NORTH NORFOLK COAST

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Introduction

The North Norfolk Coast GCR site extends from Hunstanton to Sheringham (see Figure5.13). It includes not only internationally renowned locations such as Blakeney Point (see Figure10.9) and Scolt Head Island, but also many smaller, but no less significant, beaches that form an integral part of the coastal system. Much of the site is characterized by a low upland fronted by gently sloping abandoned cliffs separated from sand and shingle beaches by extensive saltmarshes and intertidal flats. The saltmarshes of north Norfolk have been described as the finest coastal marshes in Great Britain (Steers, 1946b) and are among the best-documented and researched in the world. The marshes exhibit a progression of age and development from east to west, manifested through changes in marsh height and assemblage of geomorphological features. Creeks, saltpans and marsh stratigraphy are well exhibited on the north Norfolk marshes. The marshes have been a prime research site for the investigation of rates of saltmarsh accretion and tidal creek processes. At both the east and west ends of the site the beaches rest against retreating Chalk cliffs. Together with the intertidal flats and saltmarshes, the beaches of north Norfolk form one of the outstanding assemblages of coastal forms in Britain. Each of the major features is important in its own right: together they are of the highest importance. They have been extensively researched and are internationally famous (Redman, 1864; Wheeler, 1902; Oliver, 1913, 1929; Oliver and Salisbury, 1913; Hill and Hanley, 1914; Kendall, 1926; Steers, 1926a–c, 1927, 1929, 1934a–c, 1935a,b, 1936a,b, 1938a,b, 1939a, 1940, 1942, 1946a,b, 1948a,b, 1951a, 1952, 1953b, 1954, 1960, 1964a,b, 1971b, 1977, 1981; Steers and Kendall, 1928; Steers and Thomas, 1929a,b; Steers and Slater, 1932; Chapman, 1939, 1959; Burnaby, 1950; Grove, 1953; Steers and Grove, 1954; King, 1959, 1972b; Peake, 1960; Williams, 1960; Kidson, 1961; Hardy, 1964; 1966; Ranwell, 1964, 1968, 1972; Steers and Haas, 1964; Evans, 1965; Battarchaya, 1967; Roy, 1967; Zenkovich, 1967; Cambers, 1973, 1975; Pethick, 1974, 1980a,b, 1981, 1984, 1992; Barnes, 1977; Banham, 1979; Bayliss-Smith *et al.*, 1979; McCave, 1978a–c; Murphy and Funnell, 1979; Straw and Clayton, 1979; White, 1979; Barfoot and Tucker, 1980; Bird, 1984, 1985; Bird and Schwartz, 1985; Goudie and Gardner, 1985; Carter, 1988; Funnell and Pearson, 1989; Stoddart *et al.*, 1989; French *et al.*, 1990; Pye *et al.*, 1990; Bridges, 1991; Allen and Pye, 1992; French and Stoddart, 1992; Pye, 1992; French, 1993; Allison and Pye, 1994). The site is amongst those most quoted by textbooks concerned with physical geography, physical geology and geomorphology. Within the last decade, a major interdisciplinary collaborative study has gathered information allowing a more detailed and better-dated understanding of the Holocene evolution of this coastline (Chroston *et al.*, 1999; Andrews *et al.*, 2000; and Andrews and Chroston, 2000).

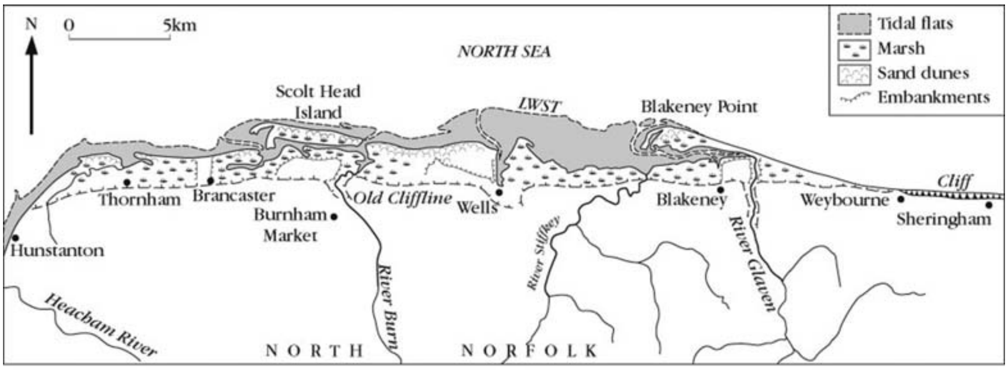
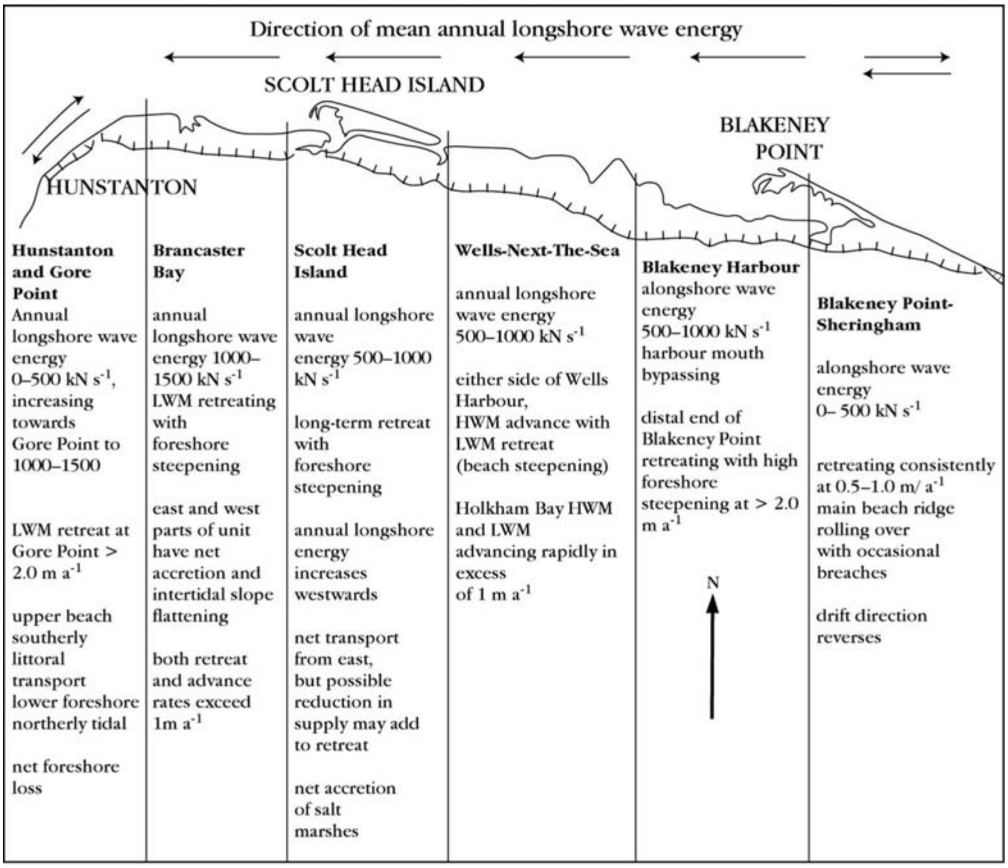


Fig 05.13

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

Figure 10.9: The distribution of saltpans on a saltmarsh at Blakeney Point, north Norfolk. (After Pethick, 1984, p. 164.)

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



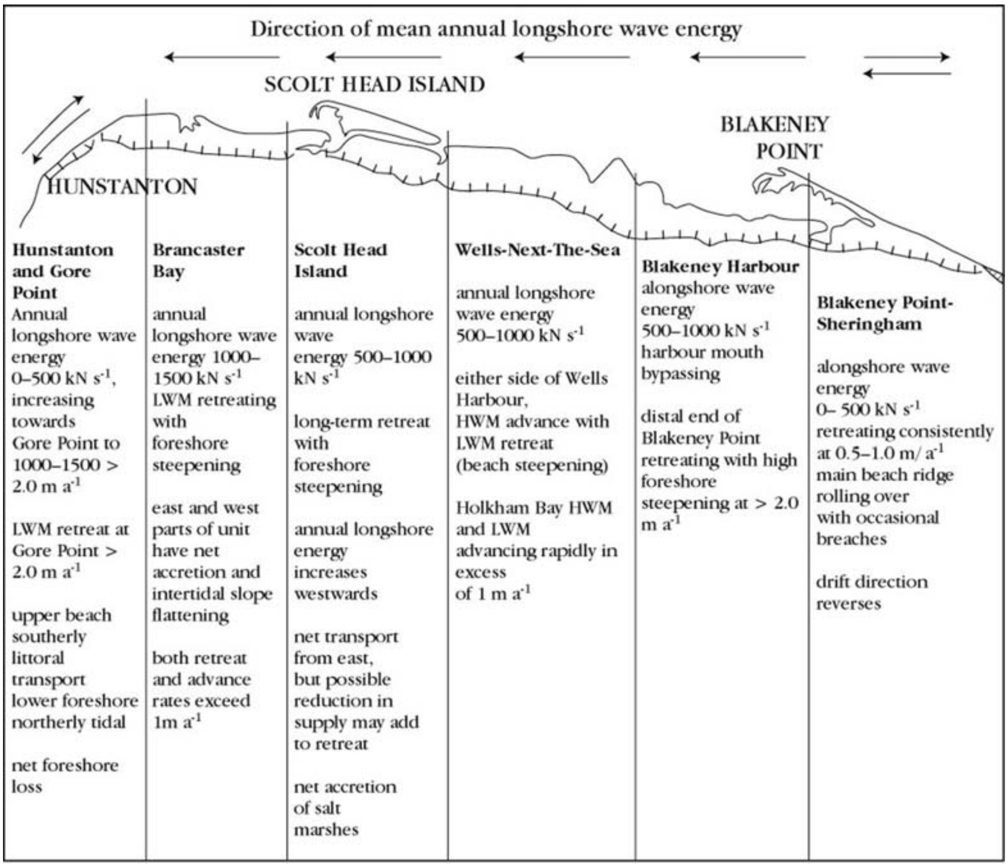


Figure 11.27: Summary features and recent dynamics of the North Norfolk Coast GCR site from Hunstanton to Sheringham, and east to west distance of about 40 km. (After Halcrow, 1988.)

1. Hunstanton to Holme-next-the-Sea: Chalk and Carstone cliffs that are undergoing erosion

are fronted by a wide sand and shingle beach that extends northwards beyond the cliffs to Holme-next-the-Sea where the fringing dunes reach their widest extent.

2. Holme-next-the-Sea to Brancaster: an area of dunes and beach ridges behind which lie both claimed marshland and natural saltmarsh.

3. Scolt Head Island: the best example of a barrier island on the British coast (Steers, 1981). Regular surveys since the early part of the 20th century make this one of the best-documented coastal sites anywhere in the world.

4. Gun Hill to Wells-next-the-Sea: dominated by a line of dunes known as ‘Holkham Meals'.

5. Wells Channel to Blakeney Spit: a large number of small bars of sand, shingle and shells, and an unusual, recurved cuspate beach.

6. Blakeney Point to Sheringham: an excellent example of a recurved spit formed mainly of a single shingle ridge (over 9 km in length) extending from a shingle beach at the foot of retreating till cliffs between Weybourne and Sheringham. Generally, but not exclusively, the inland boundary is marked by a low bluff (an earlier now degraded cliffline) or land-claim embankments.

Description

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

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

Cambers (1975) measured coastal change by comparing the 1:10 560 Ordnance Survey maps for the 1880s with those of the 1950s, and showed that for East Anglia as a whole the total area gained from the sea was 58 370 m^2 compared to a loss of 134 817 m^2. The north Norfolk coast was, however, mainly characterized by accretion, the only areas of erosion being at Brancaster Spit, the central part of Scolt Head Island and at the eastern end of Blakeney spit. Between Burnham Harbour and Wells, accretion was greater than 8 m a^{-1}, and between Holkham Gap and Wells the dunes advanced seawards over 100 m between the 1880s and the 1950s. The *Anglian Coastal Management Atlas* (Halcrow, 1988) indicates that erosion has become more widespread in the 1980s. In particular, although annual rates of retreat of high-water mark have been lower than 1.5 m over the last 100 years (Figure11.27), low- water mark has retreated by up to 4 m, so that the foreshore has generally been becoming steeper. There are in contrast many points along this coast where progradation has occurred, and the high-water mark has shifted seawards as the foreshore has steepened. In places the high-water mark and the low-water mark have both moved seaward and the foreshore slope has been maintained or even become shallower.

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

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

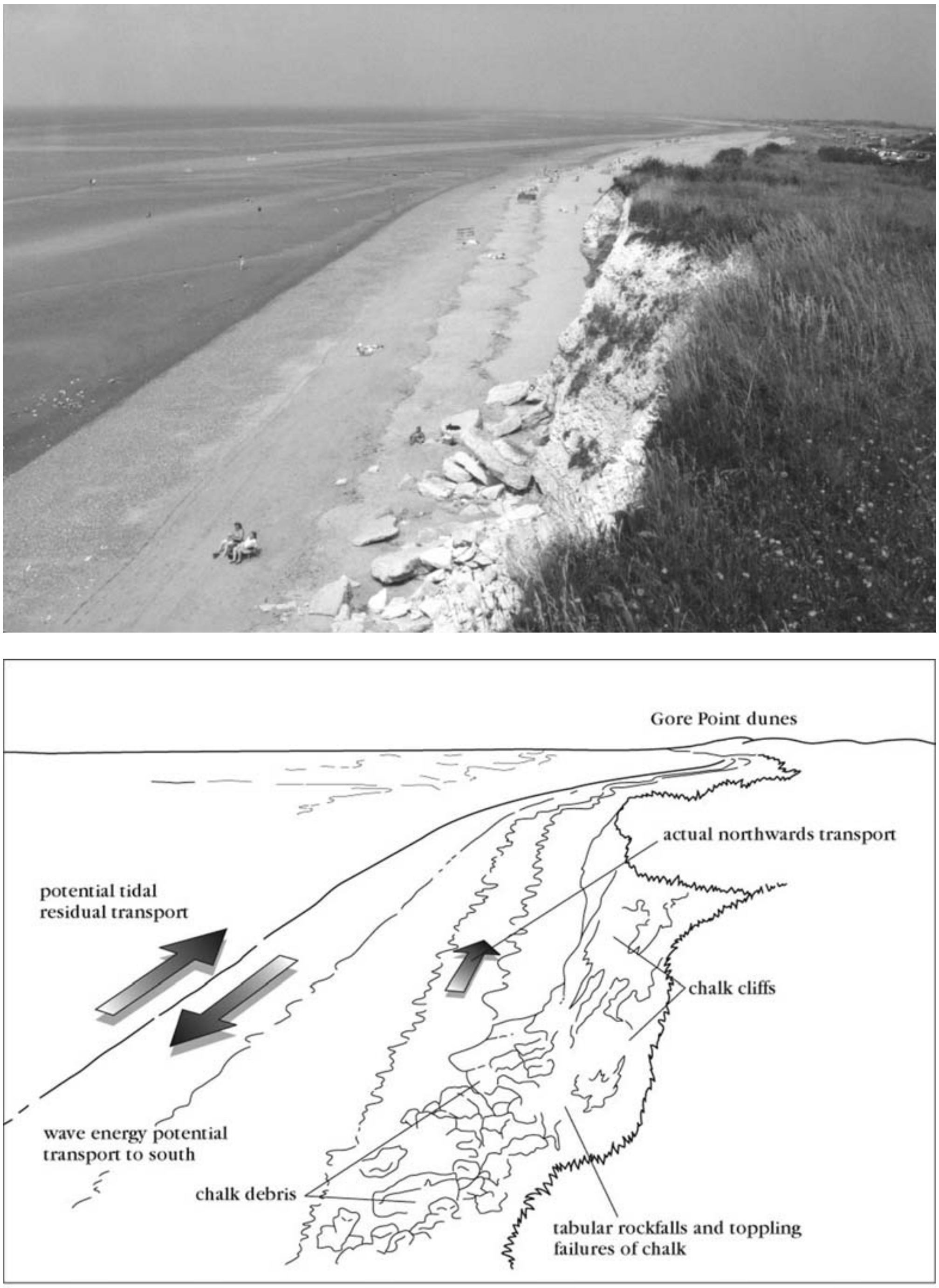


Figure 11.28: (a) The distinctive tabular chalk cliffs of Hunstanton, looking north. (b) Cartoon of potential transport mechanisms of rockfall debris from the failure of the chalk cliffs. (Photo: V.J. May.)

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

For much of the distance between Holme-next-the-Sea (TF 728 450) and Brancaster (TF 797 452), the shoreline is formed by dune ridges up to 400 m in width (Figure 11.29). Behind the dunes at East Sands and at Brancaster Golf Course there are extensive saltmarshes that have not been subject to land-claim (Murphy and Funnell, 1979), whereas the central 2 km of this beach has no dune belt and is backed by embanked and land-claimed marshland. Accretion is dominant at both ends of the beach but the central part is affected by erosion, notably along the frontage of the Golf Course. A short length of armoured embankment has been constructed to control shoreline retreat. Erosion at Brancaster revealed two peats, one at between –0.08 m OD and –0.15 m OD that included forest remnants and beech *Fagus* sp. seeds, the other higher at between 2.5 and 3.5 m OD (Bridges, 1991). Funnell and Pearson (1989; see also Andrews *et al*., 2000; Chroston *et al*., 1999) showed that there were over 8 m of Holocene sediment with a broad channel running parallel to the main dune ridge. The modern ridges are dynamic, the eastern ridges have grown eastwards, but were farther seawards in 1937 than in 1951, a trend that has continued. The spit at East Sands has grown considerably since Steers' 1935 survey, although the reason is not clear. Cambers (1975) suggested that it may be associated with material deposited via the Harbour Channel, but it is difficult to conceive how this channel, draining a mainly muddy marshland area, could provide sufficient sand for the growth that has occurred. The channel has moved away from the beach and so it seems more likely that sand is moving within the intertidal area between Holme and East Sands.

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

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

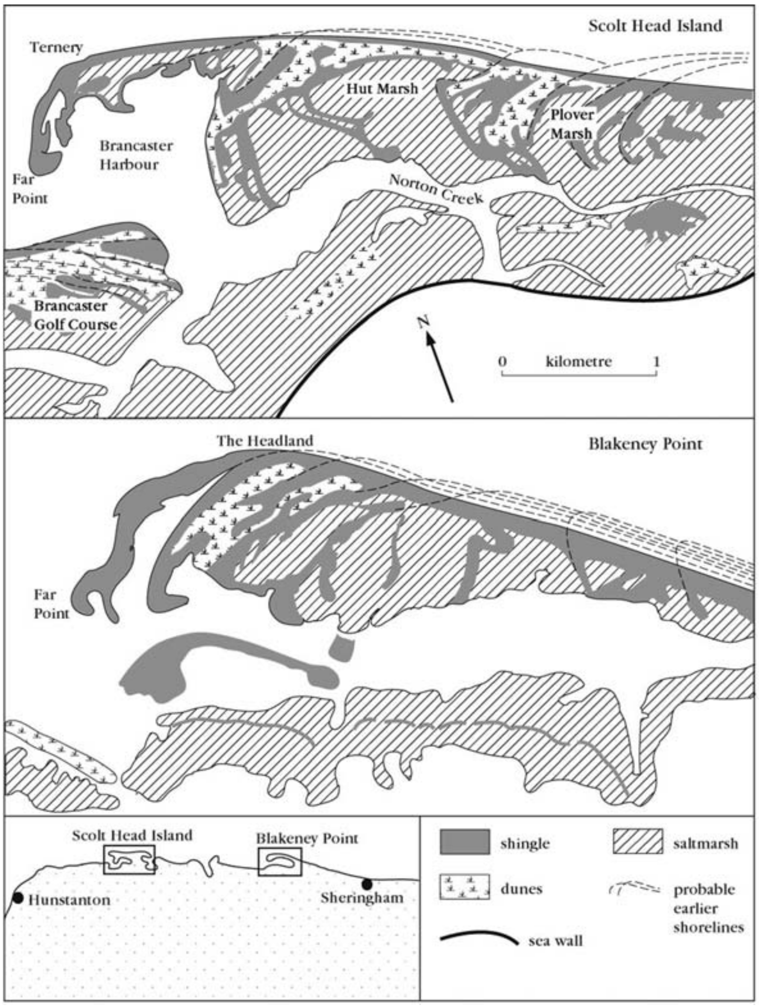


Figure 11.30: (a) Scolt Head Island geomorphological features. (Based mainly on Steers, 1946b, 1960; Bird, 1984, 1985; Halcrow 1988.) (b) Blakeney Point geomorphological features. (Based mainly on Steers, 1946b; Bird, 1984, 1985; Halcrow, 1988.)

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

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

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

Hut Marsh covers about 55 ha. The surface of its mature marsh lies at between 2.5 and 2.9 m OD (Stoddart *et al.*, 1989). Steep-sided deep creeks form a dendritic pattern, draining mostly into Hut Creek, which attains a width of over 15 m. In contrast, many of the small first-order creeks draining the upper marsh are usually less than 1 m wide and 0.5 m deep. The marsh had no vegetation in 1818 but had become vegetated and developed a creek system by 1880. The upper part of Hut Marsh lies about 7 cm higher than its eastern part, suggesting to Pethick (1980b) that it is about 50 years older. The highest rates of accretion occur in the central part of the marsh between the two major draining creeks, whereas the lowest rates occur on the highest parts which are least frequently flooded (Stoddart *et al.*, 1989). Stoddart *et al.* (1989) show that in the middle part of Missel Marsh, shrubby seablite *Suaeda vera* occurs on slightly higher areas. Samphire *Salicornia* spp. and green seaweed *Enteromorpha* spp. are seasonally abundant below the rims of the creeks. Pethick (1980a, 1981) has shown that the inception of the saltmarsh at Missel Marsh at the western end of Scolt Head Island occurred between 1880 and 1907. Steers (1960) estimated the rate of vertical accretion at 8.4 mm a^{-1} over a 22-year period from 1935 until 1957.

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

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

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

Blakeney Point (Figure 11.30) is a large shingle spit, comparable in size to Spurn Head. The shingle beach extends from Sheringham westwards for over 17 km, the first 5.5 km fringing low (up to about 30 m) till cliffs (Burnaby, 1950), and the central section forming a ridge fronting Salthouse Marsh and Fresh Marsh. The ridge is about 200 m wide and between 9 and 10 m in height. Hardy (1964) estimated that the whole structure contained about 2.3×10^6 m^3 of shingle. The western part continues as a single ridge for a further 3 km before developing a series of long recurves trending southwards that are the most recent members of a set of over 20 shingle laterals of varying length. Blakeney Point has extended and shortened several times during the last 150 years. The morphological and cartographic evidence demonstrates that the spit has grown westwards. Steers (1927) estimated that the spit lengthened by 86.4 m a^{-1} between 1886 and 1904 and by 45.7 m a^{-1} between 1904 and 1925. Between 1649 and 1924 the ridge moved inland by an average of about 1 m a^{-1} (Hardy, 1964). There is some debate about the extent to which longshore transport is consistently in this direction and it is possible that shingle moves one way and sand in the other (Battarchaya, 1967; Hardy, 1964; Steers, 1964b; Cambers, 1975). In recent years the ridge has been eroded by storms and then re-shaped by bulldozing material back into the increasingly narrow profile, similar to Hurst Castle Spit (see GCR site report in Chapter 6). This has led to a reduction in the shingle volume of the beach and in February 1995 a 200 m-wide breach through the ridge occurred. If the loss of shingle continues it is likely that Blakeney Point will become an isolated island such as Scolt Head, unless coast protection works are carried out to provide protection for low-lying settlements such as Salthouse. The geomorphological interest lies in allowing natural processes to continue unimpeded, though with the lost shingle restored by beach nourishment.

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

Interpretation

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

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

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

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

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

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

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

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

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

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

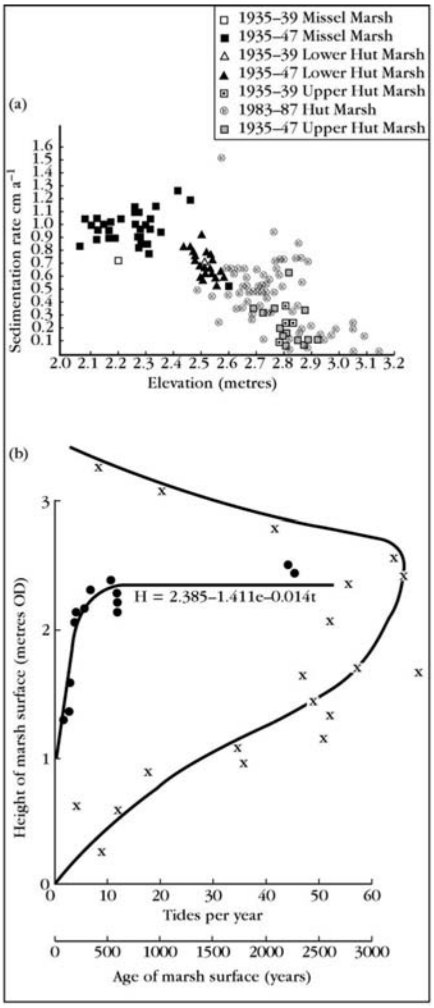


Figure 11.31: Relationship of saltmarsh elevation to tides and age of the marsh surface at Missel Marsh, Lower Hut Marsh, upper Hut Marsh and Hut Marsh. H = 2.385 – 1.411 e – 0.014t is a best-fit line based on the relationship between marsh height (H), tides per year (e) and age of marsh surface (t).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

On Hut Marsh, a tide-dominated back-barrier marsh on Scolt Head Island, 95% of total deposition is by direct settling (French and Spencer, 1993). Annual accretion varied between 8 mm a^{-1} adjacent to the larger channels and less than 1 mm a^{-1} on the saltmarsh surfaces farthest from the channels, i.e. on the highest parts of the marsh. Along the longest transport pathways, there was a reduction and then ‘exhaustion' of suspended sediment. Storm events by causing surges, and thus higher water levels, accounted for a significant proportion of long-term accretion on the highest surfaces. Although there is a general relationship between predicted tidal height and sediment deposition (Figure11.31b), French and Spencer (1993) showed that this is disrupted by meteorological conditions and resuspension of muddy sediments within the creek system. The arithmetic mean vertical accretion rate for the marsh was 3.9 mm a^{-1}, which is higher than the present-day local rate of sea-level rise (1.5–2.0 mm a^{-1}: French and Spencer, 1993), a significant finding.

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

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

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

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

Conclusions

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

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

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

The saltmarshes are one of the few areas on the coastline of England and Wales where saltmarsh morphology, including saltpans, has been examined in detail. The North Norfolk

Coast GCR site is also a Special Area of Conservation under the Habitats Directive, a Special Protection Area under the Birds Directive, and a Ramsar site; virtually the whole coastline is owned and/or managed by conservation organizations.

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