Coastal Geomorphology of Great Britain

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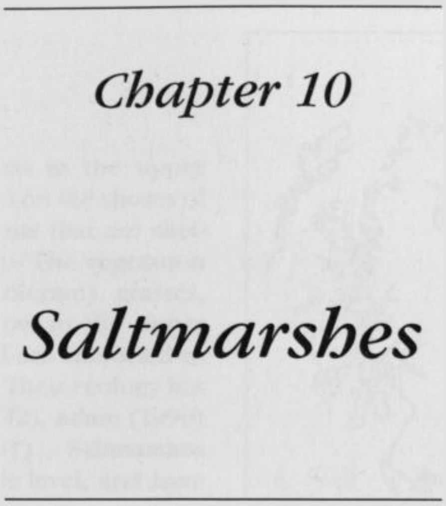


Chapter 10

Saltmarshes

INTRODUCTION

E.C.F. Bird

Saltmarshes are vegetated areas in the upper part of the intertidal zone found on the shores of inlets, estuaries and embayments that are sheltered from strong wave action. The vegetation consists of halophytic (salt-tolerant) grasses, herbs and shrubs that can grow in the upper part of the intertidal zone, and are subjected to regular inundation by the sea. Their ecology has been described by Ranwell (1972), Adam (1990) and Packham and Willis (1997). Saltmarshes extend down to about mid-tide level, and have muddy, or sometimes sandy, substrates. They are generally bordered seawards by intertidal mudflats or sandflats, bare of vegetation or with carpets of algae, such as *Enteromorpha* spp., or seagrasses such as *Zostera* spp..

The distribution of active saltmarshes in Britain is shown in Figure 10.1 British saltmarshes are extensive where the tide range is large and the intertidal zone wide, with a very gentle transverse gradient, as on the shores of the Severn and Dee estuaries, Solway Firth (see GCR site report in the present chapter), and Bridgwater Bay in the Bristol Channel. A distinction has been made between these 'open marshes', which have spread seawards, and 'closed marshes', which occupy areas between landward recurves in the lee of spits such as Blakeney Point, Norfolk, and Culbin, Moray, and barrier islands such as Scolt Head Island, on the North Norfolk coast (see GCR site reports in Chapter 11) and Morrich More, Ross and Cromarty. Closed marshes become lagoons at high tide, then drain out through a system of converging tidal creeks as the tide falls (Steers, 1977).

Although small in areal terms, the west coast of Scotland and the Western Isles support many small and fringing saltmarshes, particularly where relative sea level has risen to create sheltered conditions and a complex shoreline (e.g. Loch Maddy, North Uist). As a whole, the 6567 ha of Scottish saltmarshes comprise some 15% of the British resource. Unlike the saltmarshes of southern and eastern Britain, they generally tend to be grazed, lack high sediment inputs and have a complete transition from halophytic to terrestrial vegetation. They are also characterized by mainly sandy substrates rather than the muds of the English saltmarshes.

Figure 10.1 The generalized distribution of active saltmarshes in Great Britain. Key to GCR sites described in the present chapter or Chapter 11 (coastal assemblage GCR sites):
1. Morrich More; 2. Culbin; 3. North Norfolk Coast; 4. St Osyth Marsh; 5. Dengie Marsh; 6. Keyhaven Marsh, Hurst Castle; 7. Burry Inlet, Carmarthen Bay; 8. Solway Firth, North and South shores; 9. Solway Firth, Cree Estuary; 10. Loch Gruinart, Islay, 11. Holy Island. (After Pye and French, 1993.)

Extensive saltmarshes bordered by intertidal mudflats are seen in Poole Harbour, Dorset (Figure 10.2), Southampton Water, Portsmouth Harbour, Langstone Harbour and Chichester Harbour on the south coast of England. These large inlets formed during the Holocene marine transgression, and have persisted because the inflowing rivers are too small to supply much sediment, and because this is a subsiding coast.

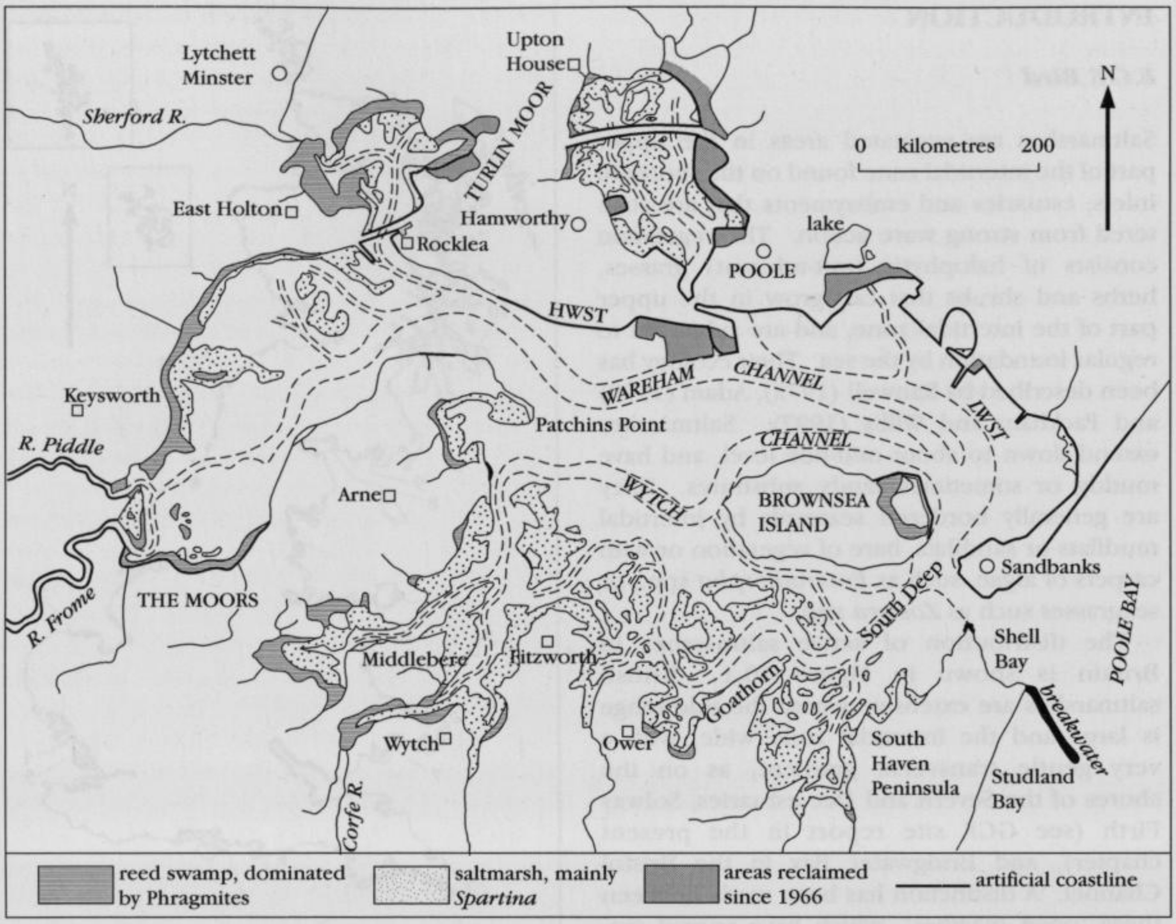


Figure 10.2 Marshes in Poole Harbour, Dorset. Common cord-grass *Spartina anglica* saltmarsh has developed here since 1899, and this is backed in the upper reaches by *Phragmites australis* reedswamp, where salinity is reduced by freshwater inflow. Saltmarsh has been reclaimed by embanking, especially near the northern urbanized fringes. (After Bird, 1984, p. 214; based on original map by V.J. May, updated to 2000)

On the west coast of Britain, notably in the Welsh and Scottish estuaries and in the Solway Firth (see GCR site reports in the present chapter), saltmarshes are generally firmer than those on the east coast because there are higher proportions of sand in the muddy sediment. Samphire *Salicornia* spp. are again the pioneers, but later colonization is dominated by grasses such as *Puccinellia*, which form a sward on marshland dissected by winding tidal creeks.

In Scotland, there are very few truly muddy saltmarshes; most of the marshes are sandy in character. Scottish saltmarshes tend to have little pioneer vegetation in comparison to those of England, although this rapidly gives way in the main to common saltmarsh-grass *Puccinellia maritima* with plantain *Plantago*, thrift *Armeria* and sea milkwort *Glaux* also common in the grazed swards. In sheltered shores of the Highland area, especially along sea lochs, patchy saltmarsh can develop on stony or rocky substrates. Saltmarsh vegetation has also been recorded on the cliff tops of St Kilda, resulting from wave spray in this exposed setting.

Evolution of a saltmarsh

Saltmarshes begin to form when vegetation colonizes the upper part of the intertidal zone (Pethick, 1984; Frey and Basan, 1985). Saltmarshes have been forming in sheltered sites around the coasts of Britain since the sea approached its present level about 5000–6000 years BP as a result of the Holocene marine transgression. For example, at St Osyth Marsh, Essex, (see GCR site report in the present chapter) shows by radiocarbon dating that saltmarsh development began at about 4200 years BP (Pethick, 1981).

In accreting intertidal zones, especially in areas where shelter from strong wave action is enhanced because of the growth of protective spits, barriers or shoals, the early stages in the development of a saltmarsh can be studied. Sandy saltmarshes are developing in the lee of The Bar, and its associated spits, within the barrier island complex at Culbin Sands, Moray (see GCR site report in the present chapter and in Chapter 11; Comber *et al.*, 1994), and behind Crow Point at Braunton Burrows, Devon (see GCR site report in Chapter 7).

On the North Norfolk coast (see GCR site report in Chapter 11), the evolution of saltmarshes – where stages in saltmarsh evolution can be traced from east to west between successively-formed recurves on spits at Blakeney Point and Scolt Head Island – has been documented, (Steers, 1960; Pethick, 1980a). There is initial colonization of muddy or sandy areas in the upper intertidal zone by individual halophytic plants (e.g. samphire *Salicornia* spp.), which expand vegetatively and eventually coalesce to form marshland dominated by single species such as common cord-grass *Spartina* spp.. Other species colonize, and the saltmarsh begins to trap sediment (mainly clay, silt and organic matter, sometimes with some fine-grained sand and shells) washed into the vegetated area by waves and currents as the tide rises, and retained by the filtering network of stems and leaves as it falls. Although often characterized as tide-dominated morphology, most saltmarshes are also influenced by wave action as the tide rises and falls. The vegetation diminishes wave action; swards of saltmarsh grass can reduce wave heights by up to 70% and wave energy by over 90%, and, as the water velocity diminishes, fine-grained sediment is deposited (Pethick, 1980b; Möller, 1998).

Sedimentation is also promoted by the growth of a subsurface root network, which binds the accreting sediment, by the presence of adhesive algal mats on the muddy surface, and by flocculation and precipitation of clay by the salt exuded from marsh plants (Pethick, 1984). In addition, mud that adheres to leaves and stems dries off and falls to the substrate. The processes of seaward spread and upward growth of a saltmarsh are aided by an abundant supply of sediment, but even in the absence of sediment input, saltmarshes can still aggrade by the accumulation of peat derived from the decaying vegetation.

In due course, a saltmarsh is built up to high spring tide level as a depositional terrace, only rarely submerged by the sea, that slopes gently from approximately the high spring tide line (HWOST) to the high neap tide line (HWONT), then more steeply (sometimes as a micro-cliff) to the mid-tide line (Figure 10.3). In the absence of saltmarsh vegetation the mudflats and sandflats remain as a more variable intertidal slope, and if the plant cover dies, or is cleared away, the saltmarsh terrace becomes dissected and degraded by erosion.

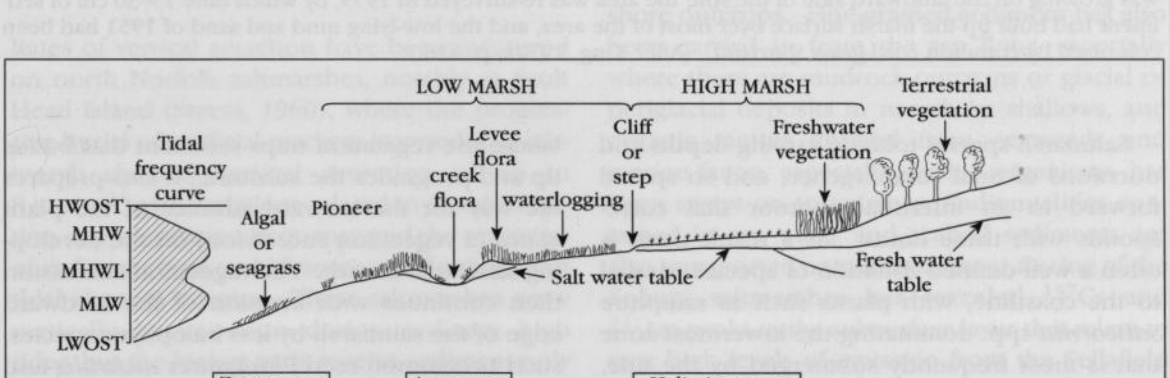


Figure 10.3 Typical saltmarsh vegetation zonation: the dominant species found in England and Wales at each level are named in the boxes. In Scotland, the sandy saltmarshes are dominated by common saltmarsh-grass *Puccinellia*. (After Carter, 1988, p. 344.)

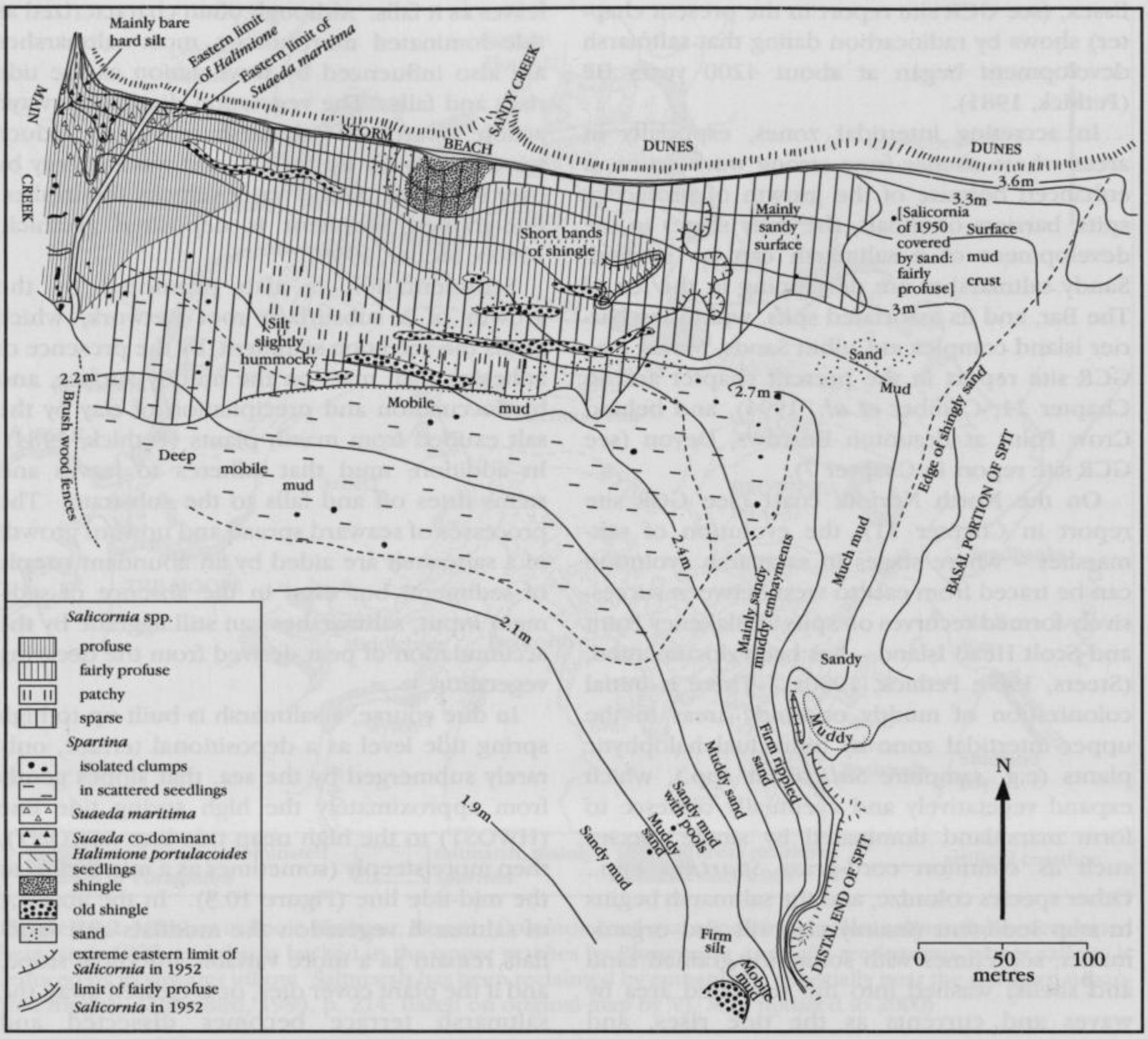


Figure 10.4 Map of the saltmarsh at Gibraltar Point, Lincolnshire, recording the position in 1951. The marsh was growing on the landward side of the spit; the area was re-surveyed in 1959, by which time 15–30 cm of sediment had built up the marsh surface over most of the area, and the low-lying mud and sand of 1951 had been colonized by common cord-grass *Spartina*. (After King, 1972a, p. 428.)

Saltmarsh species tolerate varying depths and durations of tidal submergence, and so spread forward to an intertidal contour that corresponds with these limits. As a result there is often a well-defined zonation of species parallel to the coastline, with plants such as samphire *Salicornia* spp. dominating the lowermost zone that is most frequently submerged by the tide, and sea-rush *Juncus maritimus* and other saltmarsh plants occupying higher zones that are less frequently submerged (Figures 10.3 and 10.4). These zones could simply represent the occupation by each species of a suitable habitat that moves seawards as accretion continues, but where the vegetation traps sediment that builds up and progrades the substrate, it also prepares the way for the seaward advance of the plant zones (a vegetation succession) on the developing saltmarsh terrace. The vegetation succession then continues with invasion of the landward edge of the saltmarsh by less halophytic species, such as common reed *Phragmites australis* and rushes (e.g. *Juncus* spp., *Scirpus* spp.) together with freshwater wetland species such as swamp scrub including willow *Salix* spp. and alder *Alnus* spp.. Eventually the transition is made to dry-land vegetation (Ranwell, 1972; Packham and Willis, 1997). These later stages in vegetation succession can be seen locally at the back of saltmarsh terraces around Poole Harbour (Bird and Ranwell, 1964; Figure 10.2), but they have often been destroyed by hinterland drainage and land-claim. Succession from saltmarsh to freshwater swamp and land vegetation is likely to be accelerated by coastal emergence, and evidence of this may be found in Scottish sites where post-glacial isostatic rebound is in progress, such as at Morrich More, in the Dornoch Firth (Hansom and Leafe, 1990). One of the few saltmarsh successions to woodland in the UK is in Sutherland, where the completion of an embankment in 1816 enabled alder *Alnus* to colonize the saltmarsh at the head of Loch Fleet. The resulting alder woods are so well established that they are now a National Nature Reserve.

Conventionally, algal mats (such as *Enteromorpha* spp.) and seagrasses (notably eelgrasses *Zostera* spp.), which grow on mudflats in the intertidal and subtidal zones, are not regarded as saltmarshes, even though they often prepare the way for saltmarsh encroachment. Seagrasses trap sediment because the plants are erect when the tide is high, and can form a sediment-filtering meadow in which wave heights are reduced by up to 40% and wave energy by 60% (Fonseca, 1996). The substrate is thus raised to form a seagrass bank or terrace that often grows upward and outward as the vegetation spreads. Nevertheless, some seagrass terraces are sharp-edged owing to wave activity or current scour.

Rates and patterns of accretion

Rates of vertical accretion have been measured on north Norfolk saltmarshes, notably at Scolt Head Island (Steers, 1960), where the progressive burial of artificial markers inserted in a saltmarsh showed vertical accretion of up to 8 mm a^{-1}, with variations related to marsh elevation and inundation frequency and the retention of sediment from turbid water overflowing from tidal channel margins. These saltmarshes grow vertically by accretion during ordinary high tides, but the higher parts receive sediment only in storm events (French and Spencer, 1993). In general, vertical accretion is relatively slow at the upper and lower limits of the saltmarsh, and more rapid in the intervening zone, where saltmarsh vegetation forms a relatively dense sediment-trapping cover and is regularly invaded by sediment-laden tidal water. Pethick (1981) found the upper limit of accretion on saltmarshes to lie below the level of the highest spring tides. Marshes, therefore, never quite attain this altitude.

Vertical accretion of up to 15 mm a^{-1} has been measured on saltmarshes in Essex, where coastal subsidence is in progress (Ranwell, 1972). In saltmarshes bordering the Severn estuary, French (1996) used evidence from heavy metal profiles and lead (^{210}Pb) dating to define distinct sedimentary units (between planes dating from 1840–1850, 1936±7, 1971±4 and 1958±4), and shows that vertical accretion (3–4 mm a^{-1}) has been proceeding at about the same rate as sea-level rise in the area. There are at least three saltmarsh terraces bordering the Severn estuary, representing cycles of marsh erosion and accretion. Accretion is most rapid (12.1 mm a^{-1}) on the lower terrace, submerged by every high tide, slower (6.4 mm a^{-1}) on the middle terrace, and slowest (2.3 mm a^{-1}) on the higher terrace, which is inundated only by high spring tides (French, 1996). However, where supply rates are high, accretion responds accordingly. For example, in the sandy saltmarshes of the inner Solway, Harvey (2000) has measured rates of vertical accretion of up to 51 mm a^{-1} in some areas and in excess of 20 mm a^{-1} over wider areas on account of a very healthy offshore sand supply.

The fine-grained sediment deposited in saltmarshes is derived largely from bordering intertidal mudflats and sandflats, which in turn have been supplied with clay, silt and sand by rivers, or similar sediment eroded from cliff and rocky shore outcrops. Fine-grained sediment has also been carried in from the sea floor, especially where there are mudrock outcrops or glacial or periglacial deposits in nearshore shallows, and organic matter derived from seaweeds and marine fauna, especially shelled organisms, has been swept on to marshes. Radionuclides contained in sea water and seabed sediments are also transported onto saltmarshes. Coring of the Solway saltmarshes has revealed ^{137}Cs and ^{241}Am peaks in the subsurface layer that relate to past high levels of emission from the Sellafield Nuclear Fuel Reprocessing Plant in Cumbria (Harvey and Allan, 1998; Harvey, 2000).

Providing there is a supply of fine-grained sediment, and wave action is gentle, saltmarshes can spread rapidly (Figure 10.4). The supply of mud to a saltmarsh increases where fluvial sediment yields are augmented by catchment soil erosion, where the dredging of channels increases muddy sediment in suspension, or where dredged material is dumped on or near marshes, accelerating vertical accretion and progradation. An excessive rate of mud deposition may however blanket and kill saltmarsh vegetation.

Sections through saltmarsh terraces, exposed in the banks of tidal creeks or in cliffs at the seaward edge, as on the saltmarsh at Morrich More, Ross and Cromarty (see GCR site report in the present chapter), generally comprise stratified deposits, with layers of coarser sands within the host sands or muds. These variations are related to wave conditions, storm waves washing sand into the saltmarsh, and mud accumulating as the tides rise and fall in calmer weather. In the Severn estuary the grain size of saltmarsh sediments diminishes from fine-grained sand to silt and clay landwards from the edge of the marsh as the result of sorting of sediment washed in from the seaward side, and there is a similar diminution vertically through the aggraded saltmarsh terrace because of progradation (Allen, 1996a). However, there are often storm-carried sediments, including sand and organic litter, on the upper saltmarsh (Stumpf, 1983), some of which may have been eroded from the seaward edge of the saltmarsh as occurs at Morrich More, Ross and Cromarty and Caerlaverock, Dumfries and Galloway.

Upward and outward growth of saltmarshes can be accelerated by an increase in the rate of sedimentation of the kind that occurred in Cornish estuaries in the 18th and 19th centuries when river sediment yields were augmented by mining waste. A grassy saltmarsh formed as the Fal delta grew rapidly between 1878 and 1973, when the river was carrying large quantities of kaolinite from the china clay workings on Hensbarrow Down (Ranwell, 1974). On the south coast of England rates of accretion have been very slow in areas where excavations made in saltmarshes (e.g. for salt manufacture) have persisted for many decades, as at Budleigh Salterton in Devon (see GCR site report in Chapter 6). In the Medway estuary in Kent large quantities of clay were cut for brick-making and cement production, leaving numerous pits and access canals; although this clay extraction ceased in the 1960s there has not yet been sufficient sediment deposition to obliterate them (French, 1997).

Micro-cliffs

At the seaward margins of many saltmarsh terraces there is a micro-cliff that may be up to 1.5 m high. Examples are seen on the Burry Inlet marshes in south Wales, where the marginal cliff forms a sharp drop to Llandridian Sands (see GCR site report for Carmarthen Bay, Chapter 11), and on the Dengie Peninsula in Essex (see GCR site report, this chapter), where the micro-cliff has been retreating at up to 10 m a^{-1}. Allen (1989) and Harvey (2000) found that saltmarsh micro-cliffs on sandy mud were bolder, often vertical, as in the Solway Firth, in comparison with the more subdued forms on soft mud in the Severn estuary. Where the top of the micro-cliff was bound by plant roots, recession was by way of calving, toppling and rotational slides of individual blocks of sediment together with stripping of surface vegetation (Harvey, 2000). In some sites cliffing is accompanied by continuing vertical accretion of muddy sediment in the saltmarsh, building up the saltmarsh terrace even though seaward advance has come to an end.

A saltmarsh micro-cliff may form in various ways. In some places it results from lateral movement of a tidal channel, undercutting the edge of a saltmarsh, but as this is a widespread phenomenon (there are now only a few sites where saltmarshes are spreading seawards), some more general explanation is required. It may be that, as on the sides of developing tidal creeks, seaward margins become oversteepened and cliffed, particularly during occasional storm wave episodes. In navigable estuaries, swash from boats will also tend to cut a cliff at the edge of the saltmarsh, while dredging, by steepening the submerged offshore slope, will also encourage the retreat of the marsh edge. Cliffing of this kind is repaired if there is an abundant supply of sediment to restore the profile and permit vegetation to spread again, but if there is a sediment deficit a saltmarsh cliff will persist. Alternatively, the cliffing of seaward margins of saltmarsh terraces could be a response to a rising sea level, deepening the adjacent water and allowing larger waves to attack the shore, and probably increasing tidal penetration in estuaries. This would also explain the widening and shallowing of tidal creeks that is occurring in saltmarshes in southern England, notably in Poole Harbour, Dorset.

Where the tidal range is large there is sometimes a micro-cliff separating an upper (mature) saltmarsh of firm (often sandy) clay from a lower (pioneer) saltmarsh terrace on soft accreting mud (Pethick, 1992). A double terrace of this kind borders the Solway Firth, where an upper saltmarsh occurs landwards of the high-water line, and a lower saltmarsh seawards, as in the Nith estuary near Dumfries. Similar features are seen on the northern shores of Walney Island, in Cumbria (see GCR site report, Chapter 8), and in Loch Gruinart on Islay (see GCR site report in the present chapter). It is possible that the upper terrace has been cliffed and cut back during a stormy phase, and that the lower terrace represents a stage in rebuilding.

The effects of common cord-grass *Spartina anglica*

Many British saltmarshes have been modified by swards of common cord-grass *Spartina anglica*. This is a fertile hybrid that arose by the crossing of the native British species *S. maritima* with *S. alterniflora*, a non-native species that was accidentally introduced in the 1820s from the eastern USA. After the hybrid *S. anglica* originated in Southampton Water in about 1870 (Carey and Oliver, 1918) it was introduced to many estuaries, subsequently advancing across intertidal mudflats and rapidly building up marshland, and spreading to new areas (Figure 10.5). It has been used in the past to stabilize and land-claim tidal flats in estuaries in various parts of the world.

Early stages of *Spartina* invasion can be seen in the lee of Holy Island (see GCR site report in Chapter 11), and on the Humber mudflats behind the spit at Spurn Head (see GCR site report in Chapter 8) where clones spread on to sandy intertidal areas. In Poole Harbour, the arrival of *S. anglica* in 1899 was followed by the rapid expansion of saltmarshes into broader and higher terraces covered entirely by this plant (Figure 10.2). At the same time, intervening creeks and channels became narrower and deeper, indicating that there had been a transference of muddy sediment from these into the areas of spreading *Spartina*. On the north Norfolk coast and in the Dee estuary, experimental introduction of *S. anglica* modified natural saltmarshes and led to the evolution of broad depositional terraces in the intertidal zone (Oliver and Salisbury, 1913; Bird, 1963). Marker (1967) recorded the rapid spread of *S. anglica* introduced in 1922, noting that it had become the pioneer colonist on accreting mudflats.

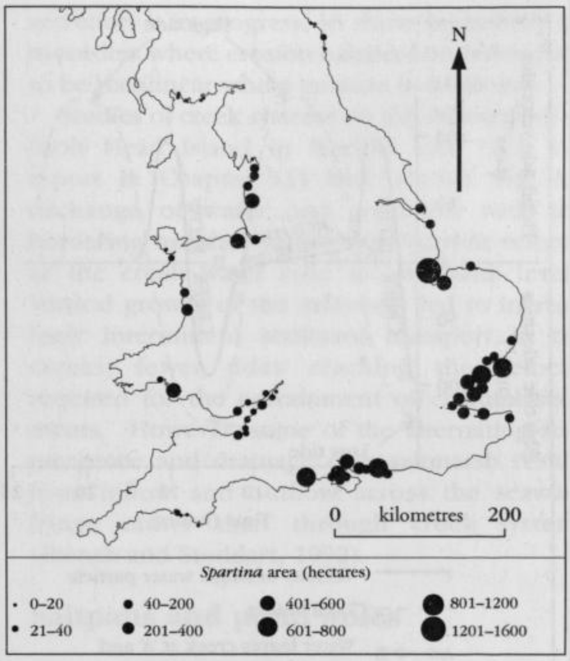


Figure 10.5 The distribution of *Spartina anglica* in England and Wales. (After Hubbard and Stebbings, 1967.)

In Britain some of the older *Spartina* marshes now show evidence of die-back, especially along the seaward margins and in enclaves that become saltpans (Doody, 1984, 1990, 1992). The ecological reasons for die-back are not fully understood, but it is often associated with nitrogen deficiency, sulphide accumulation and waterlogging. At the seaward margins where the sward dies, sediment previously trapped is released, and there is a receding micro-cliff. Die-back of *Spartina* along creek margins has led to erosion of marsh edges and resulted in the widening and shallowing of tidal creeks and channels. The process may be cyclic in the sense that released mud is deposited in new or reviving *Spartina* marshes elsewhere. Bird and Ranwell (1964) reported that in some sectors in Poole Harbour *S. anglica* was still advancing, mainly in the upper estuary, whereas in others there was die-back and erosion, notably in Brand's Bay near the marine entrance. These trends have continued, although advance was very localized by the end of the 20th century. Recent *Spartina* die-back has been noted in the Solway marshes (Harvey, 2000).

In Scotland, north of the Solway, *Spartina* is not common. It occurs on the west coast at only

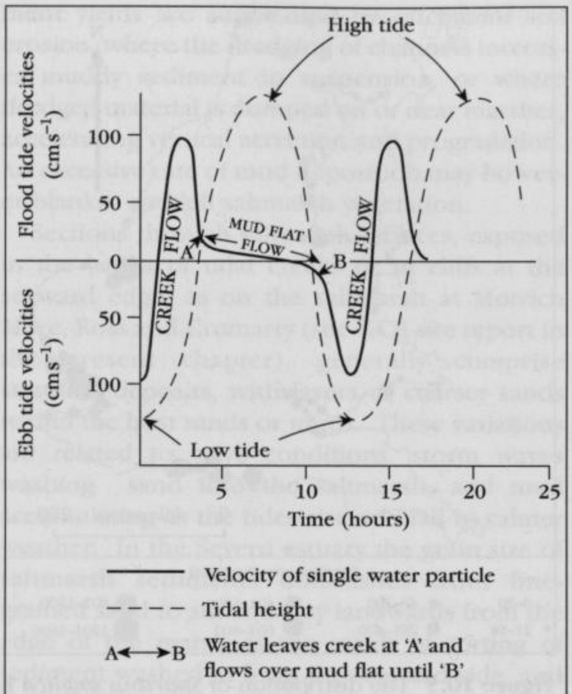


Figure 10.6 The velocities of a single water particle during a tidal cycle as it moves from a creek channel onto a mudflat surface. (After Pethick, 1984.)

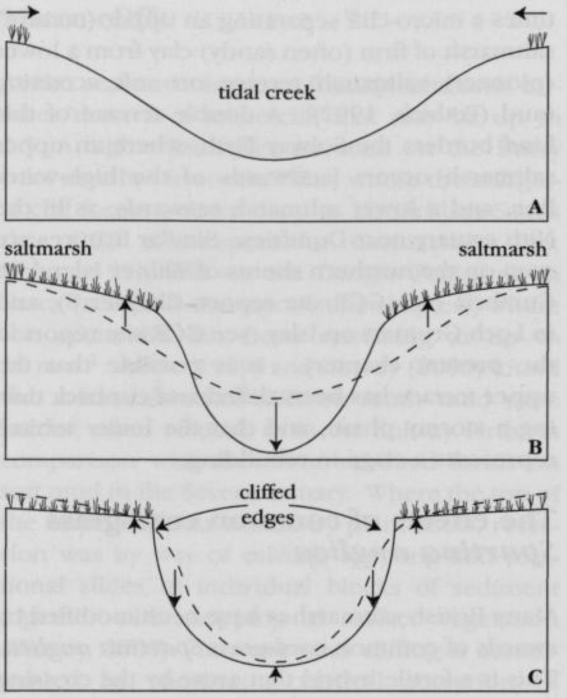


Figure 10.7 Stages in the evolution of a tidal creek as a saltmarsh encroachment takes place, forming terraces on either side of a deepening channel (B), the sides of which eventually become unstable (C). (After Bird, 1984, p. 213.)

a few isolated sites, such as Luskentyre, Western Isles (see GCR site report, Chapter 9) whereas at the east coast it is only a minor component reaching its northern limit in the Cromarty Firth (Hill, 1996, 1997).

Saltmarsh creeks

Studies of saltmarshes, particularly on the north Norfolk coast, have shown that as saltmarsh terraces are built up, the ebb and flow of the tide maintains a system of tidal creeks, the dimensions of which are related to the volume of water flowing up and down them as the tide rises and falls (Pethick, 1984, 1992; Figure 10.6). Typically dendritic and intricately meandering, they are channels within which the tide rises until the water floods the marsh surface. They are also drainage channels into which some of the ebbing water flows from the saltmarsh. They are thus like minor estuaries, particularly where they receive freshwater from hinterland runoff, or seepage from bordering beaches and dunes.

In the early stages, tidal creeks are relatively wide and shallow in cross-section, but as saltmarsh terraces rise and expand the creeks become narrower and deeper, and their banks higher and steeper, with frequent local slumping (Figure 10.7). Blocks of compacted mud, often with clumps of saltmarsh vegetation, collapse into the creek, especially where the banks are burrowed by crabs. Some tidal creeks are fringed by natural levees formed by deposition of sediment as the rising tide overflows, especially where such plants as orache *Atriplex* spp. have colonized the bordering banks. This pattern is more often found on the lower (and younger) seaward fringes of saltmarshes, the inter-creek areas becoming flatter as sedimentation proceeds.

Dendritic tidal creek systems give way to more rectilinear tidal creeks on some saltmarshes, as on the shores of Loch Gruinart on Islay and at Morrich More in the Dornoch Firth, north-east Scotland (see GCR site reports in the present chapter). Straight sub-parallel creeks across saltmarshes are more often found where the tide range is large and the transverse gradient small,

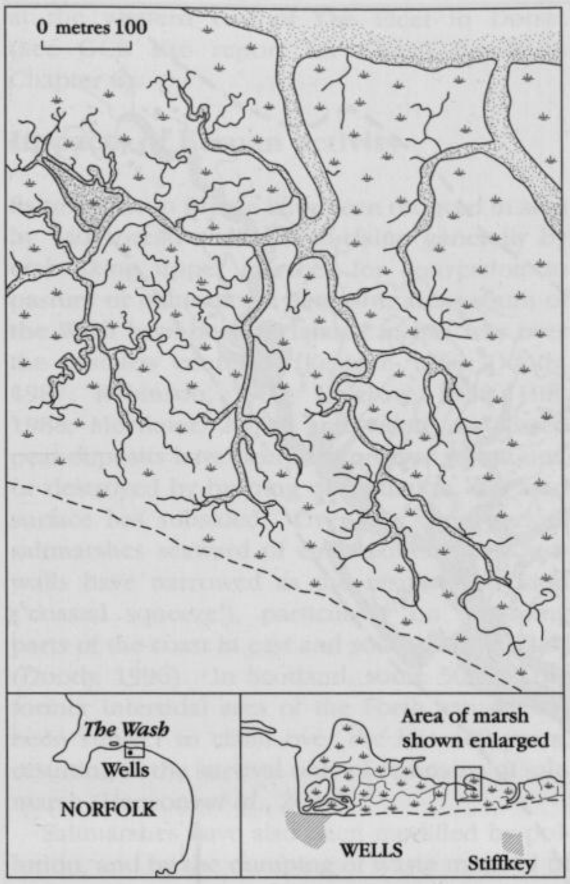


Figure 10.8 The intricate, dendritic creek network of a mature saltmarsh surface, Stiffkey, north Norfolk. (After Pethick, 1984, p. 159.)

or where the rate of seaward spread of saltmarsh has been rapid. In Bridgwater Bay on the southern shore of the Bristol Channel, where the tidal range is about 10 m, saltmarsh creeks run parallel and orthogonal to the coastline, whereas in Poole Harbour (Dorset), a microtidal estuarine embayment, creek patterns in bordering saltmarshes are mainly dendritic (Ranwell, 1972) (Figure 10.8).

The morphology of tidal creeks is related to sediment type, plant cover and tidal range. There are clearly defined steep-edged tidal creeks in saltmarsh terraces built largely of cohesive clay, as in Poole Harbour, but they become shallower and wider where the saltmarsh is sandier, as in the estuaries opening into Cardigan Bay. Saltmarsh creek patterns are trellised where linear cheniers of shelly sand have been deposited by storm surges, and channels have been cut through these. In cross-section, tidal creeks tend to be rounded furrows where accretion is in progress, to show asymmetry on meanders where erosion balances accretion, and to be rectilinear where erosion is dominant.

Studies of creek systems on the saltmarshes of Scolt Head Island in Norfolk (see GCR site report in Chapter 11) have shown that the exchange of water and sediment with the bordering marshes varied with current velocity as the creek water rose to over-bank levels. Vertical growth of the saltmarsh led to increasingly intermittent sediment transport in the creeks, fewer tides reaching the velocity required for the entrainment of channel sediments. However, some of the alternating submergence and drainage of a saltmarsh results from inflow and outflow across the seaward fringe rather than through creek systems (French and Stoddart, 1992).

Saltpans and pond holes

Saltpans (also known as 'pond holes') are small shallow depressions that may form as the result of the blocking of part of a tidal creek by slumping, as residual unvegetated areas within a developing saltmarsh, or as the result of local die-back of saltmarsh vegetation (Pethick, 1974; Steers, 1977). Some originated as the result of the collapse of subsurface cavities. They are flooded at high tide, and remain bare of plants because evaporation makes the trapped water hypersaline. Many become rounded as the result of scour by small waves and circulating currents generated by winds blowing across them. Numerous saltpans occur on saltmarshes between shingle recurves on Blakeney Point on the North Norfolk Coast (Figure 10.9; see also GCR site report in Chapter 11) and they are also extensive on saltmarsh terraces, such as those bordering the Cree estuary in south-west Scotland (see GCR site report in the present chapter). On many Scottish saltmarshes, creeks, abandoned owing to sea-level changes, form the basis of several series of linear saltpans that mirror the old creek pattern, and often drain via subsurface pipes, for example, Morrich More, Ross and Cromarty, has good examples of such abandoned networks (Smith, 1978; Hansom and Leafe, 1990.)

Freshwater swamps

Reference has been made to freshwater swamps on the landward margins of saltmarshes, where

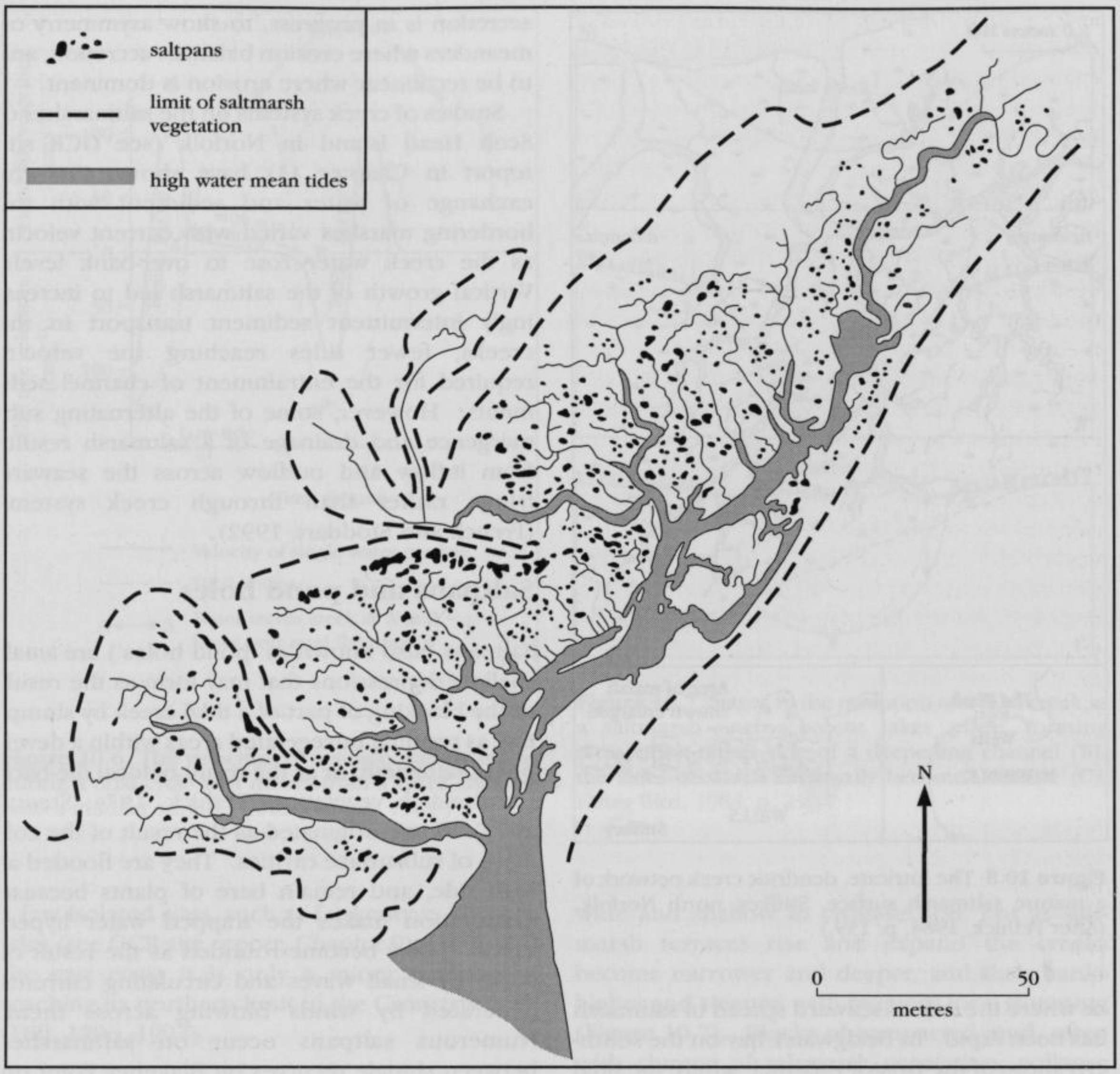


Figure 10.9 The distribution of saltpans on a saltmarsh at Blakeney Point, north Norfolk. (After Pethick, 1984, p. 164.)

they represent a late stage in vegetation succession to land vegetation, but freshwater swamps also fringe the shore in coastal lagoons, estuaries and sheltered embayments. They are dominated by common reed *Phragmites australis* often with rushes (e.g. *Juncus* spp.) and sedges (e.g. *Bolboschoenus maritimus* = *Scirpus maritimus*), which can grow out into water about 1 m deep, such as at Luce Sands, south-west Scotland (see GCR site report in Chapter 7). As in saltmarshes, freshwater swamps of this kind reduce wave action and current flow, and promote accretion of sediment, particularly silt and clay, in such a way as to build up a depositional terrace. Seasonal decay of freshwater swamp vegetation produces organic matter, which is deposited with the trapped sediment, and where the sediment supply is meagre this organic matter may accumulate on the depositional terrace as fibrous peat deposits. In due course the terrace is built up to high-water level, and land vegetation (scrub and woodland) then moves in. The outcome is progradation of the coastline by swamp encroachment, a process that is demonstrable on the shores of coastal lagoons where salinity is relatively low, as in Loe Pool in Cornwall, Slapton Ley in Devon (see GCR site reports in Chapter 6) and Abbotsbury Swannery at the western end of The Fleet in Dorset (see GCR site report for Chesil Beach in Chapter 6).

Impacts of human activity

Saltmarshes in Britain have been reduced in area by widespread coastal land-claim, generally by embanking upper marshes for conversion to pasture or cultivation. Extensive areas south of the Wash have been reclaimed in this way over the past few centuries (Kestner, 1962; Doody, 1987; Robinson, 1987; Halcrow, 1988, Hill, 1988; Mortimer, 2002), and where associated peat deposits have been compressed, dried out, or destroyed by burning or oxidation, the land surface has subsided. Over the same period, saltmarshes seaward of embankments and seawalls have narrowed as the result of erosion ('coastal squeeze'), particularly on subsiding parts of the coast in east and south-east England (Doody, 1996). In Scotland, some 50% of the former intertidal area of the Forth estuary has been subject to claim over the last 400 years, resulting in the survival only of remnants of saltmarsh (Hansom *et al*., 2001).

Saltmarshes have also been modified by pollution, and by the dumping of waste material of various kinds. Some saltmarshes have also been modified locally where channels have been excavated or tidal creeks widened and deepened to permit boat access and provide anchorages, and in some places excavated material has been dumped alongside to form hard ground for harbour facilities. Mention has been made of excavation of clay from the Medway marshes and elsewhere.

In recent years the costs of maintaining low-lying reclaimed areas by maintaining the flood banks have led to suggestions that such areas should be abandoned and allowed to revert to saltmarsh, which has plants, animals and birds with important nature conservation value (Doody, 1996). Such 'managed re-alignment' has been implemented at a few small sites, notably on Northey Island in the Blackwater estuary, Essex. A number of other land-claimed saltmarsh sites are under review, including other Essex sites, Slimbridge beside the Severn estuary, Porlock Marsh in north Devon and Skinflats in the Firth of Forth (Hansom *et al*., 2001). A small RSPB site at Nigg Bay in Ross and Cromarty has recently undergone managed re-alignment, the first in Scotland to do so. The further advantage of such managed re-alignment is that given ideal conditions the re-established saltmarshes should build up to, and in future keep pace with, rising sea levels (French, 1997).

The GCR saltmarsh sites

The sites described in this chapter and those site described in Chapter 11 that contain saltmarsh in the assemblage (see Figure 10.1) represent the five saltmarsh types in Allen and Pye's (1992) classification that divides saltmarshes on the basis of their physical site-type and situation.

1. Open coast marshes – Dengie, Solway Firth (North coast), North Norfolk, Morrich More,
2. Estuarine back-barrier marshes – Culbin, Morrich More, North Norfolk, Keyhaven, Burry Inlet, Dengie (small area), St Osyth,
3. Estuarine-fringing marshes – Cree, Solway Firth (south and north), St Osyth, Morrich More, Burry Inlet,
4. Embayment marshes – Cree, Solway Firth (south),
5. Loch- or fjord-head marshes – Loch Gruinart.

In this chapter, the site descriptions are arranged so that the northernmost on the North Sea coast is provided first, followed by the remainder in a clockwise order.

Further GCR sites that contain important saltmarsh localities are described in Chapter 11 of the present volume, where the saltmarsh forms part of a geomorphologically important coastal assemblage.

Since these GCR sites were first selected, there have been two national surveys of saltmarshes, Burd (1989) for the Nature Conservancy Council, and Pye and French (1993) for the former Ministry of Agriculture, Fisheries and Food. Readers are referred to these sources for a more comprehensive view of saltmarshes in Britain.

Saltmarshes as biological SSSIs and Special Areas of Conservation (SACs)

In Chapter 1, it was emphasized that the SSSI site series is constructed both from areas nationally important for wildlife and GCR sites. An SSSI may be established solely for its geology/

Table 10.1 Candidate and possible Special Areas of Conservation in Great Britain supporting Habitats Directive Annex I coastal saltmarsh habitat(s) as qualifying European features. Non-significant occurrences of these habitats on SACs selected for other features are not included. (Source: JNCC International Designations Database, July 2002.)

SAC name	Local authority	Saltmarsh extent (ha)
Alde, Ore and Butley Estuaries	Suffolk	390
Carmarthen Bay and Estuaries/ Bae Caerfyrddin ac Aberoedd	Abertawe/ Swansea; Caerfyrddin/ Carmarthenshire; Penfro/ Pembrokeshire	2764
Chesil and the Fleet	Dorset	21
Culbin Bar	Highland; Moray	203
Dee Estuary/ Aber Dyfrdwy*	Cheshire; Fflint/ Flintshire; Wirral	2431
Dornoch Firth and Morrich More	Highland	539
Drigg Coast	Cumbria	162
Essex Estuaries	Essex	3770
Fal and Helford	Cornwall	70
Glannau Môn (Cors heli)/ Anglesey Coast (Saltmarsh)	Ynys Môn/ Isle of Anglesey	191
Humber Estuary*	City of Kingston upon Hull; East Riding of Yorkshire; Lincolnshire; North East Lincolnshire; North Lincolnshire	840
Kenfig/ Cynffig	Pen-y-bont ar Ogwr/ Bridgend	20
Mòine Mhór	Argyll and Bute	94
Morecambe Bay	Cumbria; Lancashire	1897
North Norfolk Coast	Norfolk	19
North Uist Machair	Western Isles / Na h-Eileanan an Iar	82
Pembrokeshire Marine/ Sir Benfro Forol	Penfro/ Pembrokeshire	274
Pen Llŷn a'r Sarnau/ Lleyn Peninsula and the Sarnau	Ceredigion; Gwynedd; Powys	748
Plymouth Sound and Estuaries	Cornwall; Devon; Plymouth	192
Severn Estuary/ Môr Hafren*	Bro Morgannwg/ Vale of Glamorgan; Caerdydd/ Cardiff; Casnewydd/ Newport; City of Bristol; Fynwy/ Monmouthshire; Gloucestershire; North Somerset; Somerset; South Gloucestershire	656
Solent Maritime	City of Portsmouth; City of Southampton; Hampshire; Isle of Wight; West Sussex	2276
Solway Firth	Cumbria; Dumfries and Galloway	4171
The Wash and North Norfolk Coast	Lincolnshire; Norfolk	3341

* Possible SAC not yet submitted to EC.
Bold type indicates a coastal GCR interest within the site

geomorphology, or its wildlife/habitat, or it may comprise a 'mosaic' of biological and GCR sites that may be adjacent, partially overlap, or be co-incident. Therefore there are a number of coastal SSSIs that are primarily selected for their wildlife conservation value, but implicitly will contain interesting coastal geomorphology features that are not included independently in the GCR because of the 'minimum number' criterion of the GCR rationale (see Chapter 1; Sherwood *et al.*, 2000). Therefore there are some areas of saltmarsh that are crucially important to the natural heritage of Britain are not described in the present geomorphologically focused volume, but are conserved for their habitat value as SSSIs.

In addition to being protected through the SSSI system for their national importance, certain types of saltmarsh are 'Habitats Directive'-Annex I habitats eligible for selection as SACs (see Chapter 1). As well as being eligible for SAC selection in their own right, saltmarshes can be an important component of some SACs selected for the Annex I type 'Estuaries'. Furthermore, many saltmarshes are of international ornithological importance, primarily for breeding waders and wintering wildfowl, and for this reason may be designated Special Protection Areas under the Birds Directive, and/or as Ramsar sites.

Saltmarsh SAC site selection rationale

For the two relatively widespread Annex I coastal saltmarsh types occurring in the UK, '*Salicornia* and other annuals colonising mud and sand' and Atlantic salt meadows, sites have been selected to represent their geographical range and ecological variation. Generally, the largest areas of the habitat type have been selected. Preference has been given to sites where saltmarsh forms part of well-developed successional sequences, and there are transitions to other high-quality habitat assemblages at many of the selected sites. For the two rare saltmarsh types, 'Mediterranean and thermo-Atlantic halophilous scrubs' and '*Spartina* swards', all sites known to support significant examples have been selected as SACs. Only sites that are dominated by the native cord-grasses *Spartina maritima* and *S. alterniflora*, or the rare and local hybrid *S.* x *townsendii* have been considered for selection as *Spartina* swards, not stands of the widely introduced invasive common cord-grass *Spartina anglica*. Although a prominent feature of many estuaries, monoculture swards of the latter species are of little intrinsic value to wildlife, and in many areas *S. anglica* is considered a threat to the intertidal feeding-grounds used by large populations of wading birds and wildfowl. Attempts have been made to control *S. anglica* at several sites over many years.

Table 10.1 lists saltmarsh SACs, and indicates which of the sites are also important as part of the GCR and are described in this chapter.

CULBIN, MORAY (NH 980 615)

J.D. Hansom

Introduction

The assemblage of coastal landforms along the southern shore of the Moray Firth (see Chapter 11) is comparable to the barrier beach assemblage of the north Norfolk coast. The saltmarshes that have developed behind The Bar at Culbin represent the most recent features in the sequence of landform development. The area is therefore important for studying the evolution and development of saltmarshes in a national context. The marshes at Culbin (see Figure 10.1 for general location) are also distinctive in demonstrating a well-developed network of saltpans, but unusually few creeks (Burd, 1989; Comber *et al*., 1994).

Description

The active back barrier (Allen and Pye, 1992) saltmarsh at Culbin is 203 ha in area (Pye and French, 1993; see Figure 11.5 in the present volume). The marsh edge varies from cliffed to ramped and the limited creek system is linear (Pye and French, 1993). Saltpans are common. Although the area includes both lateral erosion and accretion, Pye and French describe the site as accreting vertically. Present relative sea-level change is estimated to be close to 0 mm a^{-1}, but the area has undergone about 9 m of isostatic rise over the last 6500 years or so, over which time sea level has fallen to present level.

As part of an assemblage of coastal features, further description of the site is given in Chapter 11 of the present volume.

Interpretation

This benign environment has allowed saltmarsh to accrete rapidly on account of the western extension of the sheltering spit and bar features (Comber *et al*., 1994). Intertidal sandflats and saltmarshes occur on the landward side of the Buckie Loch spit and The Bar in the shelter afforded by these large linear features. The saltmarsh areas are developing on an extensive sand-based intertidal zone. The seaward edge of the marsh may have a small undercut edge of *c.* 0.2 m (Ritchie *et al*., 1978) or grade smoothly from sandflat to saltmarsh. The saltmarshes range from low developmental marsh surfaces characterized by intermittent stands of common saltmarsh-grass *Puccinellia* spp. and samphire *Salicornia* spp. to substantial areas of high marsh supporting a full vegetation cover merging to freshwater marsh species to the landward side. The two largest areas are identified as the marsh surface landward of the central section of The Bar and the area landward of Buckie Loch spit. The area of saltmarsh landward of Buckie Loch spit is expanding rapidly as distal extension of the spit continues to provide an increasingly lower-energy environment in which progradation can occur. Since the longshore extension of the protective spits is known (see Figure 11.2), then an approximate age can be placed on the initiation of saltmarsh: the marsh behind The Bar began to develop after 1858, whereas behind the Buckie Loch spit, saltmarsh was developing by 1730.

The extensive saltmarshes that have accreted in the shelter afforded by the two major spits may be susceptible to erosion by the landward migration of the protecting beach forms and the narrowing of their updrift proximal ends (Comber, 1993). Such activity is presently most severe at the neck of The Bar, where saltmarsh peat is exposed and is now being eroded on the foreshore. It is inevitable that since the sandflats and saltmarshes depend on the shelter provided by the Buckie Loch spit and The Bar, any erosion and movement in these protective features will force commensurate change in the sheltered areas behind.

Conclusions

The saltmarshes of Culbin are youthful, having largely developed in the last few hundred years. They display an intimate relationship to the shelter provided by the westward-moving gravel features of the outer coast. Westwards accretion is rapid, but proximal, erosion has led to foreshore exposures of immature saltmarsh peat.

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

J.D. Hansom

Introduction

The saltmarshes at Morrich More (see Figure 10.1 for general location) have developed mainly within Inver Bay, protected by accretion of beaches to the north and west, but marshes also occur behind the two tidally connected islands in the north (see Chapter 11 for a description of the other coastal geomorphology features of interest). The marshes are the most extensive area of saltmarsh in the Highlands, and they form an integral part of a landform assemblage that has developed over the last 6500 years. The marsh sediments have an unusually high component of sand, and the marsh stratigraphy is layered – this feature is well displayed in the marsh edge along Inver Bay. The creek pattern over the saltmarsh is strongly linear and parallel. This distinctive pattern is largely confined to a few saltmarshes in Britain that are developing rapidly or are affected by isostatic uplift, as is particularly well demonstrated at Morrich More. The drainage dynamics of the saltmarsh at Morrich More exhibit an unusual drainage lag on the ebb tide, probably attributable to subsurface pipe networks (Leafe and Hansom, 1990). The saltmarsh has some fine examples of channel pans and primary pans. Together these attributes make Morrich More a key site for studies of saltmarsh geomorphology on an emerged coast.

Description

Pye and French (1993) describe Morrich More as including open coast, back-barrier and estuarine fringing marshes. The marsh edge morphology is variable from cliffed to ramped. The creek system is strongly linear, especially the younger parts, and saltpans are common (Hansom and Leafe, 1990; Leafe and Hansom, 1990). Extensive areas of intertidal sandflat have developed in the shelter provided by the barrier beaches of Innis Mhór and Patterson Island. Similar areas exist on the western flank of Morrich More and within Inver Bay. On the more elevated sections of sandflat, tidal inundation is of lower frequency and duration, thus allowing saltmarsh vegetation to colonize. The 260 ha of saltmarsh on Morrich More represents 5% of the remaining semi-natural saltmarsh in Scotland and 17% of that in the Highland Region, yet it is a distinctive system in its own right on account of the sandy nature of the substrate and its context of rapid isostatic uplift (Hansom and Leafe, 1990).

The saltmarshes are drained by creek systems that extend into the Morrich along the axes of the inter-ridge swales or hollows. Thus, saltmarsh and emerged beach ridges interdigitate, and as the saltmarsh grows and accretes through time, the extremities of the beach ridges become progressively buried. Owing to isostatic uplift over 6500 years, the altitude over the Morrich More falls seawards to the west, north and east, and so saltmarshes have developed at the edges of a domed structure, with the oldest marshes close to the centre and the youngest in the west, north and east. The complex vegetation pattern of the Morrich More is dominated by this pattern of interdigitated ridges and slacks (Smith and Mather, 1973). The strandplain carries a rich flora of over 200 flowering species, ranging from intertidal sandflat species to *Juniperus-Calluna* heath on the oldest landward ridges. The vegetation succession of the Morrich More is discussed in further detail in Smith and Mather (1973) and Dargie (1989).

As part of an assemblage of coastal features, further description of the site is given in Chapter 11 of the present volume.

Interpretation

Relative sea-level change in the Dornoch Firth area is close to 0 mm a^{-1} (Pye and French, 1993) and the marsh is characterized by vertical accretion, but variable lateral erosion and accretion; accretion is relatively rapid in the back barrier area between the islands and the main Morrich More coastline. The size and relatively undisturbed history of 6500 years of continuous sedimentation of Morrich More has led to the presence of a full range of successional stages of embryo dune through to sand plain in association with dune slacks and interfingered saltmarsh. Dargie (1989) demonstrates the importance of the vegetational transitions at Morrich More, with those between the saltmarsh and dune systems being of particular complexity and therefore of high conservation value in view of the clear relationship with geomorphology. Vegetational transitions from saltmarsh to sand dune are extremely rare in Britain, and the transition on Morrich More from saltmarsh to calcareous dune, wet acid dune or dry dune grassland makes the upper saltmarsh vegetation, and its interaction with the domed geomorphology of the strandplain, uniquely important.

Conclusions

The scientific interest of Morrich More is outstanding both in terms of variety and scale of its coastal landforms including the strandplain, parabolic dunes, stabilized dunes, foredune succession, saltmarshes and sandflats. The saltmarshes are uniquely youthful to the west, north and east, away from the emerged surfaces of central Morrich. The site shows a well-developed vegetational transition from intertidal sandflat through saltmarsh to freshwater wetland and calcareous dome.

ST OSYTH MARSH, ESSEX (TM 090 144–TM 130 126)

V.J. May

Introduction

St Osyth Marsh (see Figure 10.1 for general location) is an important site for studies of saltmarsh morphology, and is one of the few marsh areas in Britain to have been dated, the maximum age being 4280 ± 45 years BP, by analysis of a peat seam preserved in grey-black clay at the site. The characteristic assemblage of saltmarsh features – creeks, saltpans and saltmarsh cliff – are all present at St Osyth Marsh, and reflect the maturity of the marsh systems (Hussey and Long, 1982). The saltpans have been intensively researched by geomorphologists (Pethick, 1970, 1984; Leeks, 1979), and provide much information relating to the formation and development of this unique coastal landform. This is one of the few sites in Britain where chenier development has been described fully (Greensmith and Tucker, 1975). One of the main interests is the process of breaching and secondary spit genesis brought about by landward roll-over across the marsh surface. This process is well displayed in the upper levels of the system.

Description

The site comprises two main areas: a narrow beach and saltmarsh that extends some 3 km westwards from St Osyth (TM 130 127) to Colne Point, where the shoreline turns towards NNW for a further 2.3 km. The area between St Osyth and Colne Point rarely exceeds 400 m in width and is limited landwards by a low sea defence embankment (see Figure 10.10a). At its widest, the area beyond Colne Point exceeds 1.4 km and is dominated by a well-developed saltmarsh system. Longshore sediment movement is from St Osyth towards Colne Point and into the Colne estuary. The spring tidal range is 3.8 m. The beach is a narrow ridge formed predominantly of sand and pebbles and resting on the seaward-facing edge of the saltmarsh. It is a thin deposit underlain by the saltmarsh clay. Such a description follows closely that given by Price (1955) to the features known as cheniers (or marsh beach ridges). These are much shallower sedimentary features than the barrier ridges of sand and shingle that front saltmarshes in such locations as Blakeney Point and Orfordness. Whereas the latter form independently of the development of saltmarsh, cheniers depend upon the presence of the marsh deposits for their foundation. It is common for the distal end of such features to form a small, narrow barrier spit. At Colne Point this spit shows a historical pattern of extension and shortening (Greensmith and Tucker, 1975; see Figure 10.10a) as well as destruction and reworking of the landward end of two older cheniers. The modern chenier is undergoing changes at present, which are probably related to gravel extraction between 1947 and 1962 at Colne Point (Robinson, 1953a) and to the recharging of the sediment supply by reworking of older chenier and tidal flat-deposits. Steers (1960, Plate 165) shows active excavation and the beginnings of a phase of breaching of the beach ridge to the north-west of Colne Point. Greensmith and Tucker (1975) describe a possible older chenier exposed in a low cliff at Colne Point.

Burd (1992) estimated that between 1973 and 1988 the Colne estuary marshes decreased in area by just under 12%. Although about 50 ha was gained by accretion, some 130 ha was lost by erosion and land-claim. The largest single loss was on either side of Colne Point. Much of this loss occurred within creeks, but Burd (1992) suggested that the methodology used to compare aerial photographs of the area may overestimate this apparently high erosion of creeks. The causes of these changes are discussed in the Dengie GCR site report below.

The saltmarsh east of Colne Point is drained by a main creek, which parallels the beach throughout its length. Creeks and saltpans form less than 10% of the surface area of the marsh. In contrast, to the west of Colne Point, there is a more complex pattern of creeks. Hussey and Long (1982) estimated that creeks and saltpans occupied over 26% of one hectare of emergent marsh; 68% was occupied by a common saltmarsh-grass–sea purslane (*Puccinellia maritima–Halimione (=Atriplex) portulacoides)* community. Although they cover less than 1% of the surface area, saltpans are an important morphological feature of much of this saltmarsh. Their shape and size vary greatly, ranging from 1–15 m^2 in area and 5–40 cm in depth (Leeks, 1979). Although some appear to be roughly circular ('sub-circular'), many others are linear features with similar shapes to creeks. Saltmarsh morphology is affected by the evolution of the beach at Colne Point (Butler, 1978), for when the beach is breached, the hydrodynamics of the creeks alter. For example, when the beach is intact, most creek drainage from the western marsh is towards the estuary at Sandy Point, some 2.5 km away. When the beach is breached, much of the upper marshland drainage reaches the sea via channels just west of Colne Point.

The marsh is underlain by a clearly defined seam of peat overlain by grey-black clay that contains root remains. This has been dated at 4280 ± 45 years BP (Butler, 1978; Hussey and Long, 1982). The surface sediment above the clay is mainly clay (52%) and silt (43%), with 5% sand. Much of the marsh is described by Hussey and Long (1982) as emergent, except near the mouth of the tidal creek where it is degrading. The surface of the emergent marsh lies at 2.30 m OD ± 0.15 m and is covered by about 99 tides per annum (Hussey and Long, 1982).

Interpretation

Two features of this site are of especially noteworthy: the presence of both modern and older cheniers, and the large number of saltpans. The modern chenier is poorly developed at the eastern proximal end of the beach, and the saltmarsh is undergoing erosion to the extent that there is a risk of breaching and flooding of the upper saltmarsh. There are two old cheniers: the older was speculatively dated by Greensmith and Tucker (1975) as having formed between about 1550 and 1200 years BP and the more recent, (much of which is recycled by the retreat of the modern beach) might have formed between 1200 and 250 years BP. This would be consistent with the date attributed to the marsh area of 4280 ± 45 years BP (Butler, 1978). On the Essex coast, these features appear to result from longshore transport that produces spits or fringing beaches, which during periods of higher wave-energy are carried on to the marsh edge. As the beach and ridge migrate inland, the saltmarsh is first buried and then exhumed. Erosion of the exhumed saltmarsh often produces a distinct marsh cliff. The presence of former saltmarsh standing at a higher altitude than the surrounding beach may cause local refraction of waves and so affect the alignment of the beach. The cheniers at Colne Point are composed mainly of sand and gravel, derived from cliff erosion and reworking of earlier beaches. The absence from a part of an eroded chenier at Colne Point of shells of the slipper limpet *Crepidula fornicata* (which was introduced into the Essex area between 1870 and 1880), provides an indicator of the minimum age of part of this feature (Greensmith and Tucker, 1975). Although cheniers occur elsewhere in Britain, they have rarely been described in detail and the Colne Point cheniers together with those to the south at Dengie Marsh (see GCR site report below) are the best examples of this unusual form.

The saltpans are also a feature that is particularly well represented here. The earliest descriptions in the Dovey estuary (Yapp *et al*., 1917; Richards, 1934) identified two types of saltpan, the primary pan and the channel pan, which were described in more detail in north Norfok (Steers, 1946a; Pethick, 1974; Steers, 1977). The former are thought to have developed on the initial marsh surface as vegetation began to spread. Within small areas that were not vegetated evaporation of seawater produced highly saline conditions in which little plant life could survive or colonize. As a result, these hollows survive within the marsh topography. They often display circular forms that are attributed to the erosional effects of wavelets (Pethick, 1984), although this is rare here. There is, however, the possibility that some pans come into existence as a result of smothering of the surface by algal mats (Pethick, 1970) or, where cattle graze, by dung. Furthermore, the collapse of creek-banks may cut off sections of unvegetated mud that develop a partially rounded form under the influence of wavelets within the enclosed area. They are undoubtedly a feature of the marshes in north Norfolk, St Osyth, and elsewhere that need further investigation, especially in the light of improved understanding of creek sediment dynamics.

In contrast, the channel pans appear to originate when creeks are abandoned. Sedimentation at the mouth of the former creek blocks the exchange of water with active creeks and higher salinities maintain an absence of vegetation. Pethick (1984) suggests that possible causes may include changes in sea level that led to an abandonment of large numbers of creeks. Alternatively, as creeks are deepened because of saltmarsh accretion, the total volume of tidal flood water may require fewer channels. Sinuous channel pans may thus represent creek obsolescence. Although there is no evidence that subsurface piping systems occur in the marshes at St Osyth, their collapse elsewhere may also provide a mechanism for the development of elongated saltpans.

This site is of considerable importance to the understanding of saltmarsh morphology not only because it demonstrates the comparative longevity of such features in eastern England, but also because of its cheniers and saltpans. It has, however, another role as part of the coast protection of the Essex coast. The level of the saltmarsh is higher than the land that lies landwards of the site behind artificial sea defences. The continuing efficacy of the sea defences depends upon the continued presence of the beach and saltmarsh. Unfortunately, the construction of groynes at the northern end of the site has substantially reduced the supply of sediment to the beach, which is now seriously affected by erosion. As a result, not only the natural importance of the site, but also its coast protection role, are threatened.

If the sediment supply to the beach is not maintained, there is likely to be a deterioration of the proximal end of the beach, partial destruction of the saltmarshes and the sea-wall would become exposed. In these circumstances, it may prove prudent in the interest of maintaining the scientific interest to allow artificial beach-feeding by materials comparable to those that fed the beach in the past. The volume would need to be controlled so that it simulated the historical sediment transport patterns in magnitude and frequency. The coast protection needs would be furthered by such action. Like many sites on the English coast, the marsh and beach at St Osyth now depend upon human intervention for their future maintenance. The landward boundary is an artificial one (the sea-wall), without which the saltmarsh would by now have migrated well inland. The site is important, not least because it offers an opportunity to manipulate the coastal system in order to conserve features of national significance at the same time as providing insights into the links between sea defences, rising sea levels and saltmarsh development on sites restricted landwards by artificial structures.

Conclusions

One of the few dated saltmarsh sites in England and Wales, St Osyth Marsh is also important because of its cheniers, creeks and saltpans. Parts of the site are over 4000 years old and owe their preservation to the protective effects of both emergent saltmarsh and marsh-edge beaches. The cheniers at Colne Point are mainly in sand and gravel, unlike those farther south at Dengie, which are much more shelly. Understanding of the way in which saltmarshes and their protective cheniers develop has considerable importance for the protection of the low-lying Essex coastlands.

DENGIE MARSH, ESSEX (TR 030 089–TR 025 963)

V.J. May

Introduction

The Dengie peninsula (see Figure 10.1 for general location), like many parts of the Essex coast, has been progressively land-claimed by a series of embankments constructed on the upper marshes. These walls are now fronted by saltmarsh and intertidal flats in excess of 2 km wide. The tidal range is 3.8 m. The northern part of the saltmarsh is fronted by shell and sand ridges (Greensmith and Tucker, 1965, 1967, 1968, 1969, 1973a,b, 1975), and parts of the intertidal area is marked by the development of mud mounds (Greensmith and Tucker, 1965, 1967). Farther south, the main area of saltmarsh at Dengie has been the subject of a number of studies of sediment transport and creek development (Bayliss-Smith *et al.*, 1979; Reed, 1986, 1987, 1988; Reed *et al.*, 1985; Stoddart and Bayliss-Smith, 1985; Pye and French, 1993). Changes in the coastline were described by Robinson (1953a), but more recent changes in the marshland area have been estimated by Harmsworth and Long (1986) and Burd (1992). Pethick (1989, 1991) has described the effects of, and recovery from, a storm event in January 1989.

Description

The Dengie peninsula is fronted by an extensive area of saltmarsh that is narrow at its northern and southern extremities and up to 600 m wide at Bridgewick. The marsh covers about 480 ha, of which about 16% (about 80 ha) was lost by erosion between 1970 and 1981 (Harmsworth and Long, 1986). Burd (1992) estimates that between 1973 and 1988 changes within six blocks of the saltmarsh, based upon measurements of the position of the marsh front, ranged from accretion of 1.1 m a^{-1} to erosion of 7.6 m a^{-1} (Figure 10.10b). Overall the marsh front lost on average 2.6 m a^{-1}. Mean low-water mark moved landwards at an average of 28.4 m a^{-1} at Sales Point, 8.7 m a^{-1} at St Peter's channel and 13.3 m a^{-1} at Watch House, thus steepening the foreshore (Pye and French, 1993). A total area of 473.8 ha in 1973 was reduced by 10% by 1988 (Burd, 1992), and this was the smallest net loss on all the Essex and north Kent saltmarshes.

On the landward side, the marsh is bounded by a 19th century sea-wall, the latest in a series of land-claims that started in the 16th century. The saltmarsh morphology at Dengie is particularly interesting. The marsh surface stands mainly at 2.5 m OD and is essentially planar with, unusually, no differentiation into upper and lower marsh. The marsh is dissected by numerous creeks and saltpan systems. Dengie also possesses many subsurface 'pipes'. The role of these subsurface features in bringing about saltpan formation was reported initially in Nigg Bay, Ross and Cromarty, Scotland (Kesel and Smith, 1978). It was subsequently recognized as occurring more widely, in the Ythan marsh, the marshes of south Wales, and in Shetland and Lewis (Smith, 1978).

Saltmarsh erosion was dominant along the Dengie peninsula (Harmsworth and Long, 1986) during the period 1960 to 1981, a trend that has been confirmed by Burd (1992). Net loss between 1973 and 1988 was 46.7 ha, much being accounted for by the January 1978 storm (Pye and French, 1993). Greensmith and Tucker (1965) showed that erosion was not uniform with a range of saltmarsh edge retreat from zero to 270 m. Boorman and Ranwell (1977), in

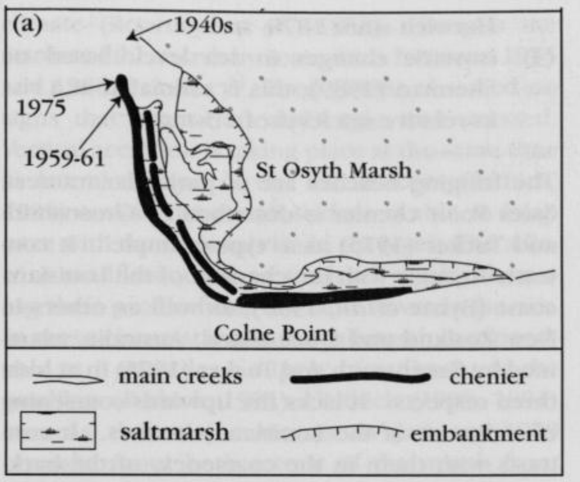
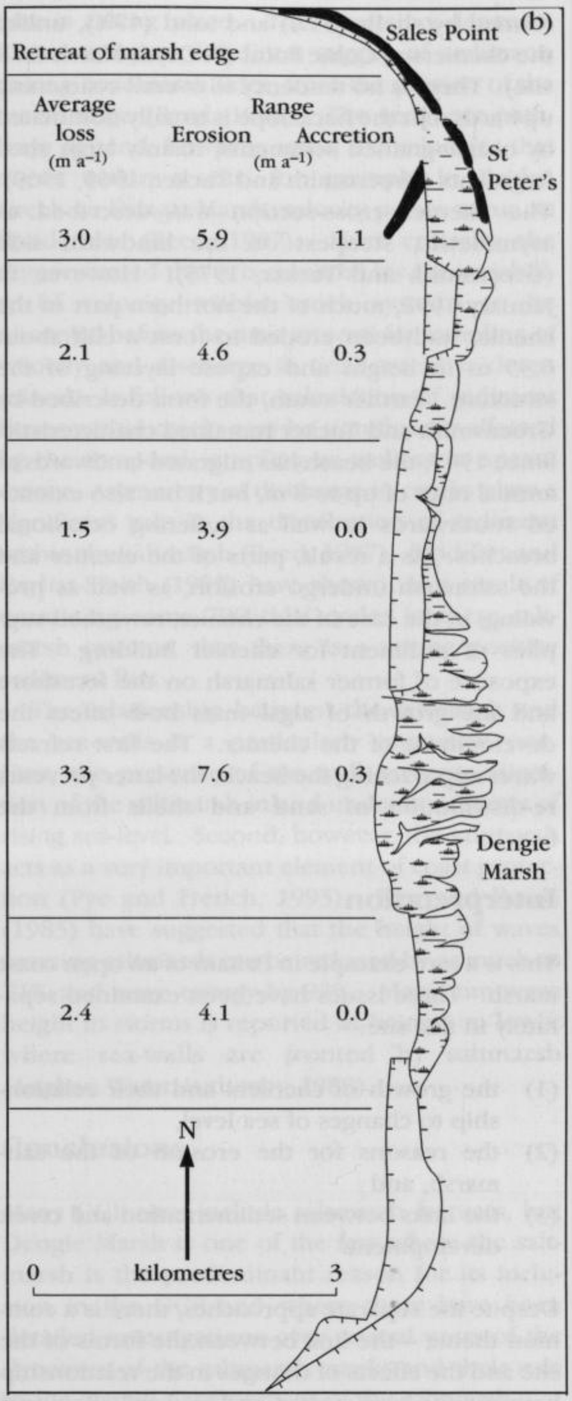


Figure 10.10 Cheniers and rates of change at (a) St Osyth Marsh (the arrows show the position of the northern end of the spit at different times) and (b) Dengie Marsh. Older cheniers occur landwards of the embankments at Dengie Marsh. Both the patterns of change in the marsh edge at Dengie Marsh and the spit at St Osyth show the tendency for these features to fluctuate in position, with erosion alternating with accretion. (Based in part on Greensmith and Tucker, 1975 and Burd, 1992.)



contrast, regarded Dengie as one of the few saltmarshes of south-east England that was accreting. Reed (1988) recorded short-term vertical accretion of 5–14 mm a^{-1}. However, the Anglian Water Authority (1980) reported the marsh as being dominated by erosion. Harmsworth and Long (1986) suggest that the characteristic pattern may be one of successive construction and erosion, depending upon rates of sea-level change and the degree of exposure to wave action. The outer edge of the marsh is marked by a distinct saltmarsh cliff (Harmsworth and Long, 1986), but much of the edge of the marsh, particularly at its northern end at Bradwell, is eroded into a zone of mud mounds (Greensmith and Tucker, 1965). The seaward rim of the marsh surface is intermittently overridden by transgressive shell ridges (Greensmith and Tucker, 1965, 1967, 1969, 1973a,b). As these cheniers transgress the saltmarsh, it is buried for a period of time before re-appearing seawards of the beach. Farther inland, the marsh lies over a series of chenier features especially at Sales Point. The coastline appears to have been affected by erosion after the Roman period for there is some evidence to suggest that the Roman fort of Othona, the present site of St Peter's Chapel, extended at least 120 m farther seawards than the present cliffline. Some fragments of submerged masonry within the marshland have been described as a Roman harbour (Johnson, 1976).

The chenier at Sales Point is predominantly formed by shells (51%) and sand (47%), unlike the cheniers at Colne Point (St Osyth Marsh GCR site). There is no tendency to overall coarsening upwards, but the backslope is usually dominated by coarse-grained sediments, mainly large shell fragments (Greensmith and Tucker, 1965, 1969). The chenier cross-section was described as asymmetric, steepest on the landward side (Greensmith and Tucker, 1975). However, in January 1992, much of the northern part of the chenier had been eroded to form a cliff about 0.35 m in height and expose layering of the structure. Farther south, the form described by Greensmith and Tucker remained characteristic. Since 1947, the beach has migrated landwards at annual rates of up to 8 m, but it has also extended southwards as well as suffering occasional breaches. As a result, parts of the chenier and the saltmarsh undergo erosion, as well as providing, in the case of the chenier, reworked supplies of sediment for chenier building. The exposure of former saltmarsh on the foreshore and the growth of algal mats both affect the development of the chenier. The first refracts waves approaching the beach, the latter prevents re-distribution of sand and shells from the beach.

Interpretation

This is a rare example in Britain of an open coast marsh. Three issues have been examined separately in this site:

(1) the growth of cheniers and their relationship to changes of sea level,
(2) the reasons for the erosion of the saltmarsh, and
(3) the links between sedimentation and creek development.

Despite the separate approaches, there is a common theme – the link between the forms of the site and the effects of changes in the relationship between the land surface and sea level. Regional sea-level rise on the Essex coast has three components, summarized by Burd (1992) as follows:

(1) the general eustatic rise in sea level: estimated to have been 15 cm ± 10 to 20 cm over the past century (Rossiter, 1967; Robin, 1986; Woodworth, 1987, 1990a,b; Misdorp *et al.*, 1990) in the North Sea,
(2) increased tidal range: for example 45 cm at Harwich since 1870, and
(3) isostatic changes in sea level: based on Shennan (1989), this is estimated at a rise in relative sea level of 1.5 mm a^{-1}.

The fringing beaches are of particular interest. Sales Point chenier is described by Greensmith and Tucker (1975) as a 'type-example'. It contrasts strongly with the cheniers of the Louisiana coast (Byrne *et al.*, 1959), as well as others in New Zealand and Queensland, Australia, examined by Greensmith and Tucker (1975) in at least three respects. It lacks the upwards-coarsening of sediment of the Louisiana cheniers. It contrasts with them in the coarseness of the backslope, and in having its steepest slope on the landward side, unlike others where the seaward slope is steepest.

Greensmith and Tucker (1975) argued that the Essex cheniers resulted from periods of coastal instability and widespread erosion, in contrast to the type region of Louisiana where coastal stability predominated. They believe that the fundamental tectonic instability of the southern North Sea explains the contrast, and outline an evolutionary sequence for the development of the Essex chenier plain of which Dengie is part. Marine transgression, probably during the period 1434 ± 110 years BP to 1265 ± 100 years BP, brought about erosion of the upper tidal flats and saltmarsh, and initiated mud mounds (Greensmith and Tucker, 1967). Shells, sand and pebbles were released from the flats and provided a source for the initiation of cheniers. Extension by merging and elongation produced spits extending onto the tidal flats. Creeks both interrupted chenier development and were affected by it as tidal flows were diverted. In the later stages of chenier development, expansion of saltmarshes isolated some ridges inland. Several can be traced within the land-claim area between Sales Point and Dengie village. At the outer edge of the saltmarsh, new cheniers developed such as that at Sales Point, but they were subject to growth by elongation and also by erosion, particularly at their landward extremities. Nevertheless, they represent the later stages of a chenier plain thas has prograded over the last 2000 years (Greensmith and Tucker, 1975).

An increase in mean high-water level could be expected to give rise to a change in community composition as a result of increased frequency and duration of submergence. Increased erosion may result simply from changes in the wave climate (Boorman *et al.*, 1989). Despite the retreat of the marsh by some 40 m between 1955 and 1988 (1.2 m a^{-1}), Reed (1988) observed no signs that vegetation at Dengie was stressed. Vertical accretion is taking place at the same time as lateral erosion of the marsh front (Pethick, 1991) and so the marsh surface is able to keep pace with the regional rise in sea level. The adjacent mudflats adjust to sea-level rise by flattening their profile from the land towards the sea. In these circumstances, the saltmarsh is expendable as it provides a supply of sediment to the mudflats (Pethick, 1991). Pethick (1989, 1991) records that major storms in January 1989 brought about both retreat of the marsh front and flattening of the profile of the mudflats. A storm event in October 1989 (Pethick, 1992) with a calculated return period of 1 in 33 years and waves of significant height of 3.4 m produced marsh edge retreat of 5 m. The horizontal surface was also lowered. Between October 1989 and March 1990 the marsh surface recovered its pre-storm altitude and by October 1990 was slightly higher (Pethick, 1992). However, as the frequency and magnitude of extreme events may be increasing (Carter and Draper, 1988), the role of storms in this process of mudflat flattening may become increasingly significant if their frequency exceeds the recovery period.

Harmsworth and Long (1986) argued that the erosion of the saltmarsh edge may result from a change of sea level (or inundation) produced by sinking of the saltmarsh area, a pattern that contrasts with upwards growth during periods of sea-level still-stand. An alternative explanation, specific to Dengie, could be the increased exposure of the saltmarsh that resulted from the loss from the intertidal mudflats of beds of eelgrass *Zostera marina*, which was wiped out by disease in the 1930s (Harmsworth and Long, 1986).

The saltmarshes here are an important area for an examination of saltmarsh sedimentation and erosion, and the linkage between tidal dynamics and sediment transport from intertidal mudflats. Parts of the saltmarshes include subsurface pipes that affect drainage as well as the development of collapse features on the marshes and may account for some development of saltpans (Leeks, 1979). Reed (1988) noted that the Dengie peninsula is affected by a sea-level rise of about 3 mm a^{-1}. However, saltmarsh vegetation shows no sign of stress due to increased submergence incidence. Reed argues that this shows that continued accretion of the marsh surface is taking place. This accretion depends, however, upon the direct supply of sediment, during over-marsh tides, from the erosion of the marsh edge (Reed, 1988). The sediment pathways depend, however, upon the velocities that occur within creeks, for example in Bridge Creek on Dengie Marsh, velocity pulses occur on flood tides (Reed, 1987). More critically, she demonstrated that it is essential for the variability of velocity within creek systems to be observed before the time interval for sampling of velocity and discharge in tidal creeks is determined. It follows that calculation of sediment fluxes within creeks may be significantly affected by the temporal sampling as well as its spatial extent. Asymmetry of discharge in creeks plays a significant role in the distribution of sediment within the saltmarsh (Reed, 1987). Stoddart and Bayliss-Smith (1985) have shown, as a result of examining some 700 tidal cycles in these saltmarsh systems, that there is a strong positive sediment flux.

The relationship between the saltmarsh and the sea-walls is a particularly important one. First, the presence of the wall prevents migration of the saltmarsh inland under conditions of rising sea-level. Second, however, the saltmarsh acts as a very important element of coast protection (Pye and French, 1993). Frey and Basan (1985) have suggested that the height of waves crossing saltmarsh can be reduced by as much as 71% and wave energy by 92%. Maximum wave height in storms is reported as being 1 m lower where sea-walls are fronted by saltmarsh (Anglian Water Authority, 1980).

Conclusions

Many GCR sites include saltmarsh features, but Dengie Marsh is one of the few where the saltmarsh is the predominant reason for its inclusion in the GCR and where there have been detailed investigations over several years of the dynamics of the saltmarsh creeks and their role in the overall development of the saltmarsh.

Dengie Marsh is important, firstly because of the development of a substantial chenier plain of which the modern part remains intact and within the site. In particular, the Essex cheniers contrast with the type-form described in Louisiana. In Britain, such features have not been reported often, and where they do occur, for example in Poole Harbour or the Solent, they have not been described in detail. Secondly, Dengie Marsh is important as a research site for monitoring the relationship between saltmarsh development, sedimentation and creek hydrology. Although these processes have been examined elsewhere, this site is the only one in which the saltmarsh is not protected by artificial beach structures and so provides an important contrast with the sites in north Norfolk. Thirdly, the relationships between erosion of saltmarsh, changing sea level and coast protection have also been investigated at Dengie Marsh. The importance of the site in providing data upon which judgements about coast protection can be based is considerable and is a particularly important application of coastal saltmarsh research.

KEYHAVEN MARSH, HURST CASTLE, HAMPSHIRE (SZ 315 905)

V.J. May

Introduction

The Keyhaven saltmarshes (see Figure 10.1 for general location) are important for the range of geomorphological features they display, particularly the intricate pattern of saltmarsh creeks. The site is an important research area for examining the relationship between creek dynamics, tidal processes and sedimentation. The western part of the saltmarshes forms an integral part of the Hurst Castle Spit system (see GCR site report in Chapter 6), a classic site for the study of coastal geomorphology.

Description

Hurst Castle Spit protects a large area of saltmarshes, known as 'Keyhaven Marshes' (Figure 10.11). They are drained by an intricate pattern of creeks dominated by three major creeks – Mount Lake, alongside the spit, Keyhaven Lake and Hawker's Lake. The first two merge and drain into the Solent after being diverted by the modern recurves of the spit. Marsh-edge beaches ('cheniers' – see GCR site reports for St Osyth and Dengie above) are formed of shells and shingle. Their sand content is very low. Low-relief cheniers have developed along the marsh edge and provide some protection against erosion. Much of the saltmarsh edge is being eroded rapidly (6 m a^{-1} over the past 50 years: Pye and French, 1993), resulting in some patches of mud mounds. The upper intertidal zone is characterized by steep microcliffs and a strong concave upward profile within the upper part of the intertidal zone. The upper marsh lies at about 2.4 m OD with a seaward marsh edge at about 2.0 m OD. The elevation of the upper tidal flats is typically about 1.0 to 1.5 m OD (Pye and French, 1993). The seaward cliffs vary in height but are typically 0.7–1.5 m. The marsh surface varies in level by about 0.4 m. The surface of the marshes is characterized by a high proportion of eroded marsh, saltpans, and broad channels. There are only small areas of higher-level, species-rich saltmarsh, located mainly close to the spit and on its older recurves. Sea purslane *Atriplex portulacoides*, common sea-lavender *Limonium vulgare*, sea plantain *Plantago maritima*, sea meadow-grass *Puccinellia maritima*, common seablite *Suaeda maritima*, glasswort *Salicornia*

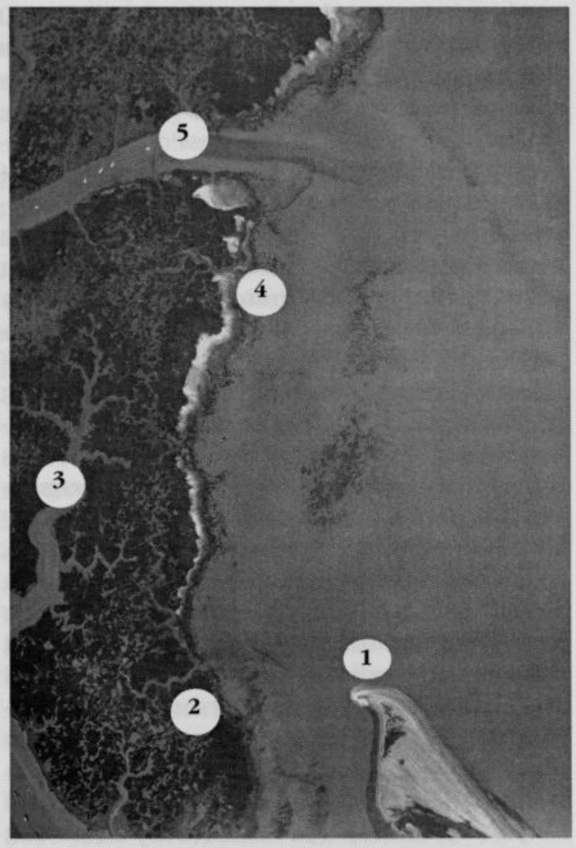


Figure 10.11 Keyhaven Marshes. (1) Distal point of Hurst Castle spit; (2) saltpans; (3) major creek; (4) retreating saltmarsh edge and chenier formation; (5) dominant channel draining upper marsh. (Photo: courtesy Cambridge University Collection of Aerial Photographs, Crown Copyright, Great Scotland Yard.)

spp., and sea aster *Aster tripolium* are common throughout these higher marshes. In contrast, the more extensive lower marshes are species-poor and dominated by common cord-grass *Spartina anglica*. The intertidal area close to the spit is often a stony mud. Before the late 19th century, much of this marsh stood as much as 1 m lower and was dominated by eelgrass *Zostera*. Colonization by *Spartina anglica* following its hybridization from the native *Spartina maritima* and the introduced *Spartina alterniflora* in Southampton Water led to a rapid build-up of the saltmarsh surface. The area of *Spartina*-dominated saltmarsh reached a maximum about 1930, after which the area declined (Bradbury, 1996). As the recurves of the modern spit have extended into the westernmost creek, they have increased local accretion of mudflats.

Bradbury (1996) describes the rapid short-term morphological and ecological evolution of the western Solent saltmarshes that include this site. There have been substantial losses of intertidal flat. Ke and Collins (1993) estimated the average annual loss of saltmarsh in the western Solent as 3.6×10^4 m^2 a^{-1}, at the same time as the saltmarsh surface is accumulating sediment at between 2 and 5 mm a^{-1}. Average erosion of the marsh edge was 3 m a^{-1} between 1992 and 1994, less than the open coast retreat but more than the fringing edge retreat of 1 m a^{-1} since 1950. Dyer (1980) showed that between 1950 and 1973 reduction in intertidal width varied between 180 and 360 m (7.8 m a^{-1}). There was a strong correlation between wind-generated wave-attack and the rate of erosion. Tidal range is 2.5 m on spring tides, but meteorological surges may raise waters levels by up to 50%. The upper marshes at Keyhaven are typically formed in sandy silts, becoming silty sand on the upper tidal flats.

Interpretation

These saltmarshes are remarkable for their rapid vertical accretion and areal extension with the arrival of *Spartina anglica* in the late 19th century. Their subsequent reduction in altitude and area was almost as rapid during the mid-20th century and is related to die-back of *Spartina* described in a series of papers (Braybrooks, 1957; Goodman, 1957, 1960; Goodman and Williams, 1961; Goodman *et al.*, 1959), which showed that it was associated with exceptionally poorly drained saltmarsh soils. Die-back occurred, however, both along channels and within the central parts of the marshes. In the latter, 'pan die-back' may have been associated with the restriction of drainage by rapid accretion around the edges of marshes. In the former, however, other factors, including algal mats, possibly resulting from local eutrophication and cloaking the surface, may have led to more extensive die-back. As channels widened, erosion of the marsh edges appears to have accelerated, although in many parts of the saltmarsh, die-back resulted in a lowering of the marsh surface rather than wholesale retreat of the marsh cliff. The saltmarshes that shelter behind the beach are also liable to damage from recreational use, as well as local pollution.

Conclusions

The development of saltmarsh in the lee of Hurst Castle Spit was limited until the arrival of common cord-grass *Spartina anglica* at the end of the 19th century. The geomorphological interest of this site lies in the rapid sedimentation and saltmarsh development associated with *Spartina* followed by an equally rapid decline and loss of saltmarsh area. Unlike the saltmarshes and cheniers of the Essex coast, those of the Keyhaven marsh are very recent in origin.

SOLWAY FIRTH SALTMARSHES (NX 829 492–NY 125 560)

J.D. Hansom

The saltmarshes ('merses') of the Solway Firth are an extensive group, comprising all those located to the east and upstream of Balcary Point (NX 829 492) and Skinburness (NY 125 560), on both the north (Scottish) and south (English) shores of the inner Solway Firth (see Figure 10.1 for general location and Figure 10.12). Defined in this way, the Solway Firth supports 3618 ha of saltmarsh (Pye and French, 1993), of which the GCR sites, Upper Solway Flats and Marshes on the south shore and the Solway Firth (North Shore), account for 2842 ha (76%). In addition, the saltmarshes at the Cree estuary in Wigtown Bay in the outer Solway Firth cover a further 553 ha. The Solway saltmarshes together account for almost 8% of British saltmarshes and although they display some different characteristics (Table 10.2), their common location, together with similarities, warrant their treatment within a combined section. The saltmarshes are, in the main, of the estuarine fringing type, being developed along the shores of the main Firth and its tributaries, although showing varying degrees of transition into open coast marsh at Caerlaverock on the Scottish shore. In addition, the saltmarsh at Moricambe Bay on the English shore shows many of the characteristics of a more enclosed embayment marsh (Table 10.2). The following text therefore describes the general topographic and hydrodynamic situation of the sites, and then seeks to describe and interpret the south shore group, the north shore group, and the Cree saltmarshes in turn.

The Solway Firth reaches almost 60 km wide between Burrow Head on the Scottish coast and St Bees Head on the English coast and extends over 130 km eastwards to the exits of the rivers Esk and Eden. With the exception of the Cree saltmarshes, the Solway saltmarshes are all located within the inner (eastern) Firth (Figure 10.12). The Firth is macrotidal; mean tidal range at Silloth on the Cumbrian coast reaches 8.4 m at springs and 4.8 m at neaps. On the northern coast the mean tidal range at Heston Islet in Auchencairn Bay is 7.4 m at springs and 3.9 m at neaps (Pye and French, 1993). The tidal streams generated can be significant especially at the mouths of tributary streams, at headlands and promontories and within channels between sandbanks. For example, the tidal stream in and out of the River Cree reaches 2.5 m s^{-1} at springs and similar velocities occur offshore of Southerness Point (Ramsay and Brampton, 2000f). The general situation is that the ebb tide runs for longer and flows at lower velocities than the flood tide. The extensive area of sandbanks retards the flood peak at successive locations upstream and contributes to a marked tidal asymmetry. This differential tidal flow accentuates the net deposition of sediment within the estuary as slower ebb currents are less able to transport sediment than the stronger flood (Comber *et al*., 1994).

The Solway Firth is exposed to waves from the south-west, although fetch lengths are rarely more than 250 km. As a result, most waves reach the shore as wind-waves generated in the Irish Sea or the Firth itself, or as refracted Atlantic swell (Ramsay and Brampton, 2000f). The net effect of what amounts to a unidirectional wave climate is that the Solway Firth, and in particular the inner Firth, is a sediment trap with sediment accreting on the extensive intertidal sandbanks. Thus there is a net build-up of sediment within the Solway, with little sediment escaping seawards (Perkins and Williams, 1966). One result of the predominantly eastward movement of sediment is that the Solway Firth saltmarshes are dominated by sandy sediments that are mainly marine in provenance.

Table 10.2 Characteristic geomorphological features of some of the main Solway Firth saltmarshes.

	Rockcliffe	**Burgh**	**Moricambe Bay**	**Caerlaverock**	**Cree**
Type	Fringing estuary	Fringing estuary	Fringing estuary, bay	Fringing estuary, transitional	Fringing estuary, bay
Marsh-edge morphology	Low cliffs and terraces	Low cliffs and terraces, locally ramped	Low cliffs and terraces, locally ramped	Low cliffs and terraces, rarely ramped	Ramped, locally cliffs and terraces
Creek system	Dendritic	Modified dendritic	Dendritic	Dendritic	Dendritic
Saltpans	Common	Common	Common	Infrequent	Common
Age of active marsh	>200 years	Unknown	Unknown	Pre-mid 19th century	Unknown
Mean sediment type					
Upper marsh	Sandy silt	Sand:fine sand /silt: clay	Sand:fine sand /silt: clay	Sand:silt:clay	Fine sand
Marsh edge	Sandy silt	Sandy silt	Sandy silt	Fine sand	Fine sand
Upper tidal flat	Sand to sandy silt	Sand to silty sand	Silty sand	Fine sand	Sand and gravel

Marshall (1962) showed that the saltmarshes of the Solway are usually composed of more than 90% fine-grained sand, with clay accounting for less than 4%. Since the average clay content of most British saltmarshes commonly exceeds 30%, and often is greater than 65%, the sand content of the Solway marshes is unusually high.

The combination of tidal regime, nature of the substrate and exposure to wave action influences the elevation at which pioneer marsh can become established. For example, in the south and west of Great Britain the lower limit of the pioneer *Spartina* tends to occur lower in the tidal frame in areas of restricted tidal range and on marshes sheltered from waves (Gray *et al.*, 1990). On sandy coasts, the lower level of all pioneer marsh vegetation lies higher in the tidal frame than on muddy coasts (Gray, 1992), and this may be because sandy substrates tend to occur in areas more exposed to wave action (Pye and French, 1993). Such sandy sediment is more prone to mobilization than muddy sediment and so mechanical removal of seedlings may occur before an adequate root structure has developed (Chapman, 1977). This may be one of the reasons why most Scottish saltmarshes, including those in the Solway Firth, tend to have little pioneer vegetation in comparison with those farther south and tend to be dominated by the communities found at higher tidal levels. Much of the Solway saltmarsh is characterized by a lawn-like sward dominated by closely cropped graminoid vegetation that has been grazed and/or traditionally stripped for Cumberland turf. These activities may have contributed to the extensive development of saltpans and creeks on the Solway marshes.

The Solway Firth is also characterized by extensive emerged flat surfaces that fringe the Firth, particularly in the north and east (Marshall, 1962). Many of the emerged flats also have a high sand content and display relict dendritic creek systems with numerous relict saltpans. The flat surfaces, locally known as 'carse', are emerged estuarine sandflats and saltmarshes and although fairly common in Scottish estuaries, they are nationally rare in the British context. They also provide evidence of past changes in sea level within the Solway Firth. For example, peat beds that now lie below sea level indicate times when sea level was lower than present, whereas the emerged carse, indicate times when sea level was higher than present. Haggart (1989) suggests that, over the early part of the Holocene Epoch, sea level rose from about –5 m OD at 10 000 years BP to reach a maximum of about +8.5 m OD at the peak of the transgression at about 6500 years BP. Haggart's (1989) Solway Firth Holocene sea-level curve is convincing and broadly matches the direction and timing of changes in relative sea-level elsewhere in Scotland such as in lower Strathearn (Perthshire) and the inner Moray Firth during mid-Holocene times. It is likely that the curve will gain support from palynological and other micro-palaeontological work under way at present in the Cree estuary, where it seems that the peak of the Holocene Transgression occurred at about 6500 years BP and reached 7–10 m OD (Firth *et al.*, 2000). This date compares well with the culmination of marine conditions at Crosscanonby in Cumbria, where Tooley (1985a) places the change in relative sea level sense from rising to falling at about 6800 years BP. Since then the overall trend has been mainly of a sea level falling towards the present day.

Based on sea-level curves and historical tide gauge records, Firth *et al.* (2000) estimate that present maximum rates of isostatic uplift are 1.8–1.95 mm a^{-1}, with the minimum rates in the range 0.4–0.56 mm a^{-1}. Since the lower estimates closely compare with uplift rates from recent geological evidence, they are probably a better estimate of actual rates. Since present-day global sea-level rise is estimated at about 1–2.5 mm a^{-1} (Houghton, 1994), the present status of the Solway coast is that it is subject to a slow rise in relative sea level.

SOLWAY FIRTH (NORTH SHORE), DUMFRIES AND GALLOWAY (NY 003 668–NY 118 652)

J.D. Hansom

Introduction

In spite of work by Marshall (1960, 1962), Steers (1973), Mather (1979) and Bridson (1980), the only recent detailed geomorphological research on the Solway (north shore) saltmarshes has concerned the inter-relationship between forms, sediments and radionuclides by Allan (1993), Harvey and Allan (1998) and Harvey (2000). Extensive saltmarshes occur adjacent to the River Nith that warrant detailed research, particularly concerning the recycling of eroded

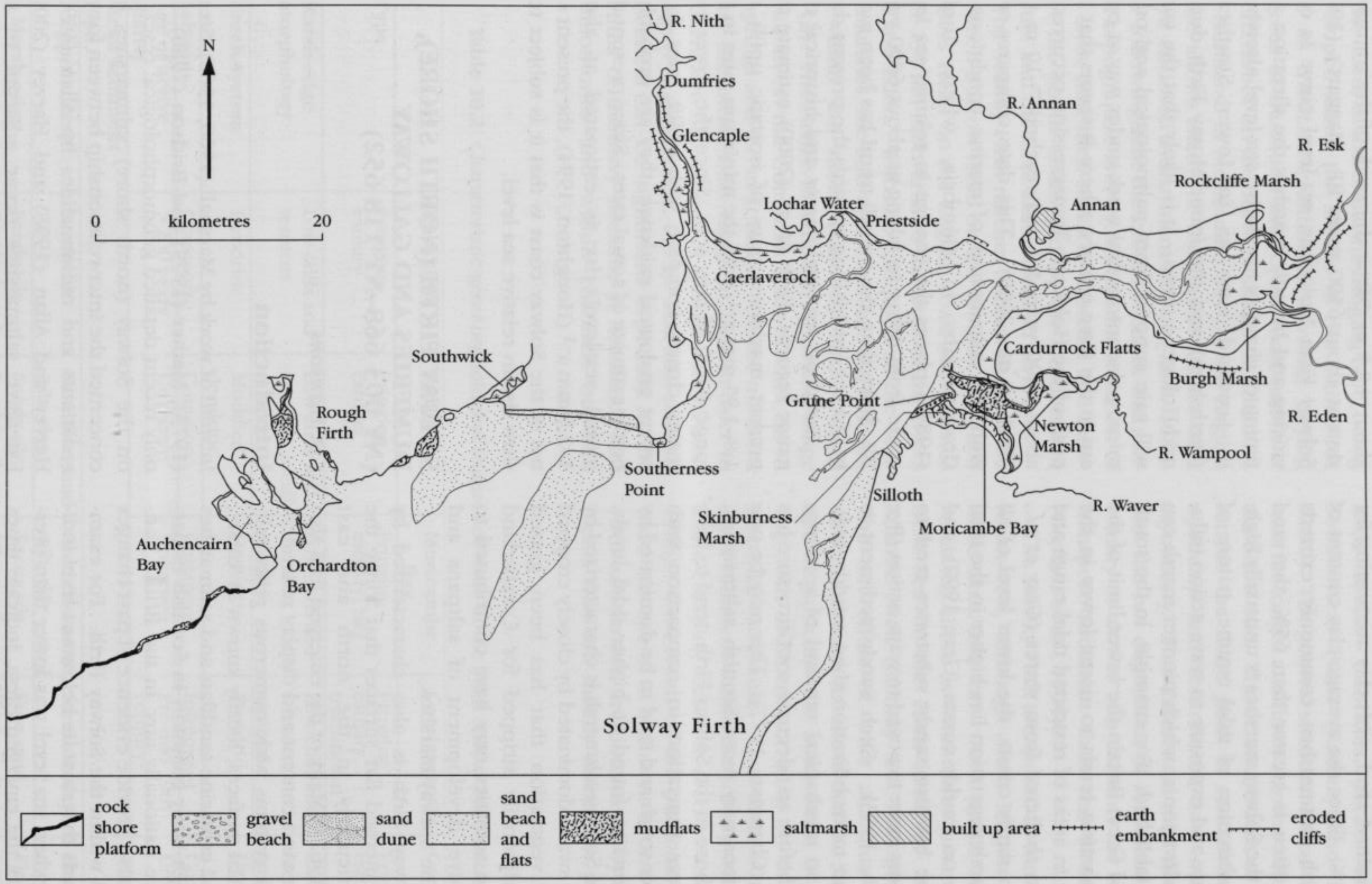


Figure 10.12 Location of the saltmarshes of the inner Solway Firth including the Upper Solway Flats and marshes on the south shore and the saltmarshes of the Solway Firth (north shore). The 2842 ha of saltmarsh found at these sites comprises 79% of all the saltmarsh in the Solway and 8% of all British saltmarshes. (After Pye and French, 1993.)

sediment in the developing marsh. Radionuclide-polluted sediment provides a useful method of quantifying such erosion and deposition.

Caerlaverock saltmarsh has been designated a Special Area of Conservation (SAC), a Special Protection Area (SPA), a National Nature Reserve (NNR) and it is part of the Nith Estuary National Scenic Area.

Description

The north Solway saltmarshes extend from the Nith estuary (NY 993 668) eastwards through the Caerlaverock National Nature Reserve across the mouth of Lochar Water to its exit at Priestside Merse (Figure 10.12). The intertidal sandflat in this area exceeds 10 km in width. Within the Nith estuary and the inner Solway, the active marshes are terraced with as many as four levels separated by unvegetated terrace edges. Flanking the west shore of the Nith, Kirkconnell Merse extends to 208 ha, much of this a *Puccinellia-Festuca* (common saltmarsh-grass –fescue) sward (Burd, 1989) (Figure 10.13). At its landward edge, the merse is entirely enclosed by earth banks, and the river edge is marked by a prominent terrace, which runs almost exactly north–south. The merse reaches 1 km at its widest to the west of Glencaple on the east bank of the Nith, but narrows southwards to disappear at Airds Point (Figure 10.13). Northwards, the merse narrows before widening and merging with Green Merse near Kelton. The marsh surface is traversed by a dense dendritic network of shallow creeks, with saltpans virtually absent other than in a narrow zone along the middle and rear of the marsh. Other than north of Kelton, where it reaches 200 m wide and is traversed by deep creeks, the saltmarsh on the east side of the Nith is narrow, intermittent and limited by the proximity of the channel of the Nith and by rising ground behind.

Caerlaverock Merse, including the 77 ha of Priestside Bank at its eastern end, extends to a total of 560 ha and is dominated by a mainly *Puccinellia-Festuca-Glaux* sward with small stands of reeds *Phragmites* (Burd, 1989; Figure 10.14). Common saltmarsh-grass *Puccinellia* and samphire *Salicornia* occur in the creeks. Caerlaverock is about 8 km long and widens from less than 100 m wide at the Nith mouth in the west, to almost 1 km wide at the Lochar Water in the east. The marsh sediments are formed almost entirely of fine-grained sand (0.2–0.002 mm in diameter) with some fine-grained silt and clay (Harvey, 2000). The landward boundary of Caerlaverock is marked by an earth bank, which extends for some distance inland along the Lochar Water. Landwards of the earth bank, a well-defined emerged beach occurs that shows two distinct surface levels at +8 m and +6.5 m OD (Steers, 1973). Using aerial photographs, Marshall (1962) indicated that these emerged beach surfaces were traversed by drainage channels that resembled old creeks and suggested that the surfaces represented emerged former saltmarshes.

The surface of Caerlaverock Merse is cut by several deeply incised creeks that run southwards to the marsh edge. However, the creeks are infrequent except in the vicinity of the Lochar Water, where a well-developed creek system exists draining eastwards. Elsewhere, the creeks are short and fed by small and infrequent surface streams. Saltpans are infrequent and tend to be located towards the rear of the saltmarsh surface. In the west of the saltmarsh, substantial lengths of the seaward edge are subject to erosion and are marked by a *c.* 1.5-m high, vertical, or in places stepped, terrace edge (see Figure 10.15). In places, the top surface of this terrace also shows extensive damage to the vegetation and surface sediment with vegetation having been stripped off for distances of up to 10 m inland. Lying below these stripped and eroded edges, and often masking the junction between terrace and sandflat below, lie numerous blocks of eroded saltmarsh sediment. The prominence and height of the terrace edge reduces to the east and is replaced by a low-angled and largely accreting foreshore. The amount of accretion increases towards the Lochar Water and this extremity of Caerlaverock is actively extending eastward, an extension favoured by the migration of the channel of the Lochar Water towards its eastern bank at Priestside.

Priestside Merse is situated on the east bank of the Lochar Water and comprises an area of grazed saltmarsh fronted by sandflat. Perkins (1973) reported that a wide saltmarsh with an erosional terrace at its front edge was present in 1964 but that by 1968 accretion was taking place at the front edge. Firth *et al.* (2000) observed a low 20–30 cm-high erosional bluff along this edge, fronted by a 5–10 m-wide zone of slumped material and turf blocks. Eastwards, the marsh

Figure 10.13 A view looking south over Kirkconnell Merse on the west side of the River Nith towards Airds Point in the middle distance and Southerness beyond. The saltmarsh is grazed and is crossed by many well-developed creeks that drain to a prominent terrace along the Nith. Part of the saltmarsh of Caerlaverock can be seen on the east side of the river and to the south lie extensive sandflats. (Photo: P. and A. Macdonald/SNH).

widens to 400 m before narrowing to a thin strip of *Puccinellia*-dominated sward at Powfoot (Mather, 1979). At Powfoot the saltmarsh is reduced to an area of 30 cm-high small hummocks capped by *Puccinellia*, locally known as 'dabs', the seaward side of which is marked by an abrupt boundary with the intertidal sandflat.

Although lying in the west, between Balcary Point and Southerness, and thus outwith the Solway Firth (North Shore) GCR site boundary, substantial saltmarshes have developed at the head of the major embayments of Auchencairn Bay, Orchardton Bay and Rough Firth and along the tidal channel of Southwick Water (Figure 10.12) as well at the head of some of the more sheltered small bays (e.g. Balcary Bay). These saltmarshes have developed in sheltered locations where extensive sandflats occur. A relatively extensive, but in the Solway context, rare, area of mudflat also occurs in Rough Firth. Many of the more extensive and mature saltmarshes, such as at Southwick, are dissected by a complex series of deep creek channels and tend to change abruptly from low marsh and pioneer communities such as samphire *Salicornia*, along the channel edges into areas of mature high marsh immediately above. At Orchardton, a substantial area of *Spartina*-dominated marsh has developed since the 1960s following the introduction of *S. anglica.* However, there are indications that this rapid accretion has been recently replaced by erosion, possibly associated with *Spartina* die-back (Harvey, 2000).

Interpretation

It is clear that the development of saltmarshes on the North Shore of the Solway is not a recent phenomenon and substantial evidence exists to indicate long-lived deposition related to shoreline emergence over the Holocene Epoch. For example, extensive level areas on either side of the Nith, and along the valley floor of its west bank tributaries, represent the emerged remnants of the Main Postglacial Shoreline and its intertidal estuarine flats (Firth *et al.*, 2000). At Barnkirk Point, the flat nature of the land immediately inland of the coastal edge is typical of emerged beaches and has been shown to include sedimentary evidence for Holocene sea-level change (Jardine, 1975). Along the Southwick section of the coast, modern salt-

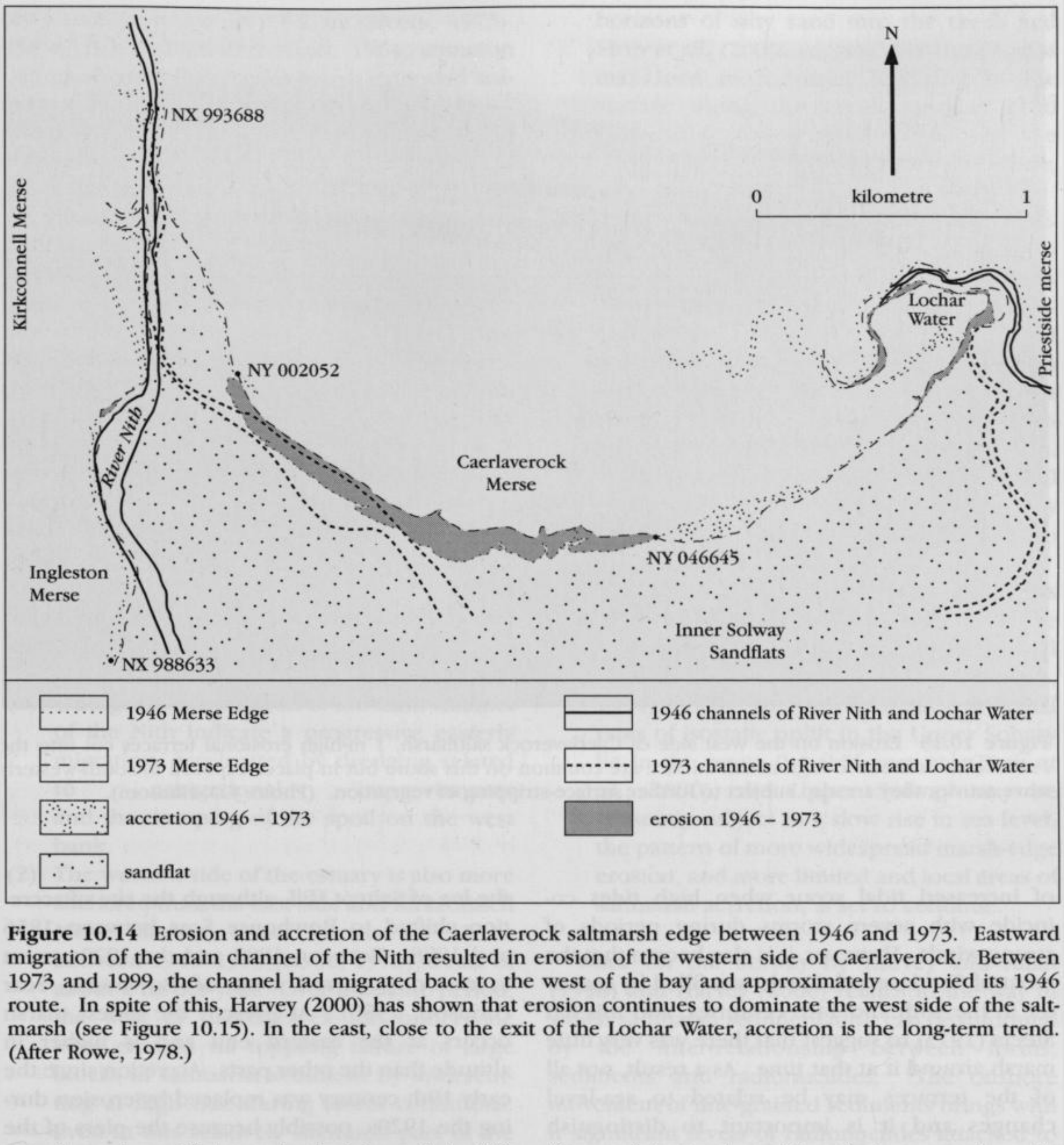


Figure 10.14 Erosion and accretion of the Caerlaverock saltmarsh edge between 1946 and 1973. Eastward migration of the main channel of the Nith resulted in erosion of the western side of Caerlaverock. Between 1973 and 1999, the channel had migrated back to the west of the bay and approximately occupied its 1946 route. In spite of this, Harvey (2000) has shown that erosion continues to dominate the west side of the saltmarsh (see Figure 10.15). In the east, close to the exit of the Lochar Water, accretion is the long-term trend. (After Rowe, 1978.)

marsh and sandflat are backed by relict cliffs 45–50 m high whose foot is adorned with emerged natural arches and stacks (e.g. at Needle's Eye and Lot's Wife). At the head of Auchencairn Bay, emerged estuarine flats up to 1 km wide lie at 8–9 m OD, and similar features lie at similar altitudes along the banks of the Urr Water as far north as Dalbeattie and make up much of the peat-covered surface behind the Mersehead Sands dune ridge. The uppermost of these surfaces at about 9 m OD and most likely date from the rise in relative sea level that occurred up to the peak of the Holocene transgression at about 6500 years BP. The lower surfaces relate to deposition that occurred on its subsequent fall (Haggart, 1989). The detailed position of terrace extent and edge location relates to the former routes of the main river channels and saltmarsh creek positions.

Such a process of adjustment to sea level and to the shifting positions of streams continues today and controls the way in which the saltmarsh and its feeder sandflats react to changing conditions. Within the Nith estuary and the inner Solway, the active marshes are terraced with as many as four levels, which Marshall (1962) suggests reflect periodic shifts and meandering of channels in the marshland or periods

Figure 10.15 Erosion on the west side of Caerlaverock saltmarsh. 1 m-high erosional terraces cut into the *Puccinellia*-dominated high-marsh surface are common on this shore but in places exposed to south-westerly wave activity, they are also subject to further surface-stripping of vegetation. (Photo: J.D. Hansom).

of increased tidal scour when high tides coincide with severe storms during periods of strong winds. However, it is also known that the moat of Caerlaverock Castle was filled by seawater in the 13th and 14th centuries, and this led Steers (1973) to suggest that there was very little marsh around it at that time. As a result, not all of the terraces may be related to sea-level changes and it is important to distinguish between the significance of the variations in altitude of the marshes and the presence of the terrace edges. The upper marshes appear likely to have been constructed at a higher relative sea level than today, but the terrace edges that separate them may not themselves represent a distinct change of sea level.

The development of most of the Solway marshes indicate that they undergo phases of erosion and deposition. For example at Caerlaverock the entire marsh seaward of the lower emerged beach seems to have developed in three phases between 1820 and 1962 (Steers, 1973). Prior to 1856 accretion had occurred in the lee of Saltcot Hill, although the site of accretion shifted to Bowhouse Scar between 1856 and 1898. Between 1898 and the 1920s, most accretion occurred west of Bowhouse Scar (Bridson, 1980). At present the oldest marsh occurs at the eastern end and is higher in altitude than the other parts. Accretion since the early 19th century was replaced by erosion during the 1920s, possibly because the piers of the Bowness to Annan viaduct, built in 1864, acted as groynes and accelerated accretion on their western side (Marshall, 1962). The rapid extension of Caerlaverock Merse and the eastern part of Kirckonnell Merse was probably related to attempts to improve the Nith river channel for navigation (Steers, 1973).

Between 1946 and 1955 erosion at Bowhouse, south-west of Caerlaverock Castle, totalled 38.1 m a^{-1} and the annual rate between 1955 and 1976 was *c.* 7.6 m (Bridson, 1980). Over similar timescales, the annual vertical accretion rate declined with altitude from 30 mm at +5 m OD, to 10 mm at +5.1 m and to very small amounts at +5.2 m (Steers, 1973). Between July 1959 and March 1961, common saltmarsh-grass *Puccinellia* marsh extended seawards by 4.9 m. However, individual events are also important, and the saltmarsh edge near Caerlaverock Castle was cut back by 3.3 m during a single storm between 30 October and 11 November 1960. Marshall concluded that generally erosion was exceeding accretion and this is borne out by saltmarsh-edge mapping conducted by Rowe (1978) (Figure 10.14) that shows the marsh edge at Caerlaverock to have retreated substantially over most of its western part while accreting in the east in the period 1946–1973. More recent work by Pye and French (1993), Hawker (1999) and Harvey (2000) show the process of erosion in the west and accretion in the east at the Lochar Water to be continuing.

The switch from deposition to erosion that has characterized the western part of Caerlaverock may be attributed to a number of factors.

(1) Changes in the position of the main channel of the Nith indicate a progressive easterly migration, accelerated by dredging related to navigational improvements and the dumping of the spoil on the west bank.

(2) The western side of the estuary is also more sheltered than the east side and Kirkconnell Merse showed a net increase of 51 ha between 1946–1973 (Rowe, 1978), a rate of about 2 ha per year. Over the same period, the west of Caerlaverock has undergone edge erosion via toppling failure of large blocks of saltmarsh sediment by undercutting at high tide during storm conditions. Even in this relatively sheltered part of the Solway, the short and steep waves that impinge on the saltmarsh edge are capable of significant erosion of unconsolidated sediments, and the stripping of layers of sediment and vegetation from the top surface of the terrace.

(3) The front edge of the saltmarsh at Caerlaverock is penetrated by a number of large creeks and within-creek erosion occurs through headward extension of the creek inland and vertical incision, forming a narrow channel. Loading pressures from overlying sediments may lead to the deformation of the lowermost saturated horizons of silty sand into the creek and Firth *et al.* (2000) suggest that the process may lead to localized lowering of the surface along the creek margins (and presumably the seaward edge) and the development of a noticeable tilt, or camber, towards the creek.

(4) It is also possible that the annual heavy grazing and trampling of the site by large numbers of wintering wildfowl (e.g. 13 000 barnacle geese), which locally damages the vegetation cover, may lower the resistance of the marsh surface to wave erosion. In this context much of the Solway saltmarsh is characterized by a lawn-like sward dominated by closely cropped graminoid vegetation. The grazing levels by cattle were recorded by Marshall (1962) as the highest on any British saltmarshes with 1 stock unit to 0.8–1.0 ha.

(5) The apparent present trend towards erosion of the saltmarsh edge may be controlled by the present rise in global sea level of about 1–2.5 mm a^{-1} (Houghton, 1994). Since the best estimates of actual rates of isostatic uplift in the Upper Solway lie in the range 0.4–0.56 mm a^{-1} (Firth *et al.*, 2000), the Upper Solway may be presently subject to a slow rise in sea level; the pattern of more widespread marsh-edge erosion, and more limited and local areas of saltmarsh accretion, is set to continue.

Work on the Solway by Harvey and Allan (1998) and Harvey (2000) relates to the way in which saltmarsh sedimentation can be informed by the inter-relationship between forms, sediments and radionuclides. The onshore movement of fine-grained sediments brings with it significant levels of radionuclides attached to the particles. These radionuclides are almost exclusively derived from the Sellafield Nuclear Fuel Reprocessing Plant in Cumbria and result in varying concentrations with depth in the saltmarsh (Figure 10.16). Coring of the saltmarsh shows that the depths of different peaks in radionuclide concentration varies spatially over the saltmarsh and so provide marker horizons from which sedimentation rates can be calculated over the time-span represented by the core length. Since erosion of older parts of the saltmarsh is ongoing then re-release of radionuclide-contaminated sediment may ultimately provide a method to estimate the relative contri-

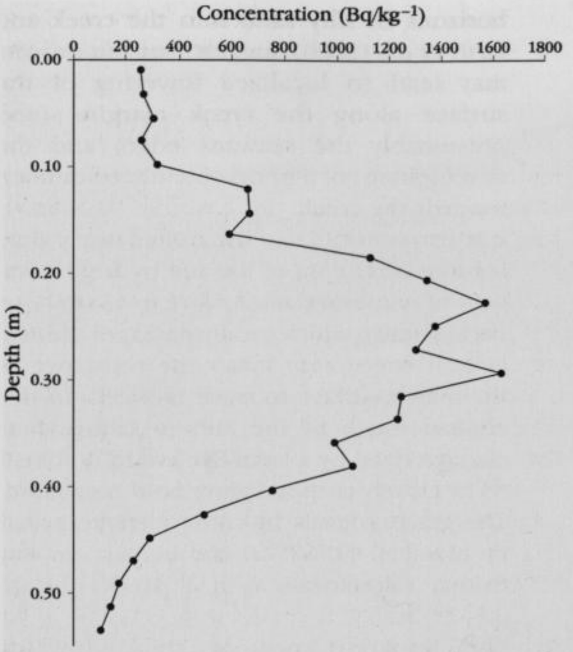


Figure 10.16 Elevated concentrations of the radionuclide ^{137}Cs occur at varying depths beneath the saltmarsh surfaces of all of the Scottish Solway saltmarshes, including at Caerlaverock. The time-integrated profile of Sellafield discharges shown here, comes from nearby Southwick saltmarsh, and shows peak concentrations at 0.30 m depth below the high-marsh surface, which represent input of sediments from the outer firth that peaked in 1978 and have declined since. These data can be used to calculate a sedimentation rate over time that can be compared with direct measurements using sedimentation plates or pins. (After Harvey, 2000.)

butions of old versus newly arrived sediment to accreting areas of the saltmarsh.

Conclusions

The saltmarshes of the Solway Firth north shore are nationally important because both their geomorphology, and that of their emerged counterparts, show evidence of past and present responses to isostatic uplift, changing sea levels and channel migration patterns. In addition, the top surface of the prominent marsh cliff that occurs along the seaward edge of the marsh has in exposed sites been subject to distinctive stripping of the vegetation cover during storm conditions. The old creek patterns that can be traced on the emerged marine surfaces landward of the present marshes represent evidence for the existence of higher and more extensive saltmarshes in the past, and radionuclides provide an additional means to estimate rates of sedimentation and thus age. Nationally, the marshes of the Solway north shore are key sites for the study of saltmarsh processes, morphology and evolution.

UPPER SOLWAY FLATS AND MARSHES (SOUTH SHORE), CUMBRIA (NY 143 569–NY 353 648)

J.D. Hansom

Introduction

The Upper Solway saltmarshes are classic estuarine marshes, which exhibit outstanding geomorphological features. A prominent marsh cliff occurs along most of the seaward edge of the Upper Solway marshes and pinpoints those parts of the marshes that are undergoing erosion. Creek systems in various stages of development are found on all of the saltmarshes and on Burgh and Rockcliffe Marshes exhibit a widely spaced dendritic pattern. Several types of saltpans are also found on the marshes. The saltmarshes exhibit some of the finest examples in Great Britain of marsh terraces that are believed to be formed by creek migration and isostatic uplift.

Description

The saltmarshes on the southern shore of the Solway Firth extend from Grune Point near Skinburness in the west, to Rockcliffe Marsh in the east at the mouth of the Esk (see Figure 10.1 for general location and Figure 10.12). Within Moricambe Bay, *c.* 1190 ha of saltmarsh extends from Skinburness Marsh south of Grune Point towards the south-east, and includes Newton Marsh, which lies between the estuaries of the rivers Waver and Wampool. Marsh is absent from the north-east shore of Moricambe Bay but occurs along a narrow fringe at Cardurnock Flatts. At Burgh Marsh, to the south of the River Eden estuary, the *c.* 524 ha (Burd, 1989) of saltmarsh is up to 1.25 km wide and is unbroken by large creeks. Rockcliffe Marsh extends to about 565 ha (Burd, 1989) and reaches over 3 km wide although it is punctuated by wide creek mouths. As with most of the Solway marshes, the Upper Solway marshes are often backed by low terraces that separate the present saltmarsh from the emerged carse surfaces, which lie to the landward side. All of these saltmarshes are based on a fine-grained sandy substrate that supports essentially similar plant communities, namely common saltmarsh-grass–fescue (*Puccinellia–Festuca)* and the dominant species, saltmarsh rush *Juncus gerardii*, which covers up to 64% of the site area (Burd, 1989). Rockcliffe is particularly important in terms of its size and its retention of an unusually wide transition between non-saline and saline habitats. Transitional grassland plants such as dog's-tail grass *Cynosurus*, buttercup *Ranunculus*, clover *Trifolium* and hawkbit *Leontodon* are found in abundance on these marshes but are not found at all in estuaries to the south of Ravenglass (Fahy *et al*., 1993). *Spartina* is not yet widespread in the Solway but is found at Southwick in small amounts and at Orchardton, on the northern side of the Solway.

The northern shore of Grune Point is composed of a gravel spit upper beach fronted by 500 m of sandflats extending to low water. Active longshore drift of gravels occurs northwestward along the northern shore (Fahy *et al*., 1993) and provides shelter for the development of saltmarshes within Moricambe Bay. The highest parts of Grune Point, particularly along the north-western side, are locally capped by dune sand. Skinburness Marsh lies south of Grune Point and is well terraced with extensive creek and saltpan development terminating at a rapidly accreting frontal margin close to Grune Point (Perkins, 1973) that is dominated by samphire *Salicornia* (Marshall, 1962). Elsewhere the marsh edge is cliffed and subject to intermittent erosion. The marshes of Moricambe Bay were noted by Marshall (1962) to be composed of over 90% fine-grained sand in both the saltmarshes and the bare sandflats, a characteristic shared throughout the Upper Solway. Most of the fine-grained sand was regarded by Marshall to be of marine origin, although some may have been reworked from the fine-grained sands of the emerged carse deposits. The modern marshes are terraced with small steps of between 0.3 m and 0.6 m in height occurring between the terraces. The higher of these terraces often separates the present marsh from the emerged carse behind. The emerged carse surface also displays terraces, the lower of which reaches up to 6.4 m OD, with the upper terrace attaining +7.3 m OD at Moricambe Bay and Burgh Marsh.

A major area of saltmarsh occurs along the southern shore of the Eden estuary at Burgh Marsh (Figure 10.12). The channel of the River Eden flows along the front edge of the marsh and appears to be migrating southwards in this area at the present time so that there is an absence of significant sandflat in front of the saltmarsh. However, extensive sandflat occurs on the northern side of the Eden channel and on the south side of the Esk channel. The highest parts of these sandflats have developed into saltmarshes dominated by saltmarsh rush *Juncus gerardii* with common saltmarsh-grass *Puccinellia* and fescue *Festuca* (Firth *et al*., 2000). Allen (1989) reports relict, partially buried, erosional bluffs on the surface of Burgh Marsh, which are interpreted to indicate that oscillations in the proximity of the channel of the Eden over time, that have resulted in cycles of erosion and accretion.

The largest expanse of saltmarsh in the Upper Solway is Rockcliffe Marsh (Figure 10.17). Much of the upper central saltmarsh is relatively flat but around the margins and in the western part the marsh surface is incised by numerous creeks with extensive intervening areas of saltpans. Many of the creek mouths on the north-eastern margin adjacent to the Esk channel are narrow and deeply incised, although elsewhere on the north-west and southern margin the creeks are wide and characterized by areas of accretion with pioneer vegetation. Both the northern and southern margins have been expanding rapidly in response to the migration of the Esk and Eden channels towards the north and south respectively, leaving between a large low-energy zone that is occupied by the present marsh. Maps dating back to 1776 (ABP, 1991, in Black *et al*., 1994) suggest that this is part of a long-term trend initiated by the southwards migration of the channel of the River Eden in the 19th century, but continued land uplift almost certainly contributes to the creation of a more emergent surface (Firth *et al*., 2000). Between 1946 and 1973, Rockcliffe Marsh experienced a net expansion of 414 ha (15 ha a^{-1}) (Rowe, 1978).

Interpretation

The vegetation quality and degree of development on the Upper Solway marshes is thought to indicate that they comprise a relatively old, stabilized marsh system (Burd, 1989). The presence of eroded seaward edges up to 2 m high on

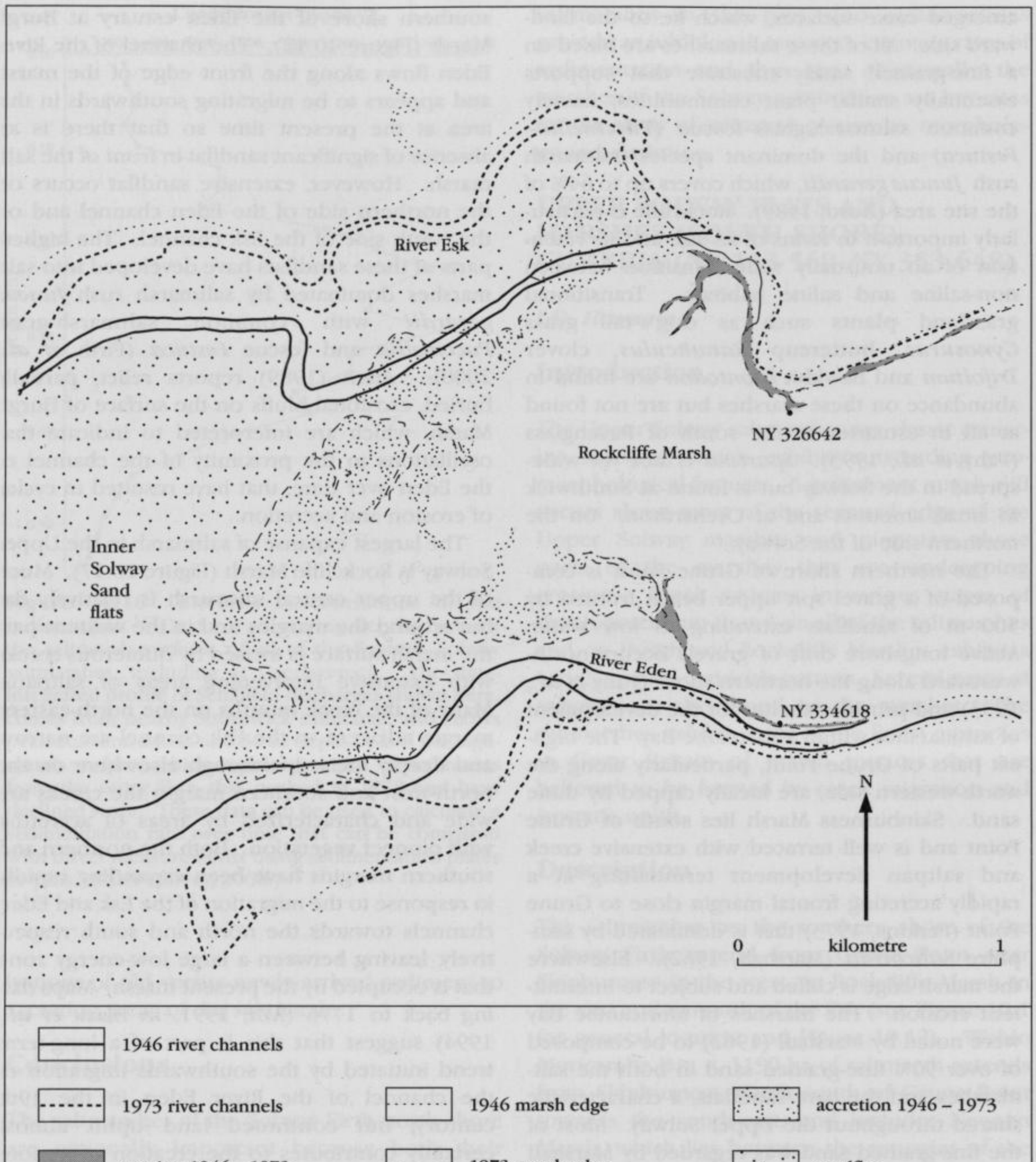


Figure 10.17 Migration of the Rivers Esk and Eden over the period 1846–1973 has contributed to rapid accretion and westward migration of Rockcliffe Marsh that continues today. A healthy supply of sediment comes from the extensive nearshore and intertidal sandflats, augmented by fluvial sediment from the two rivers. (After Rowe, 1978.)

many of the marshes lends support to this hypothesis and suggests that the developing marshes have been subject to cycles of erosion and deposition depending upon the relative proximity of river channels and the rate of sea-level change. It is likely that the broad transitions to mature upper marsh and freshwater communities that are so well displayed in the Upper Solway marshes are also related to the history of sea-level change experienced by the area. The transitions away from salt-affected vegetation so well-represented on the Upper Solway Marshes are of considerable importance because such zonations have been largely destroyed by land-claim in many other British saltmarsh systems. Although artificial embankments and walls are present along many of the intertidal reaches of rivers draining into the inner Solway and on some low-lying areas inland of Rockcliffe Marsh and Moricambe Bay, direct physical human impact on most of the Upper Solway saltmarshes remains minimal, although some of the saltmarshes have a history of turf-cutting and most are still grazed.

The Upper Solway Marshes also provide the finest examples in Britain of marsh terraces formed by the combined action of creek migration and land uplift. The terraces were first regarded by Dixon *et al.* (1926) as strong evidence for recent changes of sea level. They regarded the combination of gradual seawards decrease in altitude of the emerged 'carse' surfaces and the continued growth of Grune Point and small terraced flats on the modern saltmarsh as evidence for continuous uplift. However, Marshall (1962) interpreted the stepped nature of the marshes to be mainly erosional, since where they were present the terraces never graded into each other and the step was at an approximately constant height. This was thought to demonstrate alternation between erosion and accretion, probably the result of erosion by shifting river channels. The most likely scenario probably involves both of the above processes.

All of the marshes have eroded and accreted large areas during the 20th century. In Moricambe Bay, a loss of 39 ha of saltmarsh at Skinburness Marsh between 1860 and 1900 was balanced by accretion of 105 ha (Steers, 1946a). The *Salicornia*-dominated part of the marsh at Skinburness extended laterally by over 50 m between July 1959 and March 1961 (Marshall, 1962). At this time most of the edge of Burgh Marsh and the south-east edge of Rockcliffe Marsh the edge was characterized by high (2.0 m) cliffs, although elsewhere the marsh edge undergoing erosion was between 0.3 and 0.6 m above the adjacent sandflat (Marshall, 1962). Such erosion in this low wave-energy environment was attributed by Marshall to result largely from shifts in river channels rather than to wave activity. Indeed, with the possible exception of Cardurnock Flatts, all of the marshes are sheltered from substantial wave activity. The Moricambe Bay marshes are protected by Grune Point and a north-west-facing bay entrance that restricts the fetch of the dominant south-westerly waves. Rockcliffe Marsh lies at the head of a meandering estuary that reduces the access of westerly waves to only 1 km and is fronted by many kilometres of intertidal sandflats. As a result, patterns of erosion and accretion on the marshes are largely dictated by changes in river channels and by the long-term emergence of the coast.

Long-term estimates of erosion and accretion are possible by using areal comparisons of maps by Marshall (1962) and Pye and French (1993) over the period 1864 to 1993 (Table 10.3). These indicate that Rockcliffe and Skinburness Marshes gained area from 1864 to 1973, but

Table 10.3 Estimated areal accretion in hectares between 1864 and 1946, 1946 and 1973, 1973 and 1993 for selected inner Solway saltmarshes. (Based on data from Marshall, 1962; Rowe, 1978 and Pye and French, 1993.) All areas in ha. Caerlaverock Marsh is in the Solway Firth (north shore) GCR site.

Marsh	1864	1946	1993	1894–1964	1946–1973[1]	1946–1993[2]
Rockcliffe	664	709	565	+45	+414	–144
Burgh	688	534	524	–154	–82	–10
Skinburness	445	506	n/a	+61	+100	n/a
Caerlaverock	194	607	563	+413	–93	–44

1 Rowe (1978)

2 Pye and French (1993)

then reduced in area over the period 1946 to 1993. In the case of Rockcliffe, Rowe (1978) shows that rapid gains were made between 1966 and 1973 (430 ha) but the data of Pye and French (1993) indicate a subsequent loss in area by 1993. Such substantial and recent erosion seems unlikely given the location of Rockcliffe Marsh, and it may be that methodological differences in estimating accretion areas is responsible for this apparent anomaly. Where marsh edges undergoing erosion occur, mapping the boundaries is more secure than where accretion dominates and the actual edge is uncertain and seasonally mobile. Figure 10.17 shows the marsh edge at Rockcliffe between 1946 and 1978 as mapped by Rowe (1978). It is possible that the apparent present trend towards erosion of the saltmarsh edge suggested by Table 10.3 is related to the present rise in global sea level of about 1–2.5 mm a^{-1} (Houghton, 1994). The best estimates of actual rates of isostatic uplift in the Upper Solway lie in the range 0.4–0.56 mm a^{-1}, since these compare with uplift rates from recent geological evidence (Firth *et al.*, 2000). It thus appears possible that, after a long period of emergence, the Upper Solway is presently subject to a slow rise in relative sea level and that this may produce a future trend of more-widespread marsh-edge erosion and more-limited and localized areas of saltmarsh accretion.

Conclusions

The Upper Solway Marshes together represent an area characterized by outstanding examples of emerged saltmarsh on which the geomorphological and vegetational effects of accretion in an inner estuary location have been accentuated in the past by isostatic uplift. In spite of this, some edges undergoing erosion, and distinct terraces on both the present and emerged marsh surfaces, indicate that changing locations of river and estuary channels are also responsible for cycles of erosion and accretion. At some places and times, such local effects may be more significant to the local development of the marsh than the longer-term effects of isostasy. Although little work has been done on development of these marshes, it is likely that the creek and saltpan networks relate closely to the interaction of erosion and accretion resulting from both local river regimes and general isostatic effects. After a long period of emergence, the more recent trend towards erosion of the saltmarsh edge may be a function of a slow rise in relative sea level.

CREE ESTUARY, OUTER SOLWAY FIRTH, DUMFRIES AND GALLOWAY (NX 465 545)

J.D. Hansom

Introduction

The saltmarshes of the Cree estuary (see Figure 10.1 for general location) demonstrate well the geomorphological features of fringing estuarine saltmarsh. The creek system is dendritic, especially in the north close to the Cree exit, although the creeks in the south have been artificially straightened. Saltpans are distributed over all marsh levels, particularly on the marshes adjacent to the Cree exit. Parts of the saltmarsh have developed very recently and independently of the complex of saltmarshes in the inner Solway Firth. For example, the marsh at the Baldoon Sands on the west side of the estuary has mainly developed since 1847 (Figure 10.18). In spite of this recent development, estuarine sedimentation has prevailed in the Cree estuary over most of the Holocene Epoch because all of the present saltmarshes are backed by extensive areas of emerged estuarine flats known in Scotland as 'carse'.

Description

The total extent of saltmarsh in Wigtown Bay amounts to 553 ha (Burd, 1989), 108 ha of which lie on the western shore of the Cree estuary (Rowe, 1978), extending for over 10 km northwards from near Jultock Point to the tidal limit of the River Cree itself to the south of the town of Newton Stewart. On the eastern shore of the Cree, north of Ravenshall Point, saltmarsh occurs only within a small area north of Wigtown Sands (Figure 10.18) and small, partly enclosed, areas farther upstream. The saltmarsh communities are mostly dominated by a common saltmarsh-grass–fescue (*Puccinellia-Festuca)* sward (Burd, 1989). Much of the shoreline within Wigtown Bay is characterized by extensive sandflats that are succeeded landwards by saltmarshes, brackish reedswamps and emerged Holocene carse deposits (Figure 10.19). Within the smaller bays, more-restricted areas of saltmarsh are present. However, in spite of the wealth of information gained on Holocene sea-level changes in this area and the wide variety of features present, few studies have been undertaken to assess the evolution and processes of the modern sandflats and saltmarshes.

North of Jultock Point (Figure 10.18) the flats of Baldoon Sands extend to 3.75 km wide and are backed by saltmarshes that widen from 50 m in the south to 1 km in the north adjacent to Wigtown Sands and the mouth of the River Bladnoch. The marshes are dissected by large and generally linear channels, and extensive saltpan systems occur in places. For example, at Baldoon the saltmarsh reaches 300 m wide and is traversed by several linear creeks that have been artificially deepened and straightened to facilitate more rapid drainage from the grazed marsh surface (Figure 10.20). There is only a very restricted amount of low marsh supporting primary colonizing vegetation. In places the marsh edge is marked by a small terrace but more often there occurs a low-angled ramp of partly-vegetated sand, which merges imperceptibly to the sandflat surface. The flora of the marsh surface is typical of a grazed Solway saltmarsh, being dominated by a fescue–common saltmarsh-grass *(Festuca-Puccinellia)* sward with abundant thrift *Armeria maritima* and sea milkwort *Glaux maritima*. At Crook of Baldoon, the marsh is backed by a rubble embankment that is used for flood protection and access and has been extended southwards recently, parallel to the fence-line, to enclose the rear of the high saltmarsh surface.

North of Wigtown, the sandflats give way to muddier sediments and marshes up to 1 km wide are located on the eastern side of the River Cree as well as on the west. North of Wigtown Sands towards Newton Stewart, the river channel is deeply incised and its muddy banks are characterized by failure and toppling of saltmarsh sediment and vegetation into the channel below. The estuary becomes increasingly restricted between either artificial earth embankments, boulder groynes or low cliffs cut into emerged Holocene estuarine deposits, but a range of high-marsh vegetation with occasional reedbed occurs (Figure 10.19). Minor depositional areas occurring on the inside loops of the meandering tidal channel are characterized by narrow and steeply sloping banks of silt and clay but strong river and tidal streams along much of this section have resulted in an incised channel and limited deposition (Figure 10.19).

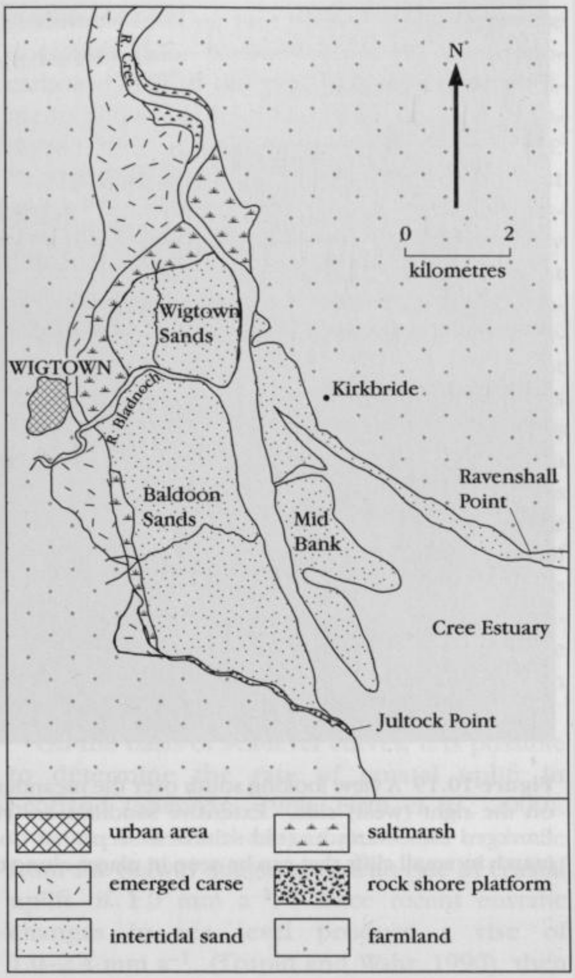


Figure 10.18 Saltmarshes and emerged carse surfaces in the Cree estuary, Wigtown Bay. The estuary is shallow and extensive sandflats are exposed at MLWS. Muddier sediments are restricted to the tidal reaches of the Cree River itself in the north where small saltmarshes fringe its course, particularly on the inside of meander loops.

South of the Cree exit, the foreshore is characterized by sand and gravels and no saltmarsh occurs until inside Fleet Bay, on the south-eastern side of Wigtown Bay, but outside the GCR site boundary. Here 1 km-wide mudflats with flanking saltmarshes occur between Skyreburn Bridge and The Canal. Low-marsh vegetation grades gradually landwards into high-marsh species and creek and saltpan development is limited, with little evidence of erosion. The

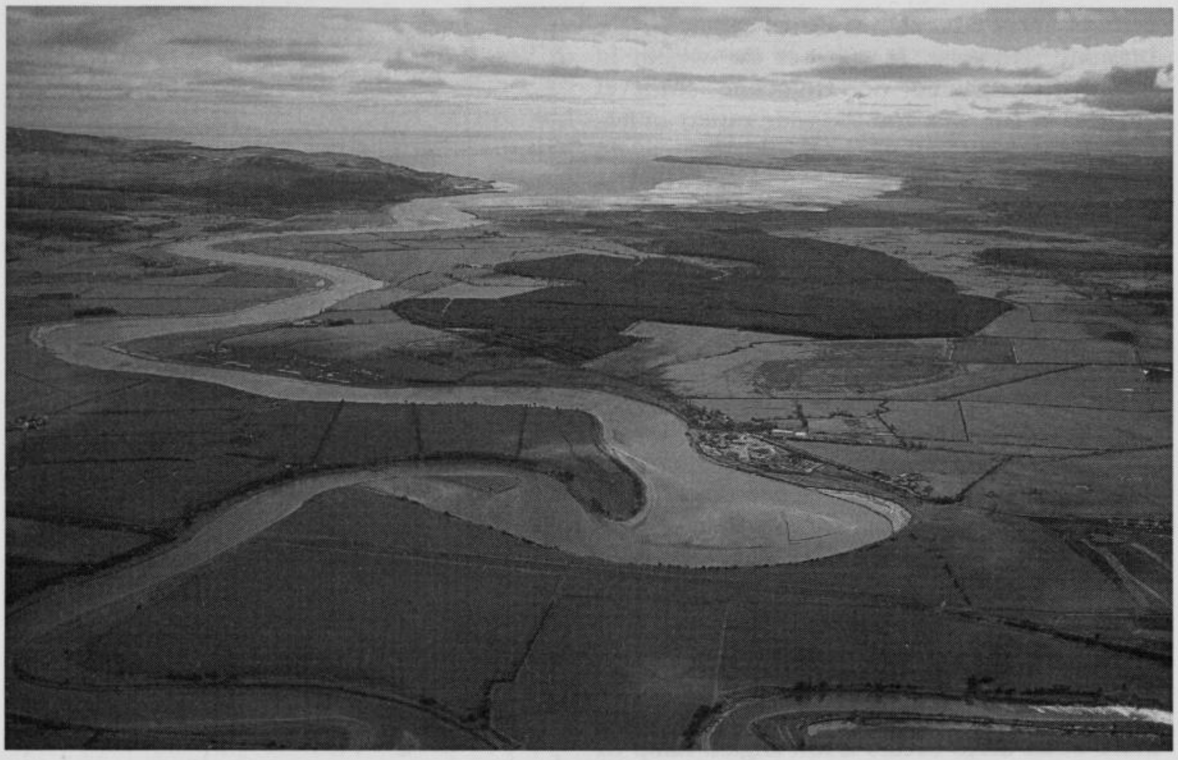


Figure 10.19 A view looking south over the meanders of the Cree estuary towards Jultock Point in the distance on the right (west) side. Extensive sandflats are visible to the south of the forest in the middle distance. Emerged carse surfaces (old saltmarsh deposits) dominate the foreground, separated from the present saltmarsh by small cliffs that can be seen in places along the main river channel. (Photo: P. and A. Macdonald/SNH.)

Canal is an artificial and embanked boulder-lined channel that is deeply incised at its landward end into emerged Holocene estuarine deposits.

Throughout the area of the Solway, there are large sections of the present shore backed by emerged Holocene marine features, good examples of which occur at the heads of the Cree and Fleet estuaries. In these areas the emerged estuarine silts and clays of the carselands attain altitudes of between 7–10 m OD. Within the Cree estuary carseland, sediments extend as far inland to the north as Newton Stewart and to within 2 km of Jultock Point in the south on the western shore. The carse deposits reach 3.5 km wide north of Wigtown, where they partially overlie and partially abut large peat beds at Moss of Cree, Carsegown Moss and Borrow Moss. The carselands in the Fleet estuary are more restricted, forming terraces up to 500 m wide.

Interpretation

The abundance of well-developed emerged landforms on the north coast of the Solway, and the Cree area in particular, has stimulated interest in the Holocene sea-level history, mainly by Jardine (1975, 1977, 1978) but also by Bishop and Coope (1977) and Haggart (1989). More recent work in the late 1990s by Wells, and reviewed by Firth *et al.* (2000), forms the basis of the following account. Recent stratigraphical evidence from cores taken from the emerged carselands flanking the Cree estuary has established the existence of a buried layer of at least 9 m of fine-grained sediments capped, at between –2 m and 0 m OD, by a thin layer of buried peat. At Carsewalloch Flow, the buried peat is itself buried by up to 9 m of emerged estuarine sediments deposited by the Main Postglacial Transgression at about 6500 years BP (Firth *et al.*, 2000), and that now form the carse surface. Estuarine microfossils from the basal

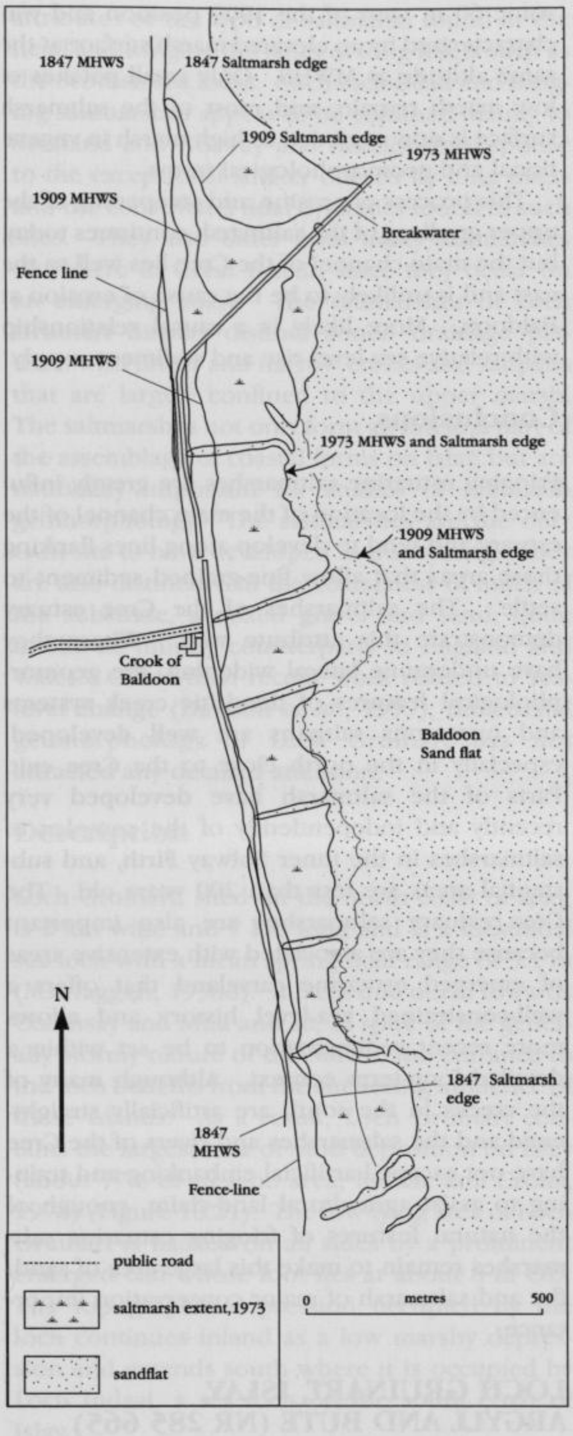


Figure 10.20 The linear saltmarshes at the Crook of Baldoon, on the western side of the Cree estuary appear to have undergone rapid accretion since the edge was mapped in 1847 but have mainly undergone edge retreat since 1973. Landward embankments along much of the Cree testify to land-claim for agricultural purposes in the past. Linear creeks at Baldoon have been artificially straightened and deepened.

sediments indicate that marine influences were dominant prior to 9600 years BP, but radiocarbon dating of the peat that caps these sediments shows sea level had fallen and had abandoned the area by at least 8300 years BP. However, radiocarbon dating of the uppermost part of the thin layer of peat indicates a transgression of the sea by 8000 years BP, followed by a rise to the Main Postglacial Shoreline at between 7–10 m OD by 6500 years BP. The subsequent fall of relative sea level from the uppermost carse surface to its present level was not uniform, because small areas of younger peats are found in the carse sediments at 5700 years BP, and evidence of a shoreline produced by a still-stand or transgression at 2000 years BP is also found. Over the past 2000 years the relative sea level in the Cree estuary and in the rest of the northern Solway Firth fell more or less smoothly to present levels. Such dating evidence produces a sea-level curve for the Cree that is broadly in agreement with elsewhere in Scotland (Haggart, 1989).

On the basis of sea-level curves, it is possible to determine the rate of crustal uplift in Scotland (Shennan, 1989; Firth *et al.*, 2000). Over the last few thousand years, the evidence from the Solway suggests a mean rate of crustal uplift of 1.0 mm a^{-1}. Since recent eustatic changes in sea level produce a rise of 1.0–2.4 mm a^{-1} (Trupin and Wahr, 1990), then the present relative sea-level trend on the north coast of the Solway is either stable or, more probably, slightly rising.

Set within this sea-level context, the saltmarshes of the Cree have developed on the fringes of an estuary where they, and their emerged couterparts, have benefited from the shelter provided by Burrow Head to the south and by a north-west–south-east orientation along the length of the inlet. The eastern shore of the Cree estuary is also indented by Fleet Bay, a major NNE–SSW-aligned embayment. Shelter within the Cree has been unchanged over thousands of years and has produced a largely unidirectional wave climate producing a sediment sink that has encouraged sediment influx but little removal. It appears that this system still operates, since many of the sandflat and saltmarsh systems of the Cree are accreting, although the relative contribution of the sediments of different provenance is more difficult to determine. The extensive sandbanks in the Cree and Water of Fleet estuaries suggest that most of the material passes landwards up the tidal channels and the presence of Sellafield-derived radionuclides attached to the sediment confirms the outer Solway as a major source (Harvey and Allan, 1998). Within the Cree mouth itself, increasing amounts of mud suggest a fluvial source augmented by active reworking of emerged Holocene sediments from the carse deposits.

The position of the main channel of the Cree is likely to have a major influence on the local erosion or accretion regime of the sandflat and saltmarsh. For much of its route south from Newton Stewart, the present channel is now guided by embankments designed to allow land-claim of the saltmarsh behind, but which also serve to contain and train the river along a relatively inflexible course, especially on the outer bends of meander loops. At the exit of the Cree to the north of Wigtown Sands, the river has been further deflected to the east by a series of boulder groynes, which, by protecting the northern extent of Wigtown Sands, its saltmarsh and claimed land, serves to direct the main channel of the river onto the eastern shore. As a result the eastern shore to the south of Creetown is scoured by stronger currents that limit the deposition of fine-grained sediments and so is mainly developed in sands and gravels with little or no saltmarsh. The land-claim embankments and the training breakwaters of the River Bladnoch at Wigtown on the west shore also serve to encourage depositional conditions on the west shore by deflecting the main channel of the Cree towards the east.

It is evident that there has been change to saltmarsh extents over the historical period. For example, Figure 10.20 shows the movement of the MHWS and saltmarsh extent at Baldoon, on the west side of the estuary. Although embankments enclose a substantial area of former saltmarsh, the relative positions of the 1847 MHWS and 1847 saltmarsh edge show a very narrow and linear saltmarsh, which suggests that the date of enclosure was just prior to 1847. Subsequent to this, accretion, and the construction of a 600 m-long breakwater, resulted in the eastward migration of the MHWS by up to 100 m and eastward migration of the 1909 saltmarsh edge by up to 400 m, presumably at a lower height and characterized by an extensive area of low marsh colonized by pioneer species. By 1973, the edge of the saltmarsh coincided with mean high-water springs and lay on average some 60 m west of the 1909 position and was characterized by an elevated marsh surface at the same altitude as MWHS. Only small patches of low marsh remain, and most of the saltmarsh surface is now regarded as high marsh in vegetational and geomorphological terms.

This process of erosion and steepening of the upper gradient of the saltmarsh continues today, but the main channel of the Cree lies well to the east and is unlikely to be the cause of erosion at Baldoon. More likely is a causal relationship with relative sea-level rise and sediment supply.

Conclusions

Fringing estuarine saltmarshes are greatly influenced by the location of the main channel of the estuary and tend to develop along lines flanking those areas that allow fine-grained sediment to settle. The saltmarshes of the Cree estuary demonstrate this attribute well. Where they have undergone lateral widening, the geomorphological features of dendritic creek systems and numerous saltpans are well developed, especially in the north close to the Cree exit. Parts of the saltmarsh have developed very recently and independently of the complex of saltmarshes in the inner Solway Firth, and substantial areas are less than 200 years old. The Cree estuary saltmarshes are also important because they are associated with extensive areas of emerged estuarine carseland that offers a well-constrained sea-level history and allows more recent sedimentation to be set within a detailed long-term context. Although many of the creeks in the south are artificially straightened and the saltmarshes and rivers of the Cree have not escaped artificial embanking and training to assist agricultural land-claim, enough of the natural features of fringing estuarine saltmarshes remain to make this large area of sandflat and saltmarsh of major conservation importance.

LOCH GRUINART, ISLAY, ARGYLL AND BUTE (NR 285 665)

J.D. Hansom

Introduction

The saltmarshes within Loch Gruinart, Islay (see Figure 10.1 for general location), demonstrate particularly well the geomorphological attributes of the type of saltmarsh found at the head and fringing the sides of long inlets such as the Scottish sea lochs. Such loch-head and fringing saltmarshes appear to be confined mainly to Scotland and Norway and develop in response to the exceptional shelter offered by long inlets and the constricted tidal dynamics found in such sites. They also differ from many saltmarshes elsewhere in Great Britain since they occur on an emerging coast. The saltmarshes of Loch Gruinart display distinct zoned drainage patterns with linear and narrow creeks and saltpans that are largely confined to the upper marsh. The saltmarshes not only form an integral part of the assemblage of coastal forms on Islay, but are nationally important for studies of saltmarsh geomorphology. The saltmarshes are the only GCR site to have developed in this setting. They are also distinctive in the coarseness of much of the substrate, a mixed gravel and sand, quite unlike its muddy counterparts in England and Wales. Other than recent work related to sea-level change (Dawson *et al.*, 1997), the coastal geomorphology of Loch Gruinart has not attracted any detailed attention.

Description

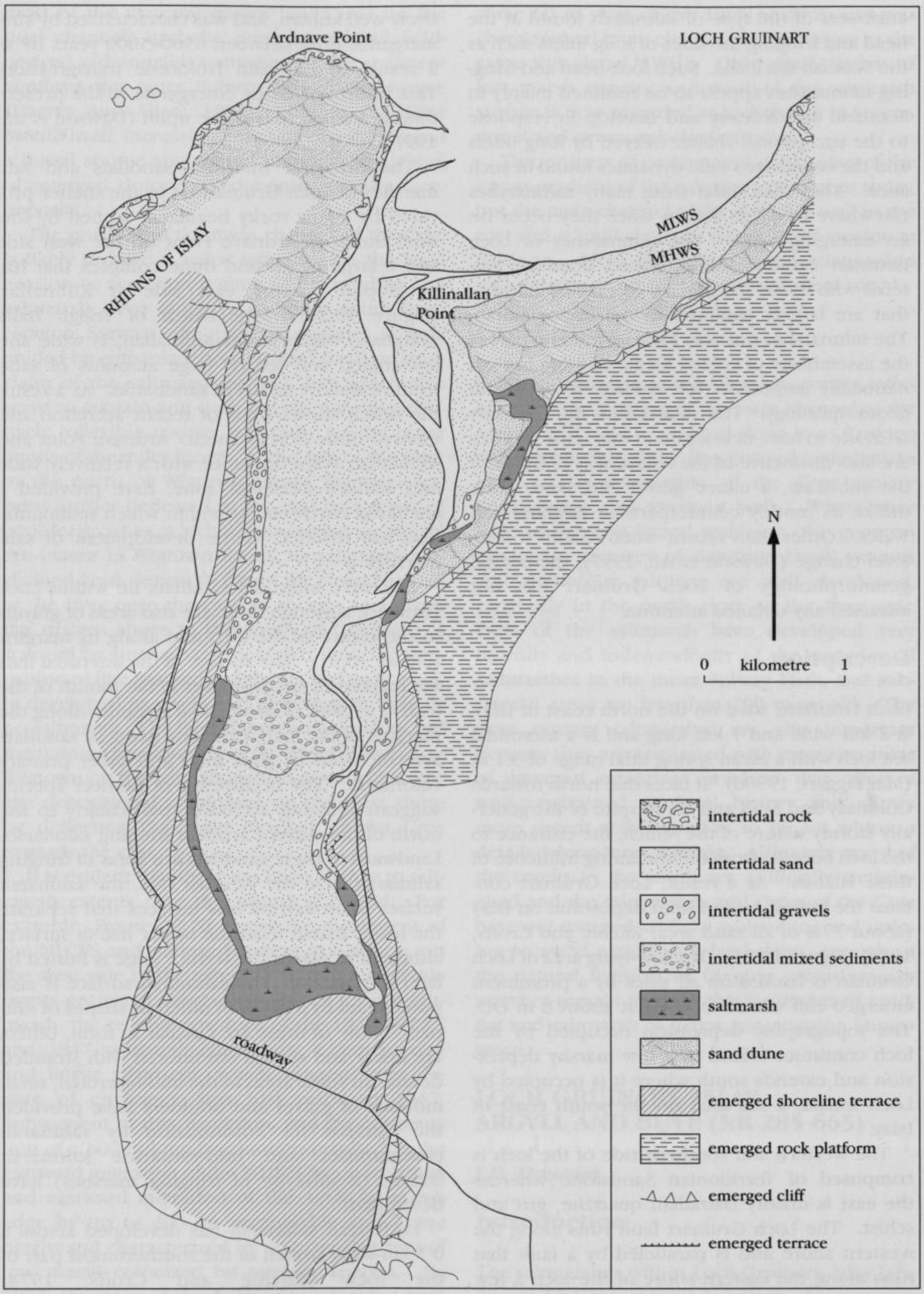
Loch Gruinart, sited on the north coast of Islay, is 2 km wide and 7 km long and is a mesotidal sea loch with a mean spring tidal range of 3.1 m (MacTaggart, 1998d). It faces due north towards Colonsay and Mull and so, in spite of the generally stormy nature of the Minch, the entrance to the loch benefits from the sheltering influence of these islands. As a result, Loch Gruinart contains the largest area of sand deposition on Islay (about 77% of all sand area; Ritchie and Crofts, 1974) (Figure 10.21). The low-lying area of Loch Gruinart is backed on all sides by a prominent emerged cliff whose foot lies at about 8 m OD. The topographic depression occupied by the loch continues inland as a low marshy depression and extends south where it is occupied by Loch Indaal, a sea loch on the south coast of Islay.

The western and southern side of the loch is composed of Torridonian Sandstone whereas the east is mainly Dalradian quartzite, grit and schist. The Loch Gruinart fault runs along the western shore and is paralleled by a fault that runs along the eastern shore of the loch a few kilometres to the east (Ritchie and Crofts, 1974). The Holocene sea-level history of Islay is relatively well known, and was characterized by submergence until between 6500–5000 years BP as a result of the main Holocene transgression. This was followed by emergence to the present time as a result of isostatic uplift (Dawson *et al.*, 1997).

The extensive intertidal sandflats and saltmarshes of Loch Gruinart lie in the shelter provided by a low rocky headland capped by low sand dunes at Ardnave Point on the west side and a large beach and dune complex that has developed on the east side at Killinallan (Figure 10.21). The beach of Tràigh Baile Aonghais, which fronts Killinallan, is wide and low-angled and fed by large amounts of sand from nearshore adjacent sandbanks. As a result the beach shows signs of recent accretion and embryo dune development. Ardnave Point and Killinallan Point, together with a relatively wide and shallow intertidal zone, have provided a sheltered environment within which sedimentation has resulted in the development of saltmarshes.

Extensive intertidal sandflats lie within Loch Gruinart, although there are also areas of gravels in the centre of the loch and along its margins (Figure 10.21). The surface of the intertidal flats are marked by mega-ripples at the mouth of the loch as a result of strong tidal streams. Along the margins of the loch, extensive areas of sandflats are colonized by algal mats and other primary colonizers. The occurrence of pioneer species suggests ongoing accretion, particularly to the north of the current areas of fringing saltmarsh. Landward of these sandflats are areas of fringing saltmarsh. On the western side, the saltmarsh surface is broken by low terraces that separate the lower marsh from the upper marsh surface, although in places the terrace edge is buried by later deposition. The saltmarsh surface is also punctuated by a range of different shapes of saltpan. Some of these are circular in form, others are linear and several are littered with stranded debris. In some areas in the mid-intertidal, small mounds of gravel and boulders have provided the nucleus for colonization by saltmarsh communities and mid-estuarine saltmarsh islands (a sub-type of fringing marshes) have developed.

Loch-head saltmarsh has developed across a 0.5 km-wide stretch of the southernmost part of the loch (Ritchie and Crofts, 1974; Figure 10.21). MacTaggart (1998d), using recent aerial photography together with the presence


Ardnave Point
LOCH GRUINART
MLWS
MHWS
RHINNS OF ISLAY
Killinallan Point
N
0 kilometre 1
roadway
intertidal rock
intertidal sand
intertidal gravels
intertidal mixed sediments
saltmarsh
sand dune
emerged shoreline terrace
emerged rock platform
emerged cliff
emerged terrace

of pioneer species along the seaward edge of this stretch, suggested that progradation was ongoing. Distinct drainage patterns have developed over the saltmarsh surface. The narrow and linear creeks carry tidal flows over the upper and lower marsh surface and some of these join with artificial drainage ditches carrying freshwater from the adjacent hillsides across the upper marsh. Several of the creek sides show erosional undercutting and bank collapse. Saltpans are largely confined to the upper marsh where examples of circular and debris pans are common. The landward extent of the saltmarsh is constrained by an artificial embankment behind which are areas of reclaimed saltmarsh. A roadway crosses the southern part of the saltmarsh and emerged shoreline terrace (carse).

Interpretation

From the viewpoint of shelter, the loch-head and fringing saltmarshes of Loch Gruinart are quite normal in that they have developed in the benign wave environment offered by the presence of the rocky headland of Ardnave Point and the beach and dune complex at Killinallan. However, the saltmarshes are unusual in the British context in that they have developed, and continue to develop, on an emerging coast that is now characterized by a regional lack of coastal sediment supply. Nevertheless, the low-lying structural depression now occupied by lochs Gruinard and Indaal has been the focus for local deposition over much of the Holocene Epoch as a result of a combination of a supply of glaciogenic material from the adjacent low-gradient slopes and sea-level changes that have resulted in the inundation of the area at least twice in the last 10 000 years. Although the initial cutting of the prominent cliff probably took place soon after deglaciation, re-occupation and re-trimming occurred most probably at several times over this period before its final abandonment and the accretion of beaches and terraces at its foot later in the Holocene Epoch.

Detailed coring, biostratigraphy and dating indicates that marine–brackish–freshwater and marine–freshwater transitions occur in the diatoms that occur within the Gruinart subsurface sediments. Based on this evidence, Dawson *et al.* (1997) argue that the Rhinns of Islay were separated from the mainland of Islay by a marine inlet that formed following deglaciation about 13 000 years BP (Figure 10.22). Subsequent sea-level fall in the Lateglacial resulted in emergence for a period between 11 000–9000 years BP. However, the culmination of the Holocene transgression then resulted in the subsequent inundation of the Loch Gruinart area. Although Holocene sea-level rise in much of Scotland is generally thought to have been completed by *c.* 6000 years BP, the age of the sediments within Loch Gruinart appear to be young, dating from 2000 years BP, and suggest that a tidal strait may have existed between the Rhinns of Islay and the mainland of Islay between 8000–2000 years BP (Dawson *et al.*, 1997). Whatever the date of separation, ongoing isostatic uplift resulted in an increasingly shallow marine environment within Loch Gruinart that has been conducive to sedimentation and the resulting infill of the margins and heads of both lochs Gruinart in the north and Indaal in the south.

Set within the context of its Holocene sea-level history, the depositional regime of Loch Gruinart locally reflects progressive shallowing, shelter from waves at its entrance and the availability of locally derived sediments. As a direct result of its provenance the intertidal flats and saltmarshes are dominated by sandy sediments with little silt and mud, unlike the saltmarshes elsewhere in Britain. The underlying sediments include locally derived gravels that have become lag deposits that are undergoing encroachment by saltmarsh vegetation. It is also possible that ongoing uplift is reflected in the marked terracing that occurs on the fringing saltmarsh. Elsewhere, Pye and French (1993) describe seasonal erosion and accretion in saltmarshes resulting from storm waves or channel migration leading to terracing that may become obscured where conditions favour further accretion. At Loch Gruinart, channel migration may well be a function of ongoing shallowing, leading to abandonment of some upper saltmarsh surfaces and the relocation of accretion to lower surfaces at the rear of the intertidal sandflat. Such down-

◂**Figure 10.21** The coastal geomorphology of Loch Gruinart, Islay is dominated by a history of sea-level changes with emerged erosional and depositional features flanking the north-south axis of the loch. In the shelter provided by Ardnave and Killinallan Points, extensive linear and loch-head saltmarshes have developed, some of which are extending onto intertidal gravels. (After Ritchie and Crofts, 1974.)

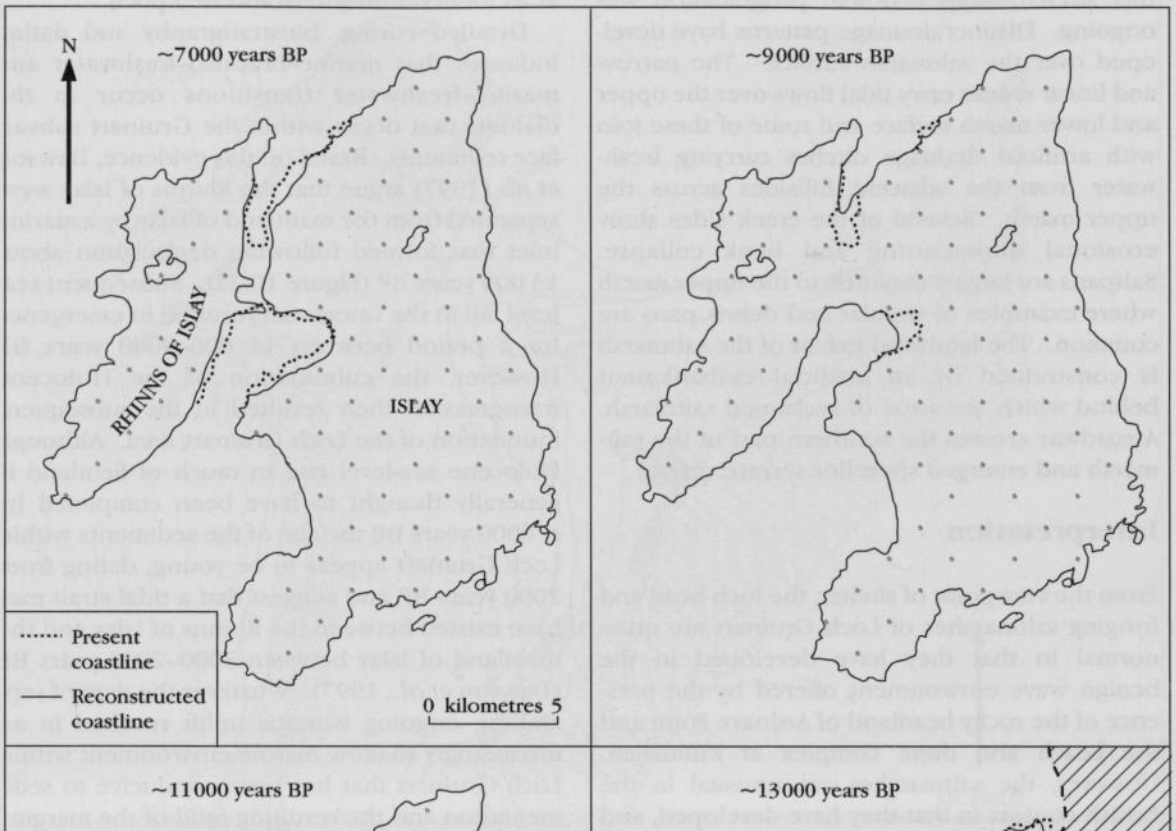


Figure 10.22 The changing coastline of the Loch Gruinart–Loch Indaal area, Islay, at 7000, 9000, 11 000 and 13 000 years BP, showing phases of marine inundation and land emergence. Since 7000 years ago the relative sea level has shown a more or less constant falling trend towards the position of the present coastline. (After Dawson and Dawson, 1997.)

marsh migration of sedimentation has almost certainly been exacerbated by the rapid uplift experienced by this part of the Islay coast and indicates that this would be an ideal site in which to study the effects of emergence on accreting saltmarshes.

It is possible that the distribution of saltpans solely on the upper levels of the marsh may be related to recent and rapid uplift of the upper marsh. However, it is equally likely that the development of saltpans requires a fairly dense and continuous cover of vegetation and this is found only on the upper marsh at Loch Gruinart. The occurrence of several collapsed pans may be related to the failure of subterranean pipe networks similar to those that exist elsewhere on Scottish saltmarshes (Leafe and Hansom, 1990).

Conclusions

The saltmarshes of Loch Gruinart are typical of the type of saltmarsh found at the head and fringing the sides of the Scottish sea lochs. Found in Scotland and Norway, they have been influenced by the ongoing emergence of the host coastline and so are nationally important for studies of saltmarsh geomorphology on emerging shores. The saltmarshes of Loch Gruinart display drainage patterns with linear and narrow creeks and saltpans that are largely confined to the upper marsh. In spite of being suited to the study of the effects of emergence on saltmarshes, the coastal geomorphology of Loch Gruinart has not yet attracted any detailed attention other than work related to sea-level change.