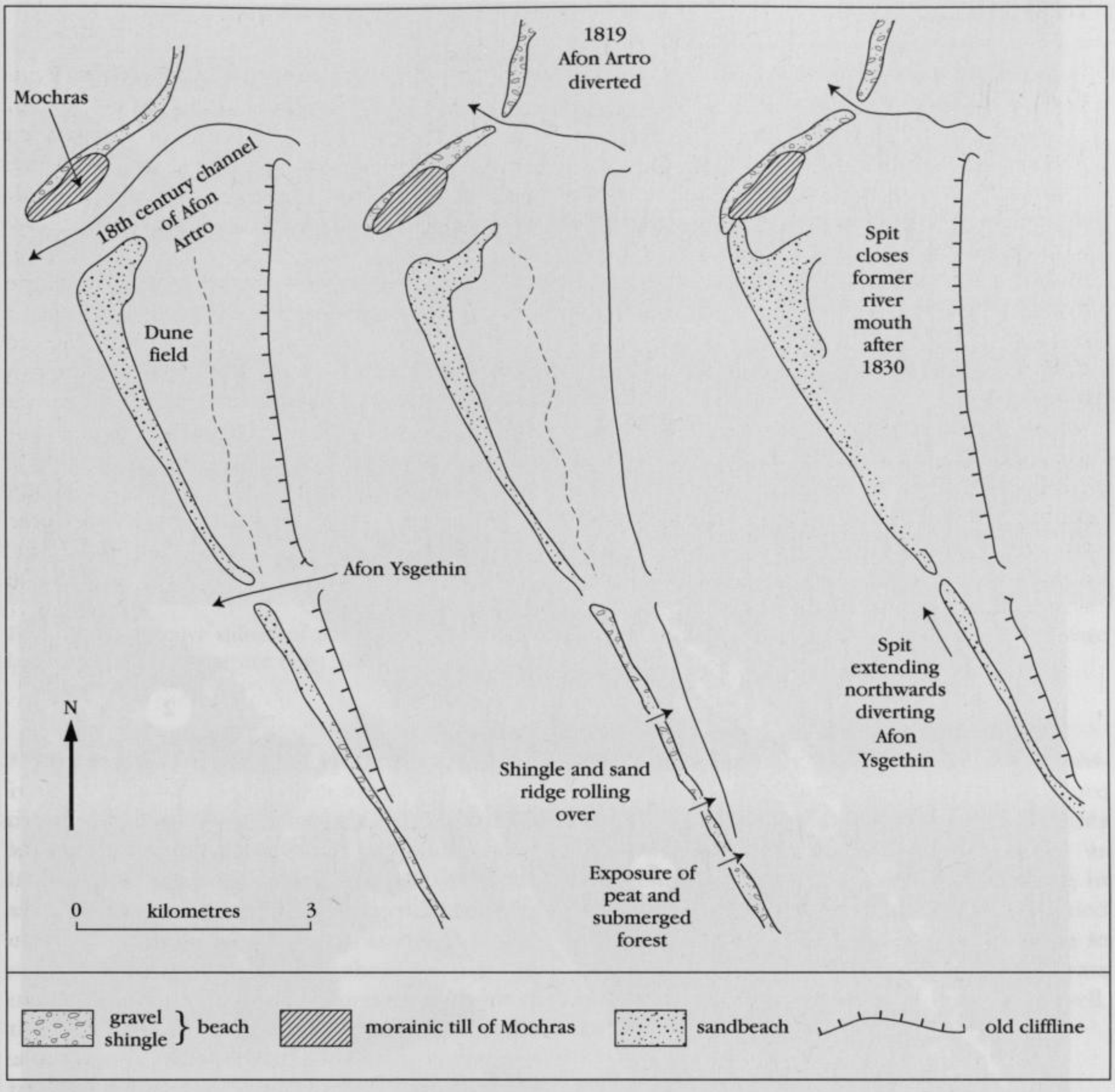

Figure 8.20 The historical development of Morfa Dyffryn. During the eighteenth century the sand beach was separated from the morainic hill of Mochras by the channel of the Afon Artro and formed a spit with recurves at its northern end. In 1829, the Afon Artro was diverted to the east of Mochras. About the same time, the southern beach was transgressing inland. By 1830, the spit had closed the former river mouth and had joined Mochras. In the south, a new spit was developing northwards across the mouth of the Afon Ysgethin.

been effective in providing a promontory against which the low-water beach has been aligned.

Despite its description in textbooks, Morfa Dyffryn cannot be regarded as a good example of a cuspate foreland, for the ness form is a cliffed headland rather than a coastal depositional structure. The presence of this relatively resistant headland has produced a situation in which the beach has tied the headland to the mainland and the beach has attained its present-day alignment as a result. The dune and beach system is better described as a tombolo, which makes Morfa Dyffryn a particularly large example. To some extent its size and alignment have been affected by the shallow area upon which it is built. There are many beaches whose low-tide alignment appears to be particularly influential in the long-term development of the position of the shoreline. It is apparent both at Holy Island,

Figure 8.21 Aerial photograph of part of the northern sector of Morfa Dyffryn with sand transfers and the main geomorphological features numbered. 1 = till boulder and cobble beach derived from erosion of Mochras; 2 = main active zone of dunes and spit distal link with former island; 3 = major blowthrough; 4 = bar merging with beach – maintains sand supply to dunes; 5 = intertidal ridge and runnel; 6 = prevailing and dominant wave direction. (Photo: courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

Figure 8.22 Active dunes of Morfa Dyffryn migrating eastwards (in the foreground) are affected by a large blowthrough to the centre right. (Photo: V.J. May)

Northumberland, and at Morfa Dyffryn, for example, that there has been much less change during the last 150 years in the alignment of the low-tide shoreline than of the high-tide shoreline. Because waves approaching the high-tide shoreline are refracted by the intertidal features especially on the low angles associated with sandy foreshores, the low tide shoreline plays an important role in the long-term development of the beach itself. At Morfa Dyffryn the low-tide alignment of the shoreline is strongly controlled by swell and the presence of Sarn Badrig, Mochras and the shoreline at Llanbedr, features that have not changed their positions significantly during the last 150 years. As a result, Morfa Dyffryn is not only a fine example of the process by which beaches align normal to the dominant waves (first outlined by Lewis, 1931, 1938), but also demonstrates the importance of the low tide coastal outline in controlling the alignment of the shoreline.

It is also a good example of sediment supply from the seabed. In this respect it is a comparatively rare feature in global terms for most sandy beaches are in deficit having passed the stage of sediment storage that characterized the Holocene transgression (Bird, 1985). Only about 20% of the world's sandy beaches are prograding, but Morfa Dyffryn has a shoreline that is maintained naturally, despite considerable transport of sand by wind into the dunes (Figure 8.22). Morfa Dyffryn differs from other features with which it has been compared such as Dungeness, Kent, and Benacre Ness, Suffolk, in being (a) dominated by extensive dunes, (b) tied to a headland, and (c) comparatively stable in position, although its dunes individually migrate inland at rates in excess of 6 m a^{-1} (Ranwell, 1972).

Conclusions

Morfa Dyffryn is distinguished by a beach and dunes whose alignment towards the dominant south-westerly waves is controlled by a till headland and the alignment of the low-tide shoreline. Its interest lies in its association with the subtidal and intertidal ridge of Sarn Badrig, its dunes and its comparative stability. The main present-day source of sediment appears to be the seabed. Morfa Dyffryn has been wrongly described in the past as a cuspate foreland because although its form is cuspate, this results from the presence of the headland at Mochras rather than from the realignment of beach sediments as occurs in true cuspate forelands. However, it is a fine example of a large sand tombolo and so an important and unusual feature of the British coastline.

ST NINIAN'S TOMBOLO, SHETLAND (HU 371 208)

J.D. Hansom

Introduction

St Ninian's tombolo, the largest geomorphologically active sand tombolo in Britain, is a classic geomorphological feature of national importance. The tombolo links the south-west Shetland Mainland to the small off-lying island of St Ninian's Isle (Figure 8.23). Although tombolos are by no means rare in an archipelago environment, they are numerically scarce relative to other classic forms of marine deposition (spits and bars). In the Northern Isles, tombolos (ayres) are generally formed of gravel, cobbles or occasionally boulders. St Ninian's tombolo is distinctive among its fellows in being composed mainly of sand. In addition, unlike many other ayres that are relict in terms of their evolution and relationship to contemporary sea level, St Ninian's tombolo is a geomorphologically active feature linked to a nearshore sediment circulatory system (Nature Conservancy Council, 1976; Smith, 1993; Bentley, 1996d). The tombolo is flanked on either end by areas of dunes and hill machair, enhancing the geomorphological interest. This almost perfectly formed feature set in a highly scenic part of the Shetland Isles must be one of the most outstanding tombolos in the world.

Description

St Ninian's tombolo is a large (*c.* 500 m in length along its central axis) sand tombolo linking St Ninian's Isle to the Shetland Mainland (Figures 8.23 and 8.24). By its very existence as a tombolo and its location, the beach is subject to wave activity from two completely opposing directions and is thus more liable to natural fluctuations of profile and beach area than a conventional arcuate beach. The beaches facing to the north and the south form long sweeping arcs stretching between the cliffs on either side of Bigton Wick to the north and St Ninian's Bay to the south (Figure 8.24). Waves approaching these beaches tend to break simultaneously along their entire length, suggesting that the planforms of each beach are in equilibrium with the approaching waves (Bentley, 1996d). The tombolo is strikingly symmetrical in plan (Smith, 1993; Bentley, 1996d) although it experiences changes in intertidal width and profile characteristics as a result of tidal and weather events. During low spring tides the tombolo is 60–70 m wide, while during the highest spring tides the central part may be completely covered in water. Typically the central part of the tombolo is 20–30 m wide at high tide (Figure 8.23).

St Ninian's tombolo is composed almost entirely of medium-grained sand (D_{50} = 0.24 mm) with a carbonate content of around 50%. However, there is evidence that the beach sand overlies a gravel base (Flinn, 1974; Smith, 1993). Flinn (1974) identified 'a rock base presumably of pebbles' at a depth of *c.* 2 m in two distinct locations using a probe and in several areas of the beach a scattering of flat pebbles lie on the surface. The tombolo appears to be nourished by nearshore sand sediment banks (Smith, 1993; Bentley, 1996d), although the exact mechanism of the sediment circulatory system at this site is imperfectly understood. The tombolo is a dynamic landform, repeatedly adjusting its form in response to tides and waves. During periods of constructive wave action sediment is transported from nearshore sources to the beach, raising the beach profile. The direction of sediment movement is reversed during periods of destructive wave action and the beach profile lowered. Changes in the height (and hence width) of the beach therefore occur with changing weather and marine conditions. In general, the tombolo is lower and narrower in winter, and is best-developed in summer (Mather and Smith, 1974). However short-term fluctuations, as a result of storms or periods of fine weather, can be imposed on this seasonal trend. For example, during the storms in which the oil tanker *Braer* ran aground (January 1993) the centre of the tombolo was totally underwater for several days. After such storms a temporary channel may form through the centre of the tombolo, with water typically flowing from north to south (Bentley, 1996d). There is also some evidence to suggest that the tombolo shifted slightly to the north following the January 1993 storms (Bentley, 1996d) although this may have been a temporary feature caused by predominantly southerly winds at the time.

Vegetated blown sand deposits veneer the slopes on either end of the isthmus resting on bedrock and a thin layer of till. Dunes (vegetated by marram *Ammophila arenaria*) adjacent to the beach at either end are backed by more

Figure 8.23 St Ninian's tombolo, looking south-west towards St Ninian's Isle. Dunes flank either extremity of the sandy tombolo. During the highest spring tides the central part may be completely covered in water. (Photo: G. Satterley/SNH.)

extensive areas of hill machair blown sand that encroaches on pasture. The dunes and blown sand forms the sink for most of the sediment circulation system at St Ninian's tombolo. Once sand is incorporated into the sand plain it is unlikely to be re-incorporated into the system unless there is substantial erosion of the blown-sand areas (Bentley, 1996d). The dunes and machair have a relatively subdued topography, as a result of the influence of the underlying rock surfaces.

The volume of blown sand at the eastern end of the tombolo is much greater than that at the western end; a reflection of the dominance of westerly winds in Shetland (Smith, 1993). However, the morphology of this area has been altered dramatically by commercial sand extraction during the 1970s. A former extraction pit has since been naturally infilled by blown sand (Bentley, 1996d) and at present the dunes form low (<5 m) rolling mounds and hollows with small *Ammophila*-clad embryo dunes forming in a number of places. However, the coastal edge is distinctly erosional in character, particularly on the northern flank and there are a number of small blowthroughs within the dune system. The edge of the higher blown-sand area forms a prominent triangular-shaped bench landward of the dunes, backed by a thin cover of sand that is cut by a number of arcuate erosion scars. At the west end of the tombolo the dunes adjacent to the beach are heavily eroded. There are a number of active blowthroughs developing in the steep eroded and undercut dune face. However, despite this evidence of frontal erosion there was substantial sand accretion at the foot of the dune face in March 1996 (Bentley, 1996d). The hill dunes to landward have undergone advanced deflation (Smith, 1993, Bentley, 1996d), with low erosional scarps extending for several tens of metres often parallel to the contours of the slope.

Interpretation

St Ninian's tombolo most likely formed during a period of rising relative sea level (Smith, 1993; Bentley, 1996d). The relative sea level history of Shetland is one of progressive submergence since the decay of the late Devensian ice-sheet

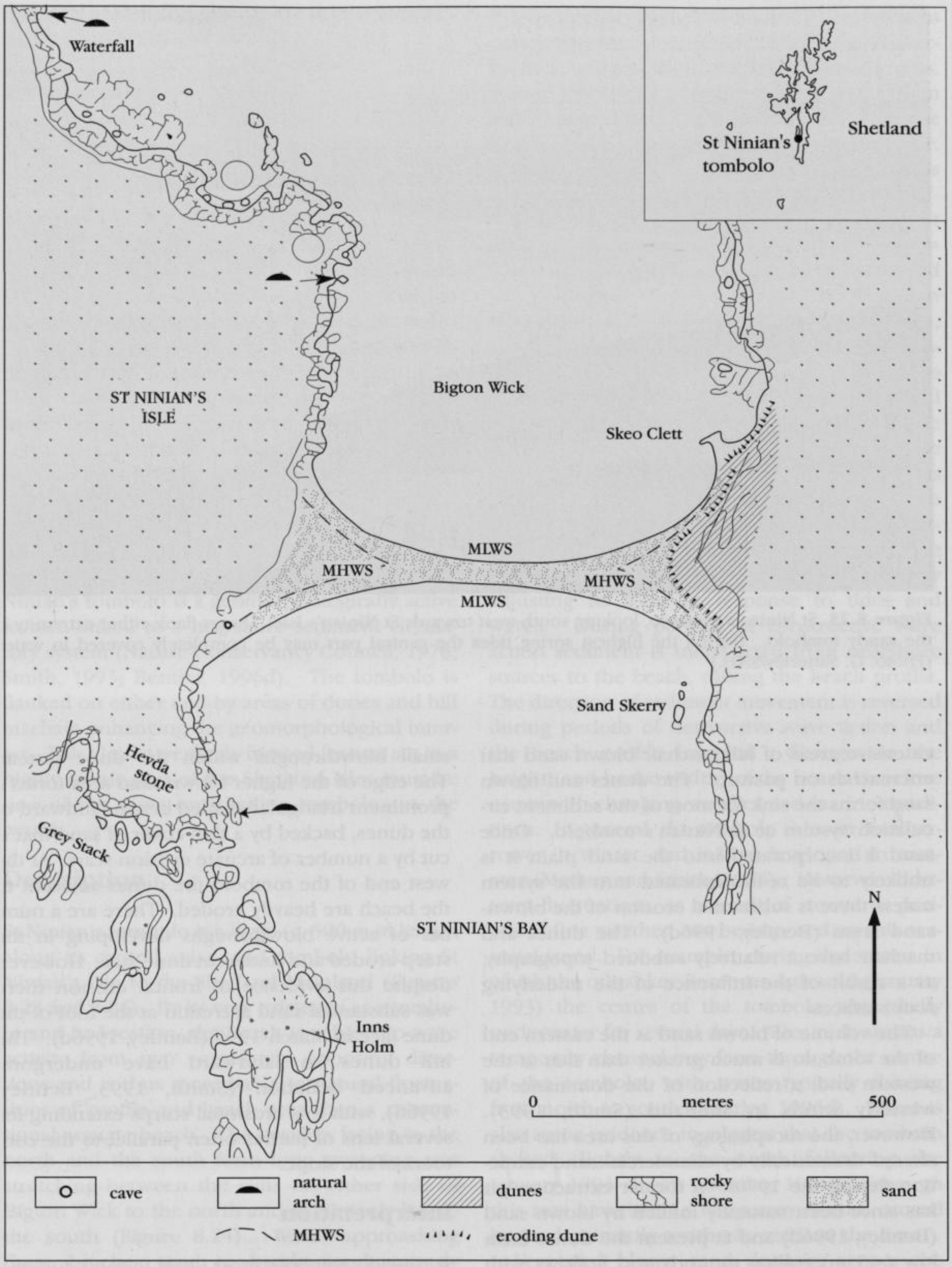

Figure 8.24 St Ninian's tombolo connects the Shetland mainland to an offshore island, and represents deposition from waves travelling south onto the north side, and vice versa in the south, in a very sheltered environment.

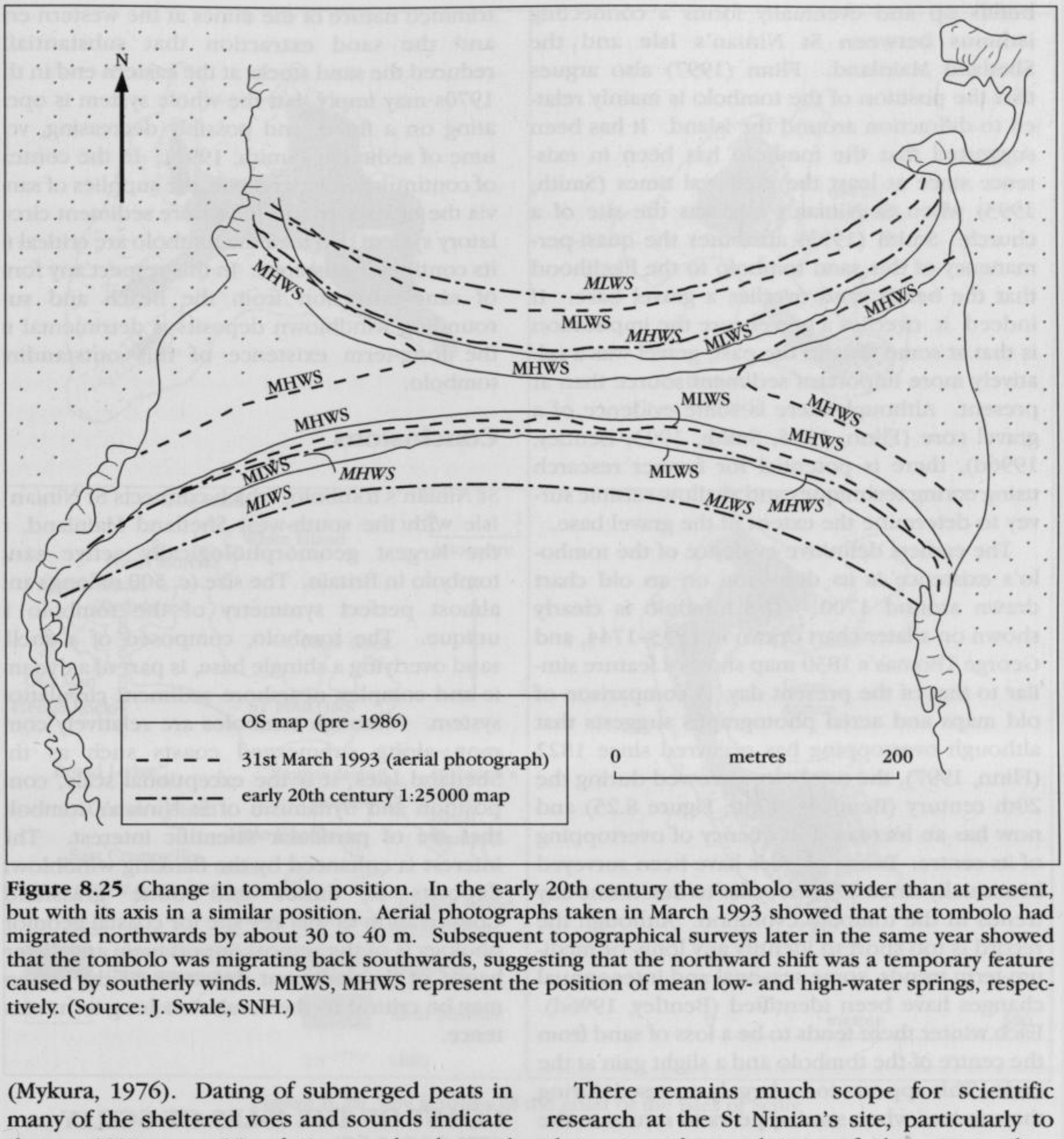

Figure 8.25 Change in tombolo position. In the early 20th century the tombolo was wider than at present, but with its axis in a similar position. Aerial photographs taken in March 1993 showed that the tombolo had migrated northwards by about 30 to 40 m. Subsequent topographical surveys later in the same year showed that the tombolo was migrating back southwards, suggesting that the northward shift was a temporary feature caused by southerly winds. MLWS, MHWS represent the position of mean low- and high-water springs, respectively. (Source: J. Swale, SNH.)

(Mykura, 1976). Dating of submerged peats in many of the sheltered voes and sounds indicate that *c*. 5500 years BP relative sea level stood around 9 m lower than at present (Hoppe, 1965). Depositional features such as tombolos, spits and bars are relatively common along recently submerged coasts (Johnson, 1919), although in the Northern Isles tombolos (ayres) are typically formed of shingle (e.g. the Ayres of Swinister, see GCR site report, this volume). The extensive sand tombolo of St Ninian's Isle, which is linked to the contemporary nearshore sediment circulation system, is distinctive in terms of its scale, composition and dynamism, and thus forms an unique component in the sand spit/tombolo GCR network.

There remains much scope for scientific research at the St Ninian's site, particularly to determine the evolution of this outstanding tombolo and investigate the complex relationship between sediment dynamics and relative sea-level change. At present, little is known concerning the exact evolution of the tombolo, except that it formed some time during the period of Holocene submergence of the Shetland coastline. The tombolo of St Ninian's Isle may have formed in a similar way to the South Ayre of Swinister. In this model, waves approaching from the west are diffracted and refracted around St Ninian's Isle, and eventually meet in the lee of the island. As the waves lose energy and deposit their load, sediment gradually builds up and eventually forms a connecting isthmus between St Ninian's Isle and the Shetland Mainland. Flinn (1997) also argues that the position of the tombolo is mainly related to diffraction around the island. It has been suggested that the tombolo has been in existence since at least the medieval times (Smith, 1993) when St Ninian's Isle was the site of a church. Smith (1993) attributes the quasi-permanency of this sand tombolo to the likelihood that the beach sand overlies a gravel base. If indeed it overlies a gravel core the implication is that at some time in the past, gravel was a relatively more important sediment source than at present. Although there is some evidence of a gravel core (Flinn, 1974; Smith, 1993; Bentley, 1996d), there is potential for further research using coring techniques and shallow seismic survey to determine the extent of the gravel base.

The earliest definitive evidence of the tombolo's existence is its depiction on an old chart drawn around 1700. The tombolo is clearly shown on a later chart drawn in 1743–1744, and George Thomas's 1830 map shows a feature similar to that of the present day. A comparison of old maps and aerial photographs suggests that although overtopping has occurred since 1822 (Flinn, 1997), the tombolo narrowed during the 20th century (Bentley, 1996d; Figure 8.25) and now has an increased frequency of overtopping of its centre. Beach profiles have been surveyed bi-annually since 1993 in order to determine any trends in the tombolo evolution. Although the record is too short to identify any long- or medium-term trends, some seasonal and inter-annual changes have been identified (Bentley, 1996d). Each winter there tends to be a loss of sand from the centre of the tombolo and a slight gain at the ends. This appears to be largely reversed during the summer when sand appears to return to the centre. However, in the interval between April 1993 and April 1994 there was a net loss of material from the centre of the tombolo, but at each end there were both localized gains and losses.

St Ninian's tombolo is linked to a nearshore sediment circulation system (Smith, 1993; Bentley, 1996d) where beach sediment is supplied from accumulations of sediment in the bays to the north and south. Smith (1993) expresses concern that the nearshore sediment bank has minimal possibilities of replenishment from nearby land sources, other than by wave erosion of blown-sand deposits at both the eastern and western ends. The seasonally wave-trimmed nature of the dunes at the western end and the sand extraction that substantially reduced the sand stocks at the eastern end in the 1970s may imply that the whole system is operating on a finite, and possibly decreasing, volume of sediment (Smith, 1993). In the context of continuing submergence, the supplies of sand via the nearshore and longshore sediment circulatory system that feed the tombolo are critical to its continued existence. In this respect any form of sand-extraction from the beach and surrounding windblown deposits is detrimental to the long-term existence of this outstanding tombolo.

Conclusions

St Ninian's tombolo, which connects St Ninian's Isle with the south-west Shetland Mainland, is the largest geomorphologically active sand tombolo in Britain. The size (*c.* 500 m long) and almost perfect symmetry of the tombolo is unique. The tombolo, composed of a shelly sand overlying a shingle base, is part of a dynamic and complex nearshore sediment circulation system. Although tombolos are relatively common along submerged coasts such as the Shetland Isles, it is the exceptional scale, composition and dynamism of St Ninian's tombolo that are of particular scientific interest. This interest is enhanced by the flanking windblown deposits of dunes and dune grassland. Conservation of this key site for coastal geomorphology is of the utmost importance; any disturbance of the sediment dynamics of the system may be critical to the tombolo's long-term existence.

COAST OF THE ISLES OF SCILLY (SV 910 165)

V.J. May

Introduction

The Isles of Scilly comprise five main islands, St Mary's, Tresco, St Martin's, Bryher and St Agnes, and over 100 smaller islands and islets (see Figure 8.2 for general location and Figure 8.26). Many of the larger islands have been formed by the linking together of smaller islands by sand tombolos, but some are linked by low terraces underlain by head and/or till (Barrow and Flett,

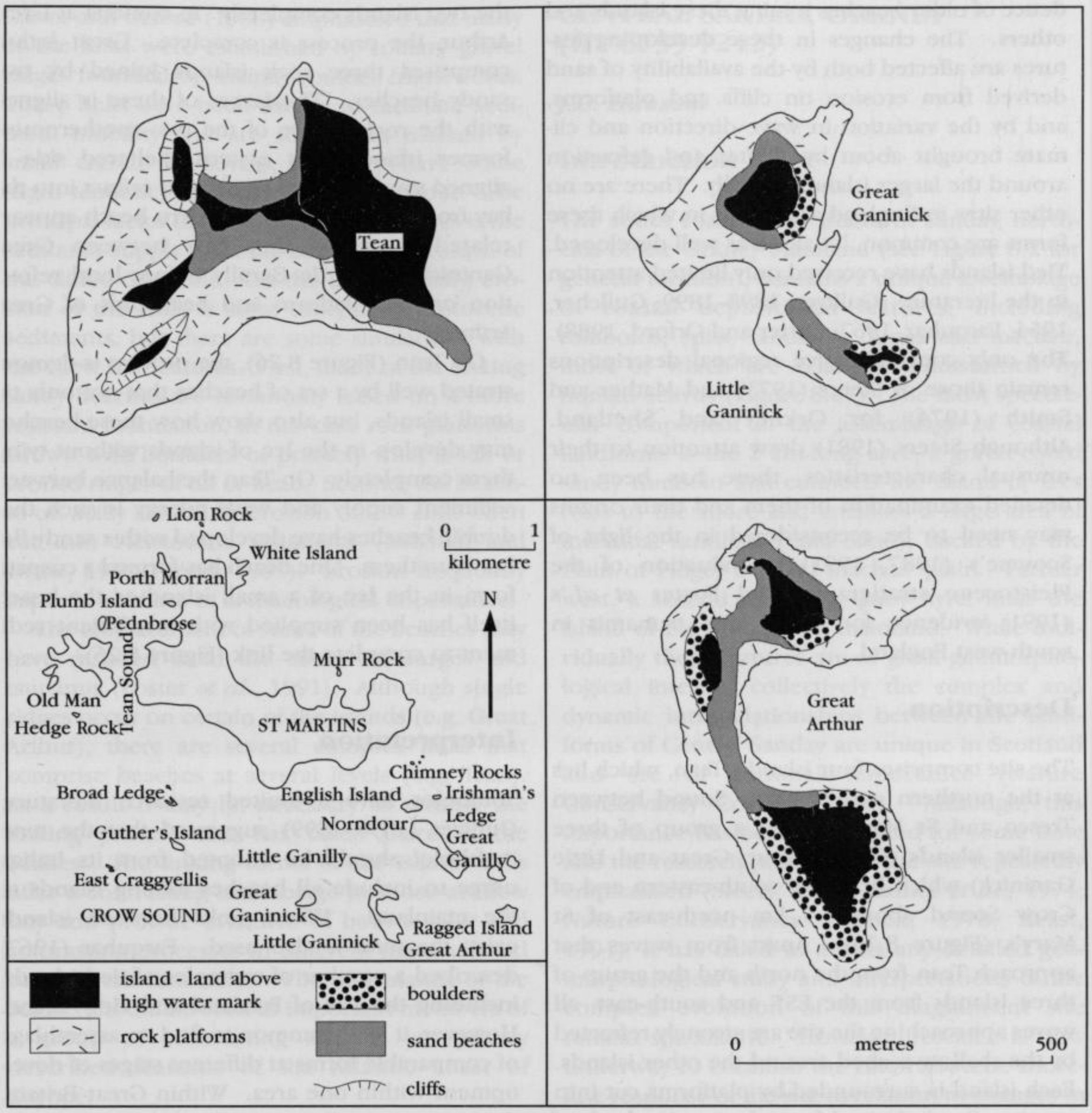

Figure 8.26 Key features of the coast of the Isles of Scilly.

1906; Mitchell and Orme, 1967). For example, the largest settlement on St Mary's, Hugh Town, is built mainly on a low isthmus fringed by sandy beaches. Apart from the islands of Scotland (mainly Orkney and Shetland) where Steers (1973) described over 40 such features, the Isles of Scilly contain the largest assemblage of tied islands in Great Britain. The beaches are predominantly sandy, derived from the weathering and erosion of head and/or till as well as the mainly granitic rocks that form the islands. Many of the linking beaches have been built upon, but the four islands that comprise this GCR site represent best the different stages of island linking.

The islands of Great and Little Ganinick represent early stages in the process of island linkage with a beach ridge extending from Little Ganinick towards Great Ganinick. On Great Arthur, the processes of beach development have linked two former islands and a third is gradually being joined to them. On Tean, not only are three small islands with links at various stages of the linking sequence, but there is evidence of older beaches joining these islands and others. The changes in these developing features are affected both by the availability of sand derived from erosion on cliffs and platforms, and by the variation in wave direction and climate brought about by shelter and refraction around the larger islands of Scilly. There are no other sites in England and Wales in which these forms are common, let alone as well developed. Tied islands have received only limited attention in the literature (Gulliver, 1898–1899; Guilcher, 1954; Farquhar, 1967; Carter and Orford, 1988). The only comprehensive regional descriptions remain those of Steers (1973) and Mather and Smith (1974) for Orkney and Shetland. Although Steers (1981) drew attention to their unusual characteristics, there has been no detailed examination of them and their origins may need to be reconsidered in the light of Scourse's (1987, 1991) re-evaluation of the Pleistocene stratigraphy and Foster *et al.*'s (1991) evidence for surges and tsunamis in south-west England.

Description

The site comprises four islands, Tean, which lies at the northern end of Crow Sound between Tresco and St Martin's, and a group of three smaller islands (Great Arthur, Great and Little Ganinick) which lie at the south-eastern end of Crow Sound about 1.5 km north-east of St Mary's (Figure 8.26). Apart from waves that approach Tean from the north and the group of three islands from the ESE and south-east, all waves approaching the site are strongly refracted by the shallow seabed around the other islands. Each island is surrounded by platforms cut into granite. Sand, derived from the erosion both of these platforms and the cliffs and cliff-top sediments, supplies the beaches that rest upon the platforms. Their exact alignment depends upon wave direction and refraction between the major islands as well as over the platforms themselves.

At Great Ganinick, there are two beaches separated by zones of boulders. On the north side of the island (Figure 8.26), the beach forms a small cuspate foreland, whereas on the south side of the island the beach fringes the island. Little Ganinick has a single beach that trends north-westwards towards Great Ganinick. Although the sand of this beach spreads across the platform towards Great Ganinick, the sediment supply appears to be insufficient to link the two islands completely. In contrast at Great Arthur, the process is complete. Great Arthur comprises three rock islands joined by two sandy beaches. The larger of these is aligned with the rocky shore of the two southernmost former islands. Its eastern sheltered side is aligned towards small waves that refract into the bay from the east. The northern beach appears related to waves that pass between Great Ganinick and Little Ganilly before local refraction on the platform and headlands of Great Arthur.

On Tean (Figure 8.26), the process is demonstrated well by a set of beaches that not only tie small islands, but also show how these beaches may develop in the lee of islands without tying them completely. On Tean the balance between sediment supply and wave energy is such that double beaches have developed with a sandy flat between them. One beach has formed a cuspate form in the lee of a small island as the beach itself has been supplied with insufficient sediment to complete the link (Figure 8.26).

Interpretation

Tombolos have a limited research literature. Gulliver (1898–1899) suggested that the term 'tombolo' should be adopted from its Italian usage to include all beaches joining islands to the mainland. Where links between islands exist, the term is also used. Farquhar (1967) described a number of examples of tied islands, including the Isle of Portland and Holy Island. However, it is uncommon to find an assemblage of comparable forms at different stages of development within one area. Within Great Britain, there are two main areas where this occurs, the Isles of Scilly and Orkney and Shetland. Carter and Orford (1988) have described similar features on the drumlin coast of Clew Bay, County Mayo in the Republic of Ireland. Elsewhere within Europe, many of the best examples occur along the Italian coast. This site is, therefore, an important element in the assemblage of coastal landforms in southern Britain. It differs, both in its scale and the variety of forms within it, from Farquhar's other tied island site (Holy Island, Northumberland). Whereas Holy Island is affected by refracted North Sea swell, the features in Scilly are related to both refracted Atlantic swell and local wave systems within the island group.

In their study of linked islands in Clew Bay, Carter and Orford (1988) emphasized that many of the links were established by solitary gravel ridges founded on coarse boulder frameworks. These links have been shown to facilitate sediment mobility and are sometimes marked by small crestal washovers, i.e. they have some slight tendency to transgressive behaviour. The principal factor in maintaining the beaches is the sediment supply from the continuing erosion of the cliffed drumlins. On the Isles of Scilly, erosion of the cliffs is slow, except in Pleistocene sediments, but there are some similarities with the Clew Bay features. First, many of the linking sandy beaches are commonly based on a more resistant foundation, in this case rock platforms strewn with boulders or possibly what is left or eroded ridges of till or head. Second, the beaches on Scilly are fed by erosion of low cliffs often cut into Pleistocene sediments (Mitchell and Orme, 1967; Steers, 1981). Erosion frequently exposes artefacts of archaeological importance.

The emplacement of some of the beaches may have resulted from the effects of surges and tsunamis (Foster *et al.*, 1991). Although single ridges occur on certain of the islands (e.g. Great Arthur), there are several complex links that comprise beaches at several levels (e.g. Tean). As a result it may be necessary to rethink the linking process that has taken place in the Scillies. The linking forms of the islands thus offer a contrasting assemblage to those at Clew Bay and provide evidence of both similar and contrasting processes in different materials and on different timescales. The tied islands of the Scillies should be seen as important members of a group of contrasting and as yet poorly described features of the Atlantic coast of Europe.

Conclusions

Tied islands are rarely observed in England and Wales, but they are more common in the islands of Scotland and in Ireland. The Isles of Scilly include the largest British group of tied islands at various stages of development outside Orkney and Shetland. Their small size and variety makes them a very important location for further research into the relationships between sediment supply, sea level, wave patterns and beach development that bring about tied island formation; the site will be important for the study of the effects of sea-level rise on the completion of island tying.

CENTRAL SANDAY, ORKNEY (HY 6739 7242)

J.D. Hansom

Introduction

The south coast of the island of Sanday, north-east of the Orkney Mainland (see Figure 8.2 for general location), contains a unique assemblage of coastal depositional features, including tombolos, spits, sandflats, dunes and machair, most of which are relatively undisturbed by human activity (Figure 8.27). The most spectacular component of the assemblage of coastal landforms is the 2 km-long ayre, a gravel-cored sandy tombolo that connects the island of Tres Ness to the shore and encloses a large area of intertidal sandflats (Cata Sand), backed by the Plain of Fidge, a broad machair plain. Farther west, a second tombolo, Quoy Ayre, links the island of Els Ness to the mainland. While individually these features are of great geomorphological interest, collectively the complex and dynamic inter-relationships between the landforms of Central Sanday are unique in Scotland and are of national importance (Nature Conservancy Council, 1978). Although, this importance has been recognized for some time and the research potential of the site repeatedly emphasized (Steers, 1973; Mather *et al.*, 1974; Nature Conservancy Council, 1978; Keast, 1994), it has failed to attract any detailed geomorphological study and interpretations of the complex evolution of this magnificent site remain speculative. However, research is now underway to establish the Late-Holocene shoreline response of the site in relation to changes in sea level and sediment supply (Rennie and Hansom, 2001).

Description

The extensive GCR site of Central Sanday, covering an area of *c.* 660 ha, consists of a complex series of depositional features. Two former islands (Tres Ness and Els Ness) are connected to the main island by dune-capped sand tombolos that partially enclose two embayments containing wide tidal sandflats (Little Sea and Cata Sand) (Figures 8.27 and 8.28). Short gravel-spits extend across the mouths of the embayments. Extensive areas of machair have formed landwards of the beaches.

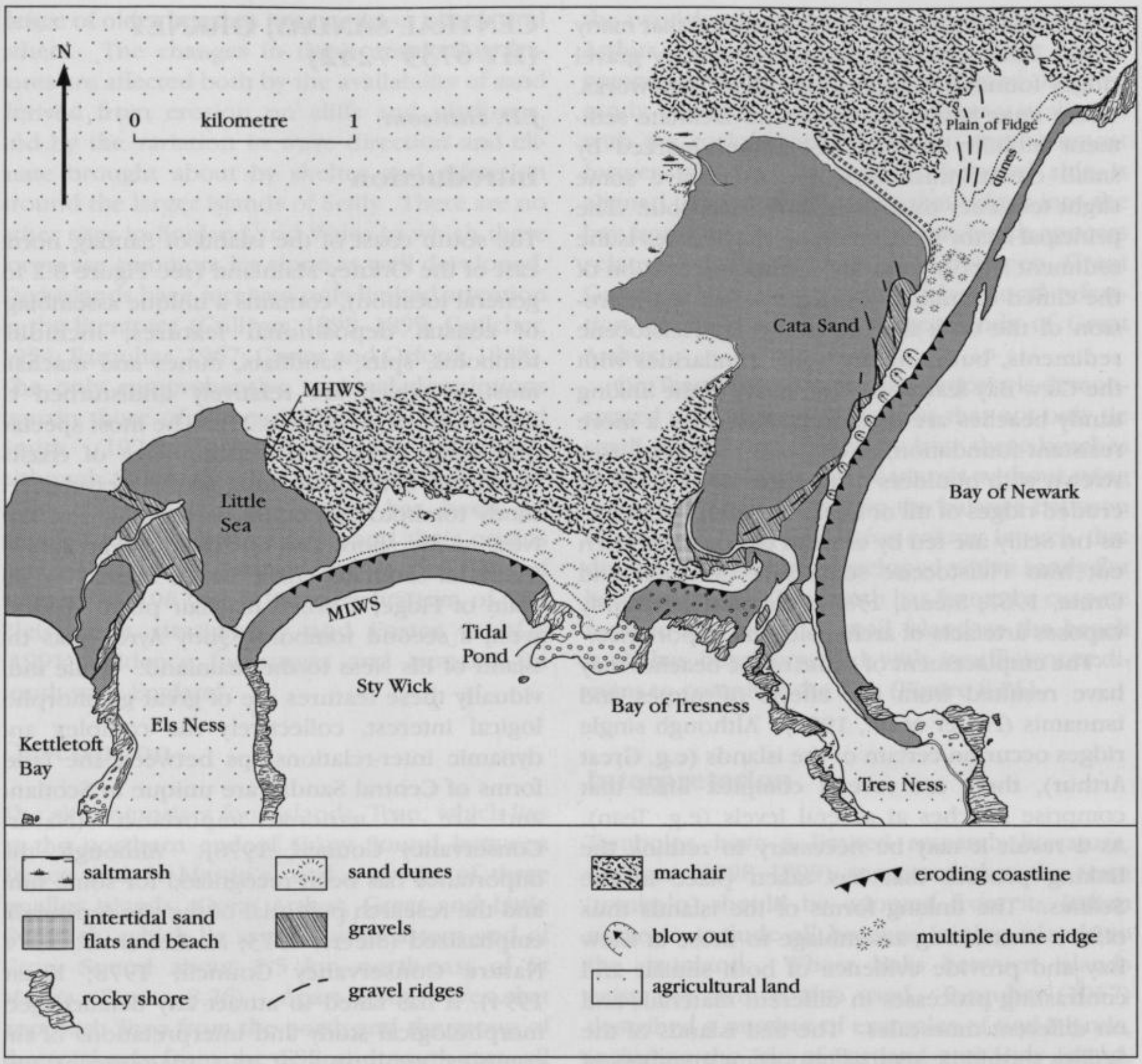

Figure 8.27 Geomorphological map of central Sanday showing the two tombolos that enclose Cata Sand and Little Sea. Note the orientation of the gravel ridges in Cata Sand. MHWS: Mean High-Water Springs; MLWS: Mean Low-Water Springs. (After Rennie and Hansom, 2001.)

The eastern part of this extensive site, the Bay of Newark is the largest and most complex beach unit in Orkney (Mather *et al.*, 1974; Nature Conservancy Council, 1978). The physiography is complex, consisting of sandflats, a dune-capped tombolo and the remnants of gravel ridges that underlie the site marking several stages in coastal evolution. The eastern end of the bay close to the Plain of Fidge consists of a complex of geomorphologically inactive sand dunes and parabolic blowthroughs. These steep, 7–10 m-high, longitudinal sand dune ridges trend almost at right-angles to the present-day coastline and although a few moribund stands of marram *Ammophila arenaria* survive, the Plain of Fidge contains the largest area of machair outwith the Western Isles (Mather *et al.*, 1974; Nature Conservancy Council, 1978). Two separate levels separated by an erosional scarp occur, the lower of these representing a deflation surface close to the water table. In places the scarp is undergoing erosion with a distinctive series of finger-like blowthroughs at the scarp edge. In the western part of the bay a 2 km-long dune-capped tombolo connects the island of Tres Ness to mainland Sanday, enclosing the tidal sandflat of Cata Sand (Figure 8.28). In plan, the tombolo is long, straight and narrows towards its southern end to only 30 m wide. The present-day beach consists almost exclusively of shell-rich, medium-grained sand (D_{50} = 0.29 mm) although gravel occurs at the extreme southern end of the tombolo where it hinges onto a low sandstone platform. The tombolo is capped by a single linear dune ridge, rising to *c.* 13 m in height, composed mainly of fixed dunes with local areas of mobile dunes (Keast, 1994). The most dynamic section of the dune ridge is at the narrow southern end of the tombolo, where unfixed dunes have been dissected by several blowthroughs, the largest of which is up to 40 m in wide. Mather *et al.* (1974) report no gravel at the base of these blowthroughs, however Keast (1994) found gravel at the base of the dunes, and substantial amounts were recorded during bi-annual field visits made by the author between 2000 and 2002. Unconfirmed reports suggest that the tombolo was breached at its southern end during storm conditions in the 1980s.

A system of gravel ridges underlie the machair of the Plain of Fidge at the mainland root of the sand tombolo and are also visible on Cata Sand where north-westerly relict gravel ridges diverge from the northward-trending dune-capped tombolo (Figure 8.28). The low gravel ridges form broad arcs, trending north and north-west from the outlet of Cata Sand. The linear dunes capping the tombolo rest on these gravel ridges, many of which are exposed at low tide (Nature Conservancy Council, 1978; Keast, 1994). The differences, both in composition and orientation, between these relict gravel features and contemporary sand landforms suggest a very different depositional environment in the past.

Farther west, a second dune-capped tombolo links the former island of Els Ness to the mainland of Sanday, enclosing the wide tidal sandflat of Little Sea. The tombolo (Quoy Ayre) forms the western part of the wide south-facing embayment of Sty Wick and is symmetrical in plan (Figure 8.27). The linear dune ridge capping the tombolo reaches a maximum height of 9 m towards the centre of the tombolo and consists almost entirely of highly stable and well-vegetated fixed dunes. Gravel is well-exposed at Quoy Ayre and appears to underlie the dune ridge.

The two sandflats (Little Sea and Cata Sand) are completely closed on their south and south-eastern sides by the dune-capped tombolos. Their outlets are towards the south-west, both of which are partly enclosed by spits. Short gravel spits project outwards from each flank of the outlet of Little Sea, but appear to be relatively inactive features in spite of lacking a cap of blown sand. Cata Sand is partly enclosed by a low, dune-capped, rounded spit, which extends 0.5 km eastwards across the outlet. This spit is underlain by low belts of gravel that are a south-west continuation of the relict ridge system visible in Cata Sand. Much of this short stubby spit is capped by stable sand dunes grading landwards into machair, although the tip of the spit supports low embryo dunes that are still developing. Comparison with aerial photographs and field evidence suggest that the spit tip is highly dynamic, alternating between short periods of erosion and accretion (Mather *et al.*, 1974; Keast, 1994). A smaller gravel spit projects northwards from Tres Ness on the other side of the outlet.

Interpretation

In spite of the wealth of the landform assemblage at Central Sanday, until recently there has been limited detailed geomorphological research carried out (Rennie and Hansom, 2001). Although the interpretation of the Central Sanday site is necessarily speculative, the inter-relationships of the landform assemblage within this dynamic system are of national importance (Steers, 1973; Mather *et al.*, 1974; Nature Conservancy Council, 1978; Keast, 1994), particularly as there has been almost no anthropogenic modification to the natural system. The two sand-capped tombolos are spectacular landforms yet the underlying gravel ridge orientations are at odds with the present-day coastal trend. The site is a key area for the study of constructive shoreline processes in an area of relative subsidence and so has great research potential.

Throughout much of the Holocene Epoch, the coastline of Orkney has undergone approximately similar amounts of submergence to Shetland (Lambeck, 1993) (see Figure 6.28). As a result, emerged shoreline features are absent in Orkney and are replaced by features of submergence so that the low gradient coast of Sanday has undergone significant alteration in planform and as bays became flooded, peninsulas became islands and beaches changed orien-

Figure 8.28 Looking north-east along the dune-capped tombolo in the Bay of Newark. Older intertidal gravel ridges can be seen extending inland towards the north in Cata Sand. (Photo: J.D. Hansom.)

tation in response. On Sanday, the pattern of sea-level rise flooding embayments and isolated islands has been in part reversed by a healthy sediment supply that has connected or reconnected islands to the mainland. Historical map evidence exists in support of these changes. On John Thomson's map of 1832 (Figure 8.29), the low-lying former islands of Tres Ness and Els Ness that lie to the south of the mainland of Sanday, together with the offshore island of Start Point to the north, are depicted as long narrow peninsulas. The nature of these peninsulas is not known, but the form of Els Ness and Tres Ness suggests that they were, at least in part, complexes of gravel ridges, substantially wider than those at present, enclosing low-lying or flooded areas behind. The same map shows the area of Little Sea as a freshwater loch and the area that is now Cata Sand as a low area, possibly of seasonally-flooded machair or 'winter loch'. However, a map of 1847 shows both the loch at Little Sea and the low land at Cata Sand to be arms of the sea as they are today and, if both maps are accurate, marine inundation may have occurred between 1822 and 1847 (Black, 1847).

Central Sanday is a good example of a feature common to the sandy and dune-backed beaches of Scotland where a backbone of gravel provides the base on which wave-deposited or blown sand later accumulates (Mather *et al.*, 1974). The gravels then play an important shaping role in the evolution of what are now mainly sandy beach complexes. For example, the gravel ridges that originally began the process of enclosure of the Cata Sand basin are visible under the machair of the Plain of Fidge (Mather *et al.*, 1974), but their mainly north-west orientations differ from the contemporary north-trending dune-capped tombolo of the present-day coast. This suggests that at some time in the past the embayment was partly enclosed by gravel ridges deposited at different orientations to the contemporary constructional sand features. In addition, at some period prior to the tying of Tres Ness to the mainland of Sanday, gravel was a relatively more important beach material than at present, highlighting a change in sediment supply over time, and possible relationships to an altered offshore sediment supply.

The orientation of the gravel ridges led Mather *et al.*, 1974 to suggest that they were hinged on a point under the Plain of Fidge and so had extended southwards as a result of long-

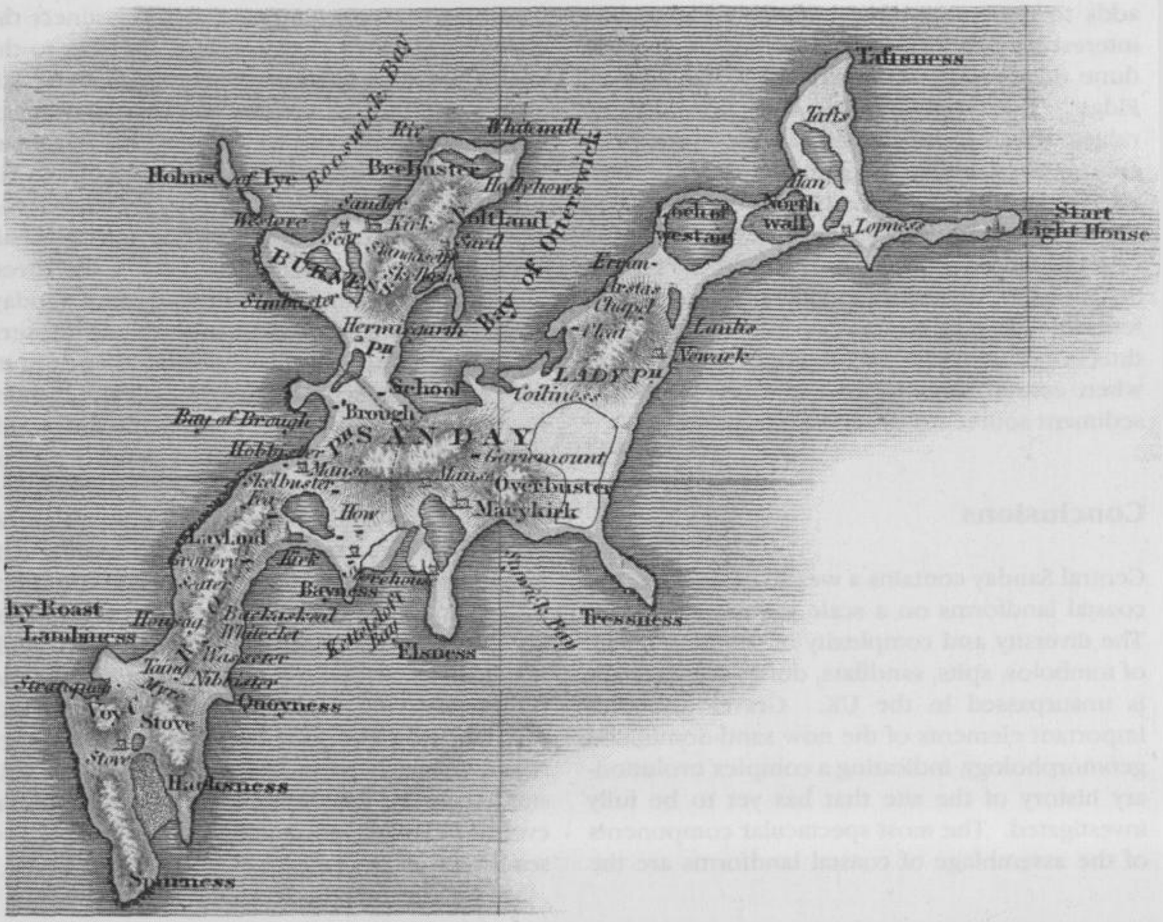

Figure 8.29 Coastline of Sanday in 1822 (from Thomson, 1832). Note the modern marine inlet at Cata Sand is mapped as a low area of land, possibly machair; the modern marine inlet of Little Sea is mapped as a freshwater lake and Start Island is mapped as a promontory with a lighthouse at the end.

shore drift from the north. Recent detailed mapping and Ground Penetrating Radar survey shows that the ridges recurve and splay northwards, suggesting drift from the south. However, not all the ridges recurve to the north, particularly those close to the outlet of Cata Sand (Rennie and Hansom, 2001). Although these relationships are not yet fully established it seems likely that gravel spit extension from the south resulted in partial closure of a wide and open bay at Cata Sand. Such spit extension requires a plentiful supply of coarse sediment, and the sequential drowning of areas of low-lying till-covered bedrock at Tres Ness, along with sediment driven onshore from glacial gravel banks offshore, may well be the source of much of the spit gravel. As sea level rose to its present-day level over the Holocene Epoch, the gravel was driven onshore from its source areas on the shallow Sanday shelf by storm conditions. Such a scenario requires an ongoing supply of gravel to allow the moving spits and barriers to keep pace with sea-level rise and extend along the coast. If the supply was insufficient then erosion of the updrift gravels would have fuelled distal extension (Hansom, 1999). Such reductions in gravel supply occur elsewhere in Scotland and co-incide with the increasing importance of sand as a beach material about 6500 years BP (Carter, 1988).

The variety of dune types, morphologies and processes at Central Sanday are unusual and are of interest in their own right, forming the most complex and complete beach–dune–machair system outside of the Western Isles (Nature Conservancy Council, 1978). The relationship of the dunes and machair with the tombolos, spits and relict gravel ridges on which they rest, adds to their scientific interest. Of particular interest are the north-west-trending longitudinal dune ridges near the south end of the Plain of Fidge. The orientations of this suite of dune ridges, which trend at a high angle to the present-day coastal edge, suggest that they are related to a period prior to the tying of Tres Ness and the mainland of Sanday. No dates exist for the onset of sand deposition in the Plain of Fidge or Sty Wick but, since the sand has a high shell content, it is likely to be sourced from offshore and thus may date to the period after 6500 years BP when coastal sand became a more important sediment source for beaches.

Conclusions

Central Sanday contains a wealth of undisturbed coastal landforms on a scale unique in Britain. The diversity and complexity of the assemblage of tombolos, spits, sandflats, dunes and machair is unsurpassed in the UK. Gravel underlies important elements of the now sand-dominated geomorphology, indicating a complex evolutionary history of the site that has yet to be fully investigated. The most spectacular components of the assemblage of coastal landforms are the two dune-capped tombolos, which connect the former islands of Tres Ness and Els Ness to the mainland. The tombolo connecting Tres Ness is over 2 km long, enclosing the tidal sandflat of Cata Sand, while the shorter, but no less spectacular, tombolo, Quoy Ayre, encloses the embayment of Little Sea. Dunes are well-developed on both tombolos, grading into machair on their landward sides. The variety and diversity of the dune and machair of Central Sanday, the largest area of machair outwith the Western Isles, is of great geomorphological interest in its own right. Collectively, the complex and dynamic inter-relationships between both the wind-blown and wave-constructed landforms of Central Sanday are of national importance (Nature Conservancy Council, 1978). Central Sanday is a rare example of where a healthy sediment supply has led to island tying and tombolo building even though relative sea level is rising. It provides an excellent comparison with the Isles of Scilly (see GCR site report in the present volume) where sediment supply reduction may now preclude island tying as sea level rises. There is great research potential at this site and it is a key area for the study of coastal evolution and development in an area of relative sea-level rise.