Coastal Geomorphology of Great Britain

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Chapter 9

Machair

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INTRODUCTION

The machair lands of the north-western seaboard of both Scotland and Ireland represent a distinctive form of dune grassland system, unique to these areas. The machair system can be described as a flat or gently sloping, coastal dune-plain formed by windblown calcareous shell-sand, sometimes incorporating a mosaic of dunes to the seaward side and a species-rich grassland (managed by traditional low-intensity agriculture), wetland, loch and 'blackland' (mixtures of sand and peat) to the landward side. Often the dune cordon may be missing owing to frontal erosion, but a characteristic of machair surfaces is that they are lime-rich, subject to strong, moist, oceanic winds and show detectable current or historic biotic interference from grazing, cultivation, addition of natural fertiliser such as seaweed and, sometimes, artificial drainage (Ritchie, 1976; Hansom and Angus, 2001). As a result, the term 'machair' has meaning not only in a botanical and geomorphological sense but also in its strong cultural overtones, the spatial extent of machair overlapping closely with the current core areas of the Gaelic language in Ireland and, with the exception of Orkney and Shetland, in Scotland (Hansom and

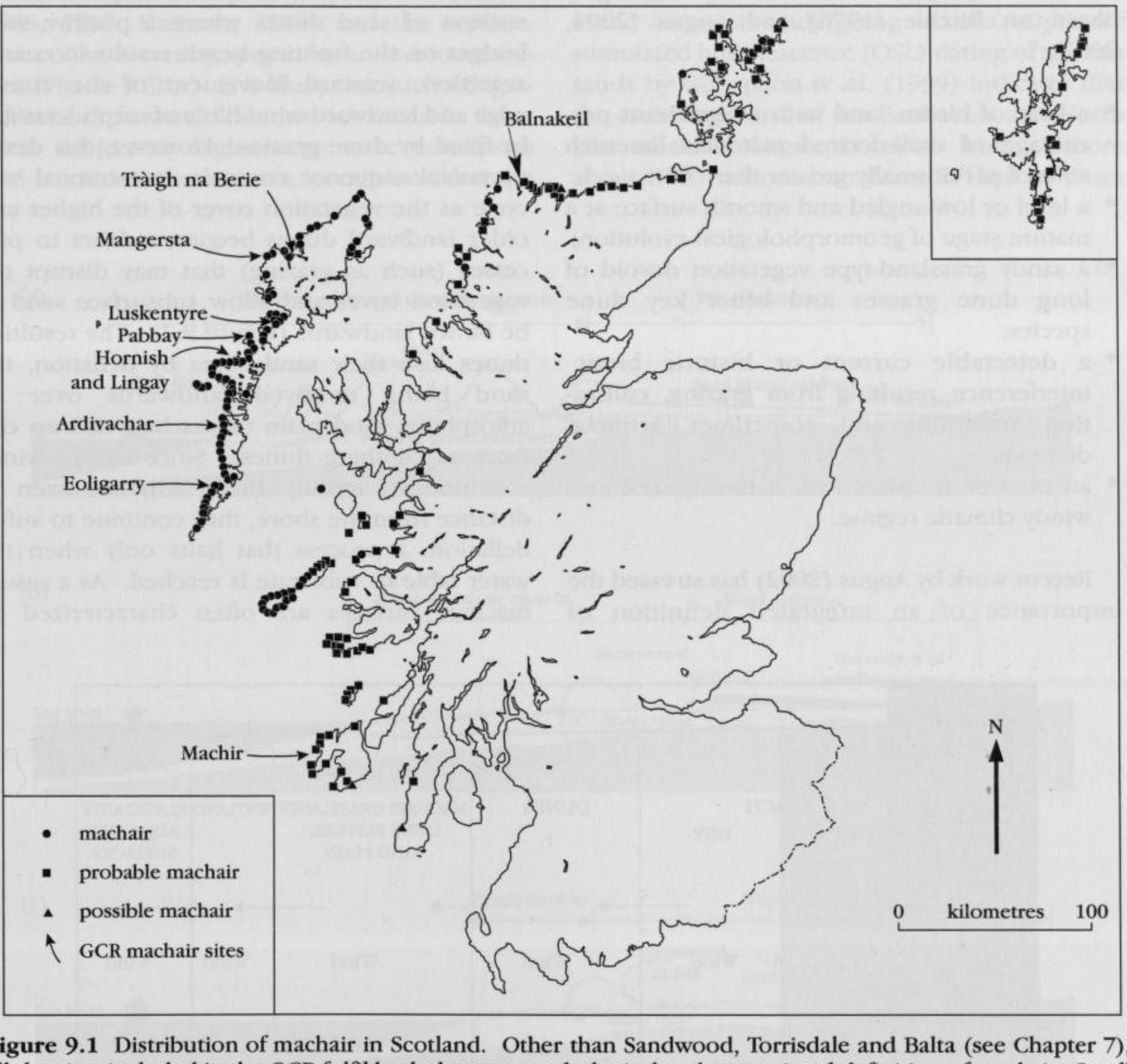


Figure 9.1 Distribution of machair in Scotland. Other than Sandwood, Torrisdale and Balta (see Chapter 7), all the sites included in the GCR fulfil both the geomorphological and vegetational definition of machair. Small vegetational differences in the above sites have resulted in the label 'probable machair'. Ongoing work that interprets the geomorphology and botany of machair aims to provide a definitive machair diagnostic test in the future and so the above classification will be subject to slight modification (Angus, 2003, pers. comm.). (After Hansom and Angus, 2001.)

Angus, 2001) (Figure 9.1). Since all of the machair lands have similarities in their land-use histories, it is likely that the present distribution and nature of machair systems owes as much to cultural factors as it does to biotic and abiotic influences.

The world extent of machair is about 30 000–40 000 ha of which 67% is found in Scotland and 33% in Ireland, although those figures are under review (Angus, 1994). Of the Scottish machair, nearly 40% has been selected for – and is protected internationally as – Special Areas of Conservation (SACs); about 80% of the Scottish resource is protected within Sites of Special Scientific Interest (SSSIs).

The following definition of machair is largely based on Ritchie (1976) and Angus (2001, 2002):

- a base of blown sand with a significant percentage of shell-derived materials lime-rich soils of pH normally greater than 7.0;
- a level or low-angled and smooth surface at a mature stage of geomorphological evolution;
- a sandy grassland-type vegetation devoid of long dune grasses and other key dune species;
- a detectable current or historic biotic interference resulting from grazing, cultivation, trampling and, sometimes, artificial drainage;
- an oceanic location with a moist, cool and windy climatic regime.

Recent work by Angus (2002) has stressed the importance of an integrated definition of machair that includes geomorphology and botany, but neither in isolation. As a result, several natural systems that in the past were identified as machair on, say, geomorphological grounds, do not fulfil the wider criteria. Therefore, such sites are deemed here not to be machair and have been included in Chapter 7 of the present volume. These sites are Sandwood and Torrisdale, both in Sutherland, and Balta in Shetland.

Hansom and Angus (2001) summarize the main features of the evolution of machair using data from a wide range of sources including Ritchie (1976), Mate (1991) and Gilbertson *et al.* (1999). Machair is in essence a sand plain produced from the normal cycle of deposition and erosion of sand dunes where a positive sand budget on the fronting beach results in coastal accretion, seaward movement of the coastal edge and landward wind-blow of surplus sand to be fixed by dune grasses. However, this developmental sequence conceals an erosional subcycle as the vegetation cover of the higher and older landward dunes become subject to processes (such as grazing) that may disrupt the vegetation cover and allow subsurface sand to be blown landwards (Figure 9.2). The resulting dunes lose their sand cores by deflation, the sand being removed landwards over an amorphous sand plain or machair and up cliff faces as climbing dunes. Since strong winds continue to modify these surfaces even at distance from the shore, they continue to suffer deflation, a process that halts only when the water table or substrate is reached. As a result, machair surfaces are often characterized by

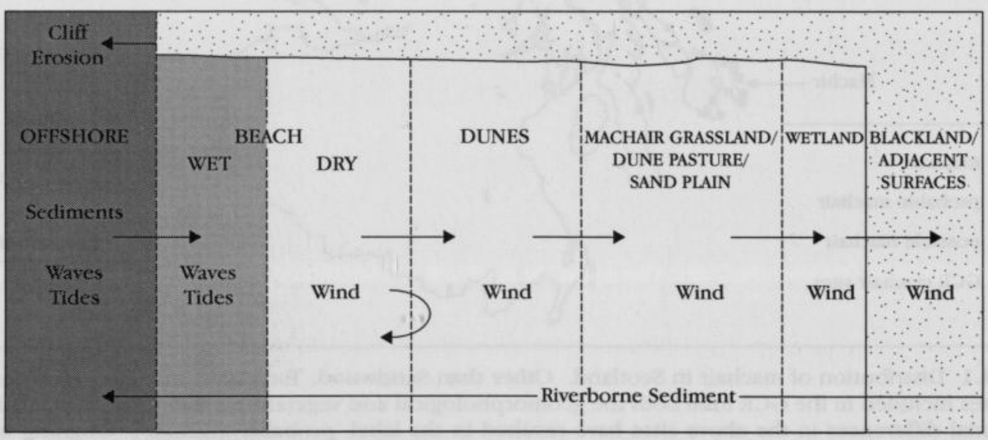


Figure 9.2 A diagrammatic representation of the beach–dune–machair system showing the general landward transport of sand broken by seaward returns via wind and streams. (After Mather and Ritchie, 1977.)

steep eroded escarpments located between low-lying landward-dipping deflation surfaces and higher dune surfaces.

The conditions that favoured a positive sand budget were widespread on the Scottish coast as the Holocene rise in sea level began to slow markedly before about 6500 years BP (see Figure 6.28). For the first time waves were able to accomplish substantial shoreface modification and bring large amounts of sediment from the nearshore shelf onto beaches and then into sand dunes (Firth *et al.*, 1995) (Figure 9.3a). However, the finite nature of this sediment seems to have resulted in a progressive reduction in sediment availability and a switch to deficit sometime after 6500 years BP (Carter, 1988, 1992; Hansom, 1999) and the replacement of an accreting system by an erosional system (Figure 9.3b,c). It is likely that such a degradational cycle would be most advanced in those areas subject to high-energy wave conditions and isostatic submergence, conditions that are both met on the north-western seaboard of Scotland. As a result, erosion of the dune cordon in these western machair areas is now well advanced and in places the machair grassland itself is now suffering erosion. The positive beach sediment budgets that fed the embryo and foredunes once sited seawards of the fixed dunes and machair have long since been reversed by negative sediment budgets and the frontal dunes cannibalized (Figure 9.3c) (Hansom and Angus, 2001).

Support for the above geomorphological evidence of an initial surplus followed by declining sand supply comes from dating the sand layers in association with archaeological sites located originally within accreting dunes and now found on coasts undergoing erosion. Optically stimulated luminescence (OSL) dating of aeolian sands by Gilbertson *et al.* (1999) indicates that the carbonate sand of the Benbecula and North Uist machairs began to arrive from offshore about 8700 radiocarbon years BP and in Barra

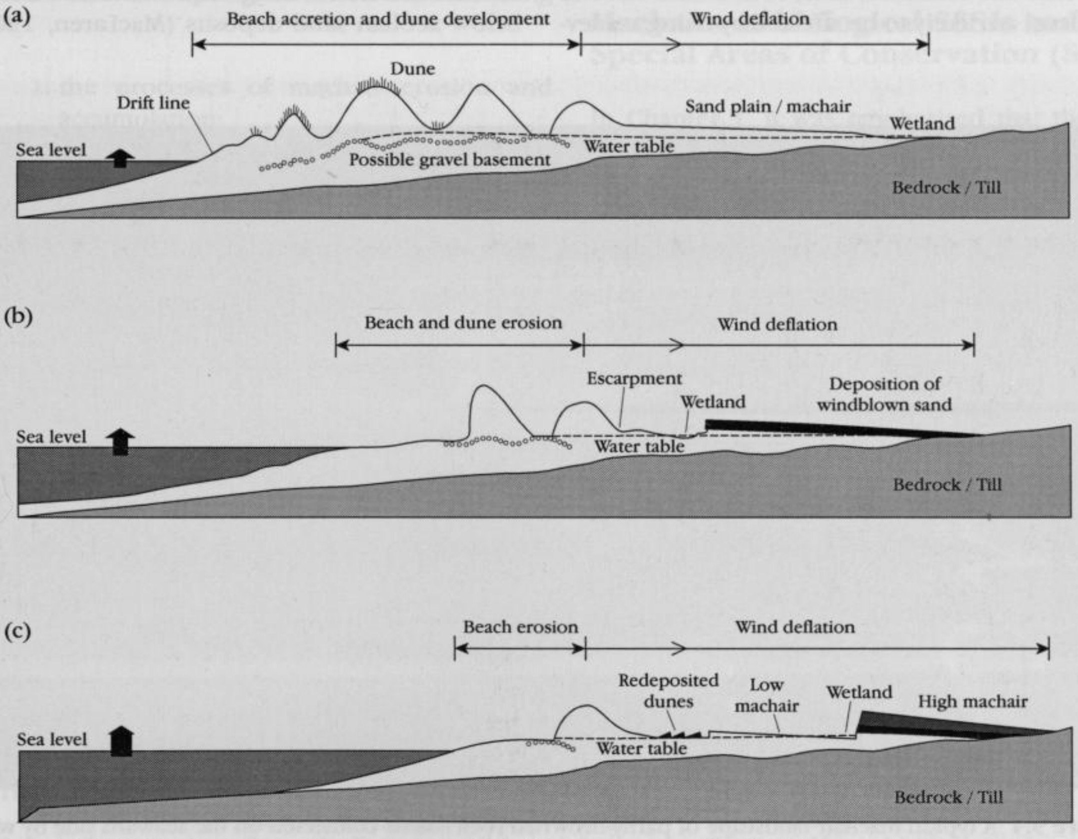


Figure 9.3 The Holocene development of machair from approximately 6500 thousand years ago to present, showing the switch from conditions of accretion of the dunes to erosion and recycling of dune sands into machair. (a) early–mid Holocene; (b) late Holocene; (c) present day. (After Hansom and Angus, 2001.)

about 6800 radiocarbon years BP. At Northton in South Harris, the onset of sand deposition that buried Neolithic remains occurred from 4500 radiocarbon years BP (Ritchie, 1979a). The discovery of exhumed archaeological sites within dunes is largely due to frontal erosion, although multiple cycles of erosion, deposition and deflation are concealed within this general erosional trend. However, in spite of the above, dating of the initiation of dune and machair formation in the Outer Hebrides remains problematic. Ritchie and Whittington (1994) report intertidal peats overlain by aeolian sands that date from 7800 radiocarbon years BP at Cladach Mór in North Uist and from 7700 radiocarbon years BP at the Landing Jetty in Pabbay. Yet other sites on these islands, for example at Quinish in Pabbay dating from 4300 radiocarbon years BP and at Borve in Benbecula dating from 5600 radiocarbon years BP, suggest that the arrival of aeolian sand and the initiation of machair development in the Hebrides was non-synchronous (Ritchie and Whittington, 1994). However, in the low and undulating coastal landscape of the Western and Northern Isles, rock basins close to sea level are likely to be affected by rising sea levels at different times and so the influence of local bathymetry and site factors represent important site-specific controls on the date of machair initiation (Figure 9.4).

Once established, the development of the machair plain is essentially erosion-driven, with new surfaces produced as old ones are consumed. However, there can be marked seasonal differences. For example, where deflation has exposed the water table, winter flooding may result in sand blowing onto wet surfaces and this results in a depositional flat surface rather than an erosional one. Archaeological studies provide evidence of fertile and stabilized sand surfaces around 2000 radiocarbon years BP (Ritchie, 1966). Several sites ascribed to the Iron Age and later are located on the low flat surfaces of machair that have been produced following deflation of earlier machair surfaces (Ritchie, 1979a). Gilbertson *et al.* (1996) document layers of thick organic palaeosols within the dunes and machair dating from Bronze Age to medieval times, together with periods of instability (particularly between the 9th and 13th centuries AD) as indicated from Viking settlements now buried below aeolian sand deposits (MacLaren, 1974).

Figure 9.4 A typical machair landscape of partly-drowned rock basins connected on the seaward side by wide sandy beaches and on the landward side by dune cordons backed by expanses of windblown machair sand. Looking north-east from North Uist over Vallay Strand in the foreground to Hornish and Lingay in the distance. (Photo: P. and A. Macdonald/SNH.)

Historical evidence extends the above pattern of phased instability and stability of the machair into modern times. During the 16th century machair surfaces were stable with well-established agriculture, but the 17th century brought widespread sand-blow on much of the Scottish coast and burial of machair surfaces and buildings in the Outer Hebrides (Ritchie, 1966, 1979a; Lamb, 1991; Angus, 1997). Although probably more stable than it has been in the past, Hebridean machair is still actively forming and the present-day machair surface has probably formed over the same timescale as it has in the past, that is over periods of less than 100 years (Gilbertson *et al.*, 1999). Nevertheless, the present machair system as a whole represents the latest manifestation of a continuum of essentially similar processes operating since at least middle Holocene times.

The conservation value of machair

The geomorphological significance, and hence the Earth science conservation value, of machair arises from its importance to our understanding of:

1. the processes of machair erosion and accumulation;
2. the interaction of sediment supply and sea-level change;
3. the interaction of sediment, vegetation and land use.

As described above, it is believed that machair grassland has been modified by humans throughout its development. Traditionally, machair supports extensive grazing regimes and unique forms of cultivation that rely on cattle-grazing and low-intensity systems of rotational cropping. This traditional agriculture sustains a rich and varied dune and arable weed flora. Some of the arable weed species are now largely restricted in the UK to these traditionally managed areas. The habitat type also supports large breeding bird populations and is particularly important for waders and corncrake *Crex crex*.

The GCR site selection rationale for machair has been to represent the range and diversity of the geomorphological features (Table 9.1). In the present chapter, sites are arranged in a clockwise order around the coast, starting with the southernmost.

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

In Chapter 1, it was emphasised that the SSSI site series is constructed both from areas nation-

Table 9.1 Machair GCR sites

Machair site	Main features	Other features	Tidal range (m)
Machir bay	Beach–dune–machair, high-level machair terraces, emerged beaches	Climbing dunes	3.0
Eoligarry	Vigorous erosional machair forms large blowouts, tombolo structure	Storm beach, wide intertidal, sheltered beach, archaeological dating	4.0
Ardivachar–Stoneybridge	Machair type site, high and low machair deflation corridors	Archaeological dating gravel barrier, palaeosols	3.6
Hornish and Lingay Strands	Flat, low-lying machair, water-table effects	Superimposed small dunes, artificial drainage	3.9
Pabbay	Climbing machair, conical dunes, wet machair	No rabbits	3.0
Luskentyre–Seilebost	Large beach–dune machair remnant of former larger system, 35m high dunes; growth/decay model site	Spits, blowouts	3.8
Mangersta	Eroded and deflated formerly extensive machair, advanced stage of erosion	Water table	3.8
Tràigh na Berie	Large dynamic beach–dune–machair dune cordon intact and well-nourished	Infill of valleys and lochs, no chronic erosion	3.8
Balnakeil	Dynamic climbing machair and dune blowouts, headland by-passing of sediment	Erosion of frontal edge, sand-fall over cliff	4.0

Table 9.2 Candidate Special Areas of Conservation supporting Habitats Directive Annex I habitat 'Machair' as a qualifying European feature. (Source: JNCC International Designations Database, July 2002.)

SAC name	Local authority	Machair extent (ha)
Coll Machair	Argyll and Bute	681
Monach Islands	Western Isles / Na h-Eileanan an Iar	292
North Uist Machair	Western Isles / Na h-Eileanan an Iar	1707
Sheigra–Oldshoremore	Highland	222
South Uist Machair	Western Isles / Na h-Eileanan an Iar	1785
Tiree Machair	Argyll and Bute	510

Bold type indicates a coastal GCR interest within the site

ally important for wildlife and GCR sites. An SSSI may be established solely for its geology/geomorphology, or its wildlife/habitat, or it may comprise a 'mosaic' of wildlife and GCR sites that may be adjacent, partially overlap, or be co-incident. Therefore, there are some areas of machair that are crucially important to the natural heritage of Britain that have been designated as SSSIs primarily 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). These sites are are not described in the present geomorphologically focused volume.

In addition to being protected through the SSSI system for its national importance, machair is a 'Habitats Directive' Annex 1 habitat, eligible for selection as Special Areas of Conservation, (see Chapter 1). Furthermore, many machairs are of international ornithological importance, primarily for breeding waders, and for this reason may be designated Special Protection Areas under the 'Birds Directive'.

Because machair is a habitat unique to the north and west of Scotland and western Ireland, the UK has a special responsibility for machair, and has recently established a UK Machair Habitat Action Plan (Angus and Dargie, 2002)

Machair SAC site selection rationale

Site selection has taken account of the wide range of variation in physical type shown by Scottish machairs and has also been influenced by the UK's special responsibility for machair conservation. The largest sites have been selected, as these demonstrate the best structure and function and include the most diverse examples of transitions to other habitats. Sites have been selected from across the range of machair in the Outer and Inner Hebrides and on the Scottish mainland.

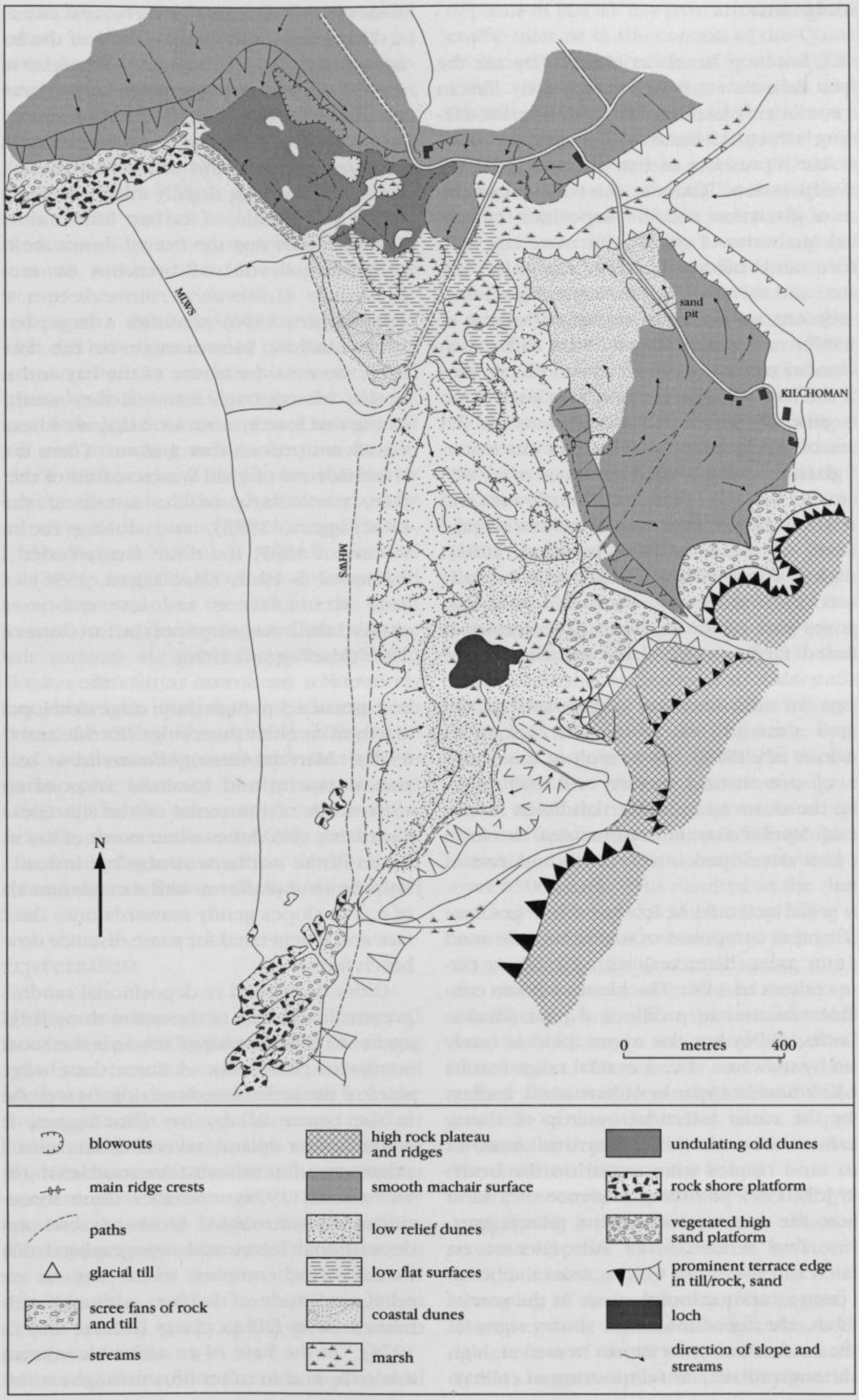
Table 9.2 lists machair SACs, and indicates which of these sites are also important (at least in part) as part of the GCR and are described in the present chapter.

MACHIR BAY, ISLAY, ARGYLL AND BUTE (NR 210 630)

Introduction

Machir Bay is a highly dynamic beach–dune–machair assemblage located on the exposed Atlantic coast of Islay (see Figure 9.1 for general location and Figure 9.5). The wide, high-energy beach is backed by a complex sequence of dune forms including low embryo dunes, an active foredune ridge, multi-ridged mature dunes, re-depositional sandhills and an extensive machair surface. The machair plain is of exceptional geomorphological interest as it drapes a number of topographical features including a series of high-level marine terraces, glacial deposits, talus slopes, and rock plateaux. Many streams drain through the dune and machair providing a strong hydrological control on morphology. Although several descriptions exist of the beach–dune–machair morphology of Machir Bay (Ritchie and Crofts, 1974; MacTaggart, 1996), greater interest has been shown in the emerged beaches, glacial terraces and relict clifflines that the machair partially obscures (Dawson, 1983; Dawson *et al.*, 1997).

Figure 9.5 Geomorphology of Machir Bay, Islay, showing a mix of machair types including substantial terraces at the rear of the system covered by high machair. (After Ritchie and Crofts, 1974.)


MLWS
MHWS
sand pit
KILCHOMAN
N
0 metres 400
blowouts
main ridge crests
paths
glacial till
scree fans of rock and till
streams
high rock plateau and ridges
smooth machair surface
low relief dunes
low flat surfaces
coastal dunes
marsh
undulating old dunes
rock shore platform
vegetated high sand platform
prominent terrace edge in till/rock, sand
loch
direction of slope and streams

Description

The 2.1 km-long beach at Machir Bay on the exposed Atlantic coast of western Islay has an open south-west fetch and lies within a SW–NE-trending structural basin of Torridonian sandstone that represents an extension of the Loch Gorm depression. There is also widespread evidence of glaciation and the deposition of substantial quantities of glaciogenic materials both onshore and offshore. For example, till, moraine and various glaciofluvial and glaciomarine deposits are common on Islay (Dawson *et al.*, 1997). At Machir Bay, a relict cliff cut in Torridonian sandstone forms the southern margin of the bay, whereas the northern part of the bay is generally lower and merges into the flat plateau of the interior. A relict cliff cut in terraced glaciomarine gravels (Dawson *et al.*, 1997) at 23 m OD extends towards the north-west end of the Bay and lowers westwards with an average gradient of 9.8 m km^{-1} (Dawson, 1983). Although a conspicuous feature, it is partially obscured by a veneer of windblown sand that comprises part of the machair. The terrace is succeeded farther south by a smaller terrace fragment, also interpreted as outwash, which declines in altitude and terminates at an emerged ('raised') shoreline at 21.4 m OD (Dawson *et al.*, 1988). As a result of the occurrence of pre-existing terrace and cliff topography, the dune and machair landform assemblage of Machir Bay is asymmetrical in form being best developed in the south and east of the site.

The wide intertidal beach has a low gradient of 1–2° and is composed of medium-grade sand (0.23 mm mean diameter) with a calcium carbonate content of 34%. The beach exhibits considerable variation in profile and plan (Ritchie and Crofts, 1974) but the upper 20 m is rarely covered by seawater. The 3 m tidal range results in a 0.32 km-wide expanse of bare sand, broken only by the rocky intertidal outcrop of Carrig Chomain in the south. Extensive areas of aeolian sand ripples were noted on the beach face in July 1996 providing evidence of a sand supply to the dune system behind (MacTaggart, 1996). Two streams, the Allt Gleann na Ceardaich and the Allt na Criche, cross the beach in the centre and north of the bay. At the rear of the beach, the foredune ridge shows signs of periodic undercutting by storm waves at high tide, although subsequent deposition of embryo dunes partly obscures the erosional faces.

The foredune ridge landward of the beach is best developed in the south, where it reaches 15 m high and displays steep seaward slopes of around 20°. The dune face and crest are extensively covered in vigorous marram *Ammophila arenaria* growth, and this broad coastal dune continues, curving slightly inland, to the stream outlet in the centre of the bay. Ritchie and Crofts (1974) report that the frontal dunes are characteristically devoid of breaches or erosional hollows. However, a more recent report (MacTaggart, 1996) identifies a large, but relatively shallow, blowthrough in the foredune ridge close to the centre of the bay and several healed blowthrough forms farther south, indicating that foredune erosion may now be a more significant process than before. There is extensive evidence of local wave-erosion of the dune face, particularly in the south of the site (MacTaggart, 1996), and during the winter storms of 1989, the dune face receded by an estimated 5–10 m (MacTaggart, 1996). Fresh sand accumulations and low embryo dunes masked the lower slopes of the foredunes in July 1996 (MacTaggart, 1996).

Between the stream outlets the coastal edge consists of a 3 m-high dune ridge developed seawards of an older dune ridge (Ritchie and Crofts, 1974). Marram *Ammophila arenaria* colonization is patchy, and localized areas of erosion exist north of the outlet of the Allt Gleann na Ceardaich. No dunes occur north of the marshy outlet of the northern stream but instead a low altitude sand platform with a maximum altitude of *c.* 2 m slopes gently seawards onto the beach face and is vegetated for some distance down the beach face.

Older dunes and re-depositional sandhills are present landwards of the active dune ridge and again are best developed towards the south and south-east of the bay. A linear dune ridge seaward of the active foredune ridge is well defined in the centre of the bay (MacTaggart, 1996), while farther inland several other relict dune ridges trend north-west to south-east (Ritchie and Crofts, 1974). Smaller dune forms and ridges, blowthroughs, erosional scars and re-depositional forms add topographical diversity to this dune complex, which has an average relief amplitude of 5–10 m, although altitudes exceed 20 m OD in places (Ritchie and Crofts, 1974). At the base of an active blowthrough in this area, and in other blowthroughs within the dunes, MacTaggart (1996) identified outcrops of indurated aeolian calcarenite, blown sand cemented by the precipitation of calcium carbonate from subsurface water. In the south a distinctive amphitheatre-like depression supports a variety of machair and relict dunes on its sides and is floored by a semi-permanent, marshy loch (Figure 9.5).

The extensive machair at Machir Bay can be classified according to topographical situation. In the south, a series of fan-like deposits cover the face of the relict rock cliff as well as the screes beneath. Sand deposits banked against the relict cliff have been eroded to form a terrace feature. An extensive machair plain some 50 m above sea level has developed on the plateau surface of the glaciomarine gravel terrace cut into till and extending as far inland as the old church of Kilchoman. This plateau machair is predominantly stable, although characterized by several areas of bare sand (Ritchie and Crofts, 1974; MacTaggart, 1996). Higher areas of machair at up to 60 m OD have developed in ledges or depressions in the rocks to the south of the site. In the northern part of the site the machair surfaces are generally more subdued and high relief forms are rare. Numerous streams drain into Machir Bay, crossing both dunes and the cliffs in the south, resulting in an elevated and fluctuating water table that adds to the geomorphic diversity of the machair and dune forms. The two streams that cut across the beach in the centre and north of bay are responsible for locally high water-tables that form the base level for deflation of the dunes and machair.

Interpretation

Machir Bay contains a great variety of dune and machair forms, probably the result of the strong control of structure, subsurface morphology and hydrology and the dominance of winds from the north-west. It is this variety of dune and machair landforms and their relationships to a variety of geographical controls that is of outstanding geomorphological significance. The relatively undisturbed nature of Machir Bay provides a excellent opportunity to study the evolution of a variety of dune forms and the effects of water table and drainage controls on morphology, but as yet no detailed geomorphological research has been undertaken.

The emerged marine terraces and glacial deposits of Machir Bay have attracted greater scientific interest in the context of the Quaternary evolution of Western Isles of Scotland (Dawson, 1983). The coarse gravel terrace that underlies the extensive machair plain has been interpreted as a Lateglacial glaciomarine deposit that graded to a sea level lower than *c.* 23 m OD during the decay of the last ice sheet (Dawson, 1983). The terrace declines in altitude westwards at an average gradient of 9.8 m km^{-1} towards Machir Bay where it passes beneath accumulations of blown sand. The terrace is succeeded farther south by a smaller Lateglacial terrace fragment, also interpreted as glaciomarine, which declines in altitude and terminates at an emerged shoreline at 21.4 m OD (Dawson, 1983).

In the period following deglaciation, rapid sea-level rise inundated many of the coastal bays on Islay and at Machir the lower parts of the southern rock cliffs and central glaciogenic deposits were re-occupied by the Holocene sea. Glaciogenic sediments available on the seabed were likely driven onshore to accumulate in sandy beaches such as those at Machir Bay. The subsequent process of sand delivery to the dunes and machair at Machir Bay is similar to that outlined for the Outer Hebrides (Ritchie, 1979a), but in Islay sea levels were falling in Late Holocene times. The late Holocene decline in sediment supply noted elsewhere in Scotland was delayed in Islay as a result of ongoing isostatic uplift that allowed waves to access new areas of sea-floor sediment while progressively elevating the rearmost coastal features by *c.* 8 m over 6500 years. This resulted in the dune and machair landforms of Machir Bay being draped over pre-existing structures and deposits up to 60 m OD. The dominance of strong winds from the north-west also contributed to the apparent asymmetry in the distribution of windblown sand and imparted a strong southerly bias to this distribution. The machair and dune forms also reflect the strong hydrological and water-table controls of the Machir Bay basin, in particular around the depression in the south and close to the streams that cross the beach.

At present the coastal dunes at Machir Bay are undergoing a period of erosion. Frontal dune erosion appears to be caused by storm wave action undercutting the dune face, causing slumping of the vegetation (MacTaggart, 1996). However, it is unclear whether this is the seasonal effect of winter storms. Ritchie and Crofts (1974) suggested that Machir Bay was stable or accreting but MacTaggart (1996) observed that the foredune ridge was almost everywhere undergoing frontal erosion and that this appeared to contribute to blowthrough initiation and dune instability. However in the north, the continued extension of vegetation onto the low area at the back of the beach indicates that, in this sheltered part of the bay, accretion still occurs.

Conclusions

Machir Bay on the exposed Atlantic coast of western Islay is an excellent example of a well-developed and topographically diverse beach–dune–machair system. The site contains a great variety of dune and machair forms, as a result of the control of subsurface morphology and hydrology, and the dominance of winds from the north-west. The machair, which reaches altitudes of *c.* 60 m OD, is of exceptional geomorphological interest as it drapes a number of topographical features including a series of high-level glaciomarine terraces, talus slopes and rock plateaux.

EOLIGARRY, BARRA, WESTERN ISLES (NF 700 060)

Introduction

The sand isthmus of Eoligarry connects the rocky northern part of Barra, in the southern Outer Hebrides to the rocks of Ben Eoligarry Mór (see Figure 9.1 for general location, and Figure 9.6). Eoligarry is a wedge-shaped complex of sand dune and machair flanked to the east by an extensive intertidal beach named Tràigh Mhór, and to the west by Tràigh Eais, which faces the Atlantic Ocean. Tràigh Mhór, a vast, creamy-white beach of shell-sand, is well known for its locally harvested cockles, source of shells for building work (although the factory has now closed) and spectacular intertidal landing-strip for the air link between Barra and the Scottish mainland. The geomorphological interest of this beach lies in its size and gradient together with a well-defined series of intertidal bars and mega-ripples. Tràigh Eais, is a narrow, steep, high-energy beach composed of both gravel and sand with a high shell content. Between these beaches, the peninsula of Eoligarry is of scientific interest on account of the vigorous erosional processes at work. Some 20% of the area of Eoligarry above mean high-water springs consists of windblown bare sand, and most of the typical erosional and non-erosional landform features of Hebridean dune and machair landforms occur (Ritchie, 1971, 1979a; Hansom and Comber, 1996). The site has considerable geomorphological, archaeological and botanical interest (Farrow, 1974; Ritchie, 1979; Hansom and Comber, 1996; Gilbertson *et al.*, 1996, 1999)

Description

The GCR site of Eoligarry extends from MLWS on Tràigh Eais to MLWS on Tràigh Mhór, including all of the machair and dune area between and the hilltop machair of Ben Eoligarry Mór (Figure 9.6). It is noted for its range of classic machair erosional landforms within such a small area. The beach of Tràigh Eais on the exposed Atlantic coast of Eoligarry has a narrow, concave-upwards profile and is composed mainly of sand resting on a basement of gravel. Gravel up to *c.* 10 cm b-axis is evident on the upper profile, particularly in the north and also floors some of the depressions within the backing dunes. The break in slope between the upper and lower beach is indistinct in the south but in the north well-developed cusps occur in the prominent gravel storm ridge. The mean sand size on Tràigh Eais is *c.* 0.8 mm. There is evidence of an offshore bar lying about 80 m offshore from MLWS upon which waves break. Tràigh Eais is backed by a steep and unvegetated scarp eroded into the mature sand dunes. The extensive intertidal beach of Tràigh Mhór on the east coast of the Eoligarry isthmus, is characterized by a 1.3 km-wide platform of sand at low tide, although this narrows to 10 m at high tide (Figure 9.7). On Tràigh Mhór sand of 0.2–0.3 mm is found with a calcium carbonate shell component of 80% (Hansom and Comber, 1996). The interface between the low-tide platform and the narrow (*c.* 10 m wide) upper beach is marked by a distinct break in slope, with an associated change in colour, reflecting an increase in calcium carbonate content with distance up-beach. Distinctive bars and cusps composed of cockle shells occur on Tràigh Mhór, their genesis having been discussed by Farrow (1974). The mean diameter of the sand grains is 0.3 mm on the upper beach and 0.2 mm on the lower. The beach displays varied topography with an abundance of intertidal mega-ripples

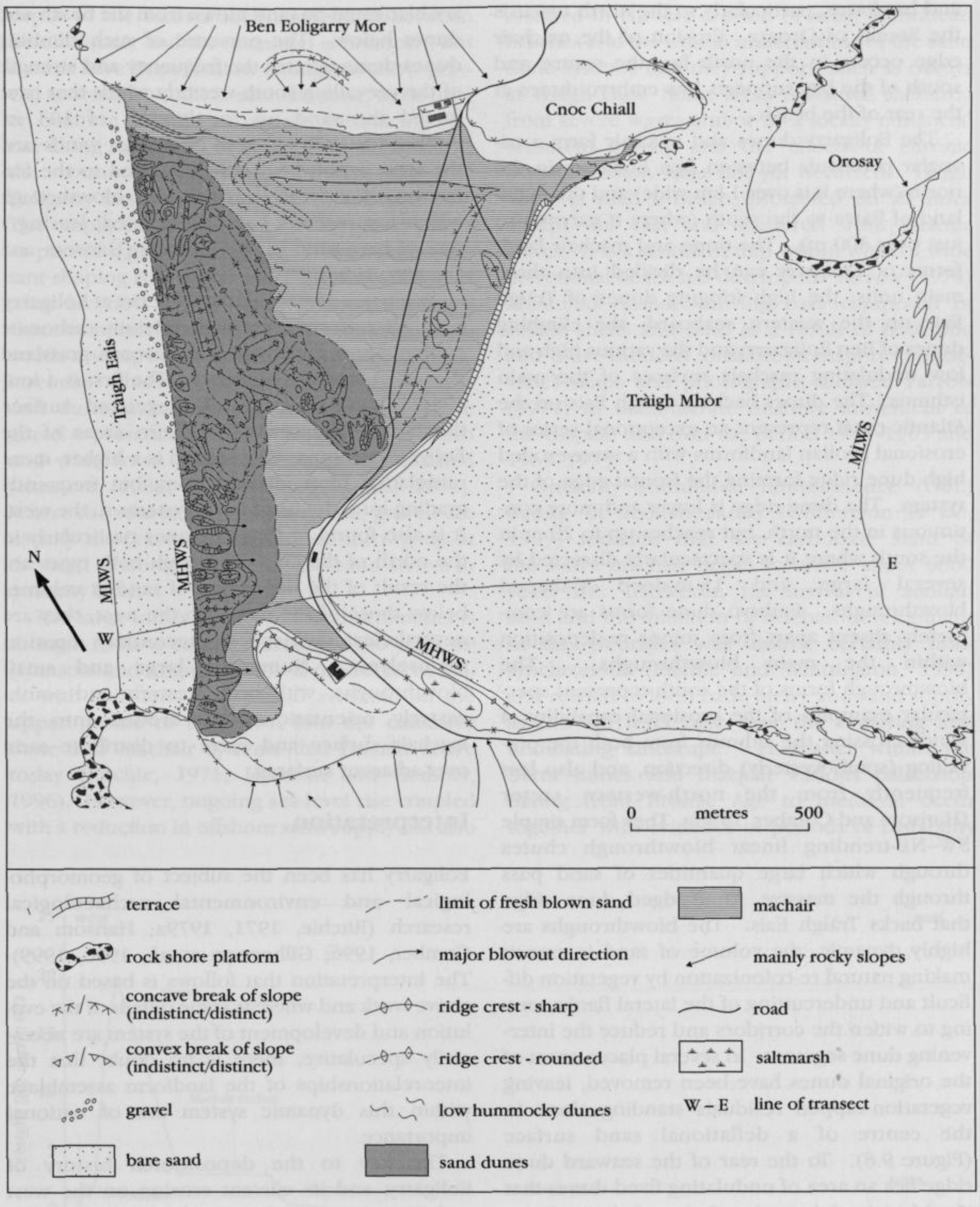


Figure 9.6 Geomorphology of the Eoligarry isthmus. Note the narrow Atlantic beach of Tràigh Eais and the extensive flat beach of Tràigh Mhór between which lie a cordon of high dunes punctuated deeply by blowthroughs. The otherwise extensive machair surfaces are extremely narrow at the southern end of the isthmus. The position of the west–east cross-section of Figure 9.7 is indicated. (After Hansom and Comber, 1996.)

and bar-forms, particularly to the north towards the Sound of Orosay. Erosion of the machair edge occurs in the north but the centre and south of the bay supports low embryo dunes at the rear of the beach.

The Eoligarry dunes and machair form a triangular peninsula between Ben Eoligarry in the north (where it is over 1 km wide) and the mainland of Barra to the south (where it narrows to just over 300 m). The dune and machair landforms of Eoligarry can be divided into three main units: the high fringing dunes of Tràigh Eais on the western seaboard; the climbing dunes of Ben Eoligarry; and the various high and low undulating machair surfaces of the main isthmus. The dunes backing Tràigh Eais on the Atlantic coast represent an exceptional series of erosional aeolian landforms with a wave-eroded high dune ridge forming the frontal edge of the system. The dune ridge is lower and more continuous in the north, but reaches up to 20 m in the south where it is spectacularly dissected by several large and 15 m-deep V-shaped blowthroughs. Embryo dune forms are completely absent apart from minor re-deposition within the main blowthroughs. The blowthrough forms of the south represent spectacular examples of the erosional capability of winds crossing the isthmus from both the prevailing (south-westerly) direction, and also less frequently from the north-western sector (Hansom and Comber, 1996). They form simple SW–NE-trending linear blowthrough chutes through which large quantities of sand pass through the massive, knife-edged dune ridge that backs Tràigh Eais. The blowthroughs are highly dynamic, the volume of sand in transit making natural re-colonization by vegetation difficult and undercutting of the lateral flanks serving to widen the corridors and reduce the intervening dune segment. In several places, most of the original dunes have been removed, leaving vegetation-capped residuals standing alone in the centre of a deflational sand surface (Figure 9.8). To the rear of the seaward dune ridge lies an area of undulating fixed dunes that is widest in the north. Some of these dunes show ridges and depressions that are orientated both west–east and north–south, at odds with the preferred orientation of the large active blowthroughs in the south. These are ridges that were artificially constructed as part of dune rehabilitation works in the 1970s.

The south-facing flanks of Ben Eoligarry Mór are blanketed by sand blown from the beach and dunes below. The presence of such climbing dunes demonstrates the frequency and strength of the prevailing south-westerly winds that have forced the sand up to altitudes of 103 m. Surface instability, due to both high winds and the large rabbit population, has led to the formation of a large, bowl-shaped blowthrough which has recently been re-activated, leaving a scar of bare sand on the hillside (Hansom and Comber, 1996).

Two types of machair surface exist at Eoligarry, both characterized by high calcium carbonate contents and a distinctive calcareous grassland devoid of long dune grasses. The first is a low, almost horizontal, closely vegetated surface dominating the central–southern areas of the Eoligarry isthmus. The second is a higher, more undulating form, distinct from, but frequently grading into, the fixed dune systems to the west. It is also found in isolated zones particularly in the north of the area. Although both types are the result of the deposition of sand at volumes below those of the dunes to the west, they are nevertheless subject to secondary erosion themselves. Numerous large and small blowthroughs, with both westerly and south-easterly orientations, are eroded into the machair surface and serve to distribute sand over adjacent surfaces.

Interpretation

Eoligarry has been the subject of geomorphological and environmental archaeological research (Ritchie, 1971, 1979a; Hansom and Comber, 1996; Gilbertson *et al.*, 1996, 1999). The interpretation that follows is based on the above work and whereas some details of the evolution and development of the system are necessarily speculative, there is no doubt that the inter-relationships of the landform assemblage within this dynamic system are of national importance.

The key to the depositional history of Eoligarry, and its current erosion on the west and deposition on the east, lies in the altitude and geometry of the low-lying former peninsula of Ben Eoligarry and Orosay that once jutted northwards from the Barra mainland. Such low-lying peninsulas have become subject to increasing amounts of marine influence as a result of the rise in sea level that has affected the Hebrides throughout the Holocene Epoch. The depth of the former rock connection between Ben Eoligarry and the mainland is unknown but it must have been shallow enough to allow gravels, sourced from the nearshore zone, to be driven onshore to build an arcuate, west-facing barrier along the length of Tràigh Eais. In contrast, the connection between Orosay and Ben Eoligarry has become flooded by sea-level rise. The emplacement of one or more gravel ridges as part of a gravel barrier has played an important shaping role in the subsequent evolution of what are now largely sandy beach complexes. Once complete, the gravel barrier adjusted landwards and upwards in the face of ongoing sea-level rise. This is a common feature of the sandy and dune-backed beaches of Scotland where gravel is present on which wave-deposited beach and windblown sands have later accumulated (Hansom, 1988; Hansom and Angus, 2001). Where the source sediment is mixed, gravels are usually the first to arrive and are thrown up at the limit of storm waves, whereas sand arrives in quantity later.

The large influx of these coastal sediments is thought to have occurred around 6500 years BP (Hansom and Angus, 2001). It produced beaches with sufficient excess sand available on the upper profile to be blown into the extensive dune and machair systems that remain active today (Ritchie, 1971; Hansom and Comber, 1996). However, ongoing sea-level rise coupled with a reduction in offshore sand supply has also resulted in chronic erosion of many Hebridean beaches and the frontal undercutting of the sand dune systems that they support, such as occurs at Tràigh Eais. Some areas remained sheltered from severe waves and/or by a locally enhanced sediment supply and the effects of chronic frontal erosion have not yet occurred. Tràigh Mhór is such a beach, protected on all sides except the east and sheltered from Atlantic waves. It is a sediment trap within which a wide accretional beach has developed. Farrow (1974) identified onshore-moving bars composed of cockle shells and sand as a result of both tide and wave-induced onshore transport. Time-series maps and photographs allowed Farrow (1974) to demonstrate onshore movement of the cuspate bars over the period 1948–1965 and 1965–1973.

Optically stimulated luminescence (OSL) dating of aeolian sands (Gilbertson *et al.*, 1999) indicate that the carbonate sand of the Barra machair began to arrive about 6800 years BP. However, the arrival of aeolian sand and the initiation of machair development in the Hebrides was almost certainly non-synchronous (Ritchie and Whittington, 1994) and related to local bathymetry and sand supply as the sea level rose over the low-lying and undulating landscape. Thereafter within the Barra dunes and machair various palaeosols dating from Bronze Age to medieval occur together with evidence of periods of instability

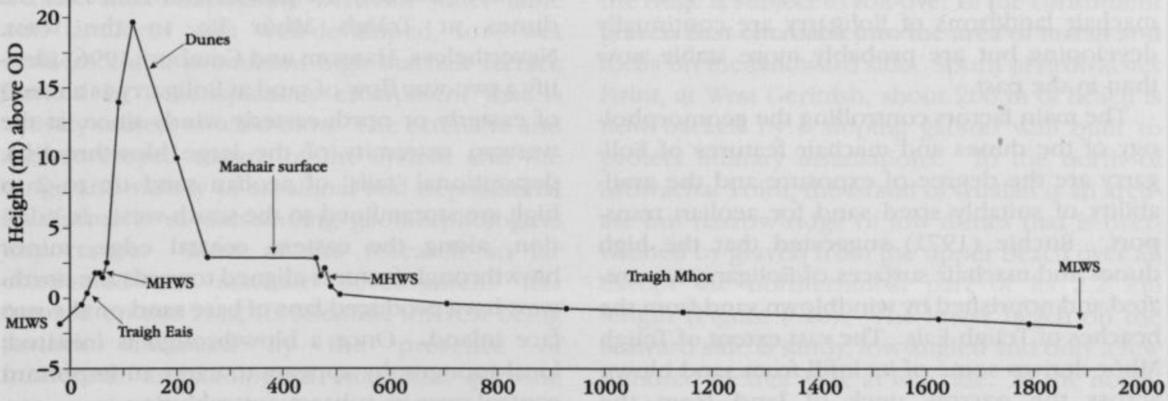


Figure 9.7 Representative cross-section levelled west to east over Eoligarry (see Figure 9.6 for line of section). Note the expanse of Tràigh Mhór and the relatively narrow cordon of coastal dunes that are currently undergoing severe wind erosion. (After Hansom and Comber, 1996.)

Figure 9.8 Looking south over the large blowthroughs on the west side of Eoligarry. Some remedial work has been undertaken but deflation is now so extensive that several dunes have been reduced to isolated 'buttes'. Tràigh Eais is to the right. (Photo: J.D. Hansom.)

and sand-blow that extend into modern times. Gilbertson *et al.* (1999) show that the upper surfaces of the Eoligarry machair are only 100 years old. Hansom and Comber (1996) and Gilbertson *et al.* (1999) emphasize that the machair landforms of Eoligarry are continually developing but are probably more stable now than in the past.

The main factors controlling the geomorphology of the dunes and machair features of Eoligarry are the degree of exposure and the availability of suitably sized sand for aeolian transport. Ritchie (1971) suggested that the high dunes and machair surfaces of Eoligarry are created and nourished by windblown sand from the beaches of Tràigh Eais. The vast extent of Tràigh Mhór derives some of its infill from sand blown across the narrow neck of land from the blowthroughs of the west. Sediment analysis of Tràigh Mhór beach shows that sands of 0.2 mm and 0.3 mm diameter are found on the lower and upper beach respectively whereas the dune sand to the west and rear of the beach is 0.37 mm (Hansom and Comber, 1996). Since the grain size of the dune would be expected to be finer than that of the feeder beach, the present, and probably the past, feeder zones for the dunes at Tràigh Mhór lie to the west. Nevertheless, Hansom and Comber (1996) identify a two-way flow of sand at Eoligarry as a result of easterly or north-easterly winds since, at the western extremity of the large blowthroughs, depositional 'tails' of aeolian sand up to 2 m high are streamlined to the south-west. In addition, along the eastern coastal edge, minor blowthrough features aligned towards the north-west have produced fans of bare sand on the surface inland. Once a blowthrough is initiated, local topography appears to exert an important control over its subsequent evolution.

Conclusions

The scientific importance of Eoligarry rests largely in the outstanding range of well-developed active erosional features and processes that are unrivalled in any beach–dune–machair system of comparable size in the Hebrides. Most of the typical erosion forms of Hebridean dune and machair morphology are found at Eoligarry within an archaeological context that allows an unrivalled degree of dating precision of phased machair development. Scientific interest is further enhanced by the high- and low-energy flanking beaches of Tràigh Eais and Tràigh Mhór, and the resultant complex sediment interaction which occurs between beaches, dunes and machair plain.

ARDIVACHAR TO STONEYBRIDGE, SOUTH UIST, WESTERN ISLES (NF 740 464–NF 730 333)

Introduction

The 30 km-long stretch of South Uist coastline between Ardivachar Point in the north to Stoneybridge in the south (see Figure 9.1 for general location) includes excellent examples of almost every type of beach, dune and machair surface in the Western Isles. These landforms have developed in the context of a high-energy and open Atlantic coastline that is subject to ongoing submergence (Figure 9.9). In the north, the island of Gualan represents a remnant dune and machair system and in the south, the machair is replaced by a gravel beach backed by marsh and loch. Between these lies a beach–dune–machair system that demonstrates a close inter-relationship between water table and landform with well-developed, low, wet surfaces and a prominent high machair terrace fronted by a conspicuous escarpment that is actively subject to wind-blow. The extensive and well-developed nature of the system and the range and variety of erosional and depositional landforms is of outstanding geomorphological importance. Most of the research so far conducted on machair development has focused on this area, its scientific interest being further enhanced by the presence of numerous archaeological sites that provide not only a cultural context for the development of the landforms but also a dating control. It is a type area for machair development and geomorphology.

Description

The beach that extends between two outcrops of highly resistant Lewisian gneiss at Ardivachar and at Stoneybridge is effectively a single system broken only by the rocky outcrops of Sgeir Dremisdale and by the exit of the Howmore River (Figure 9.9). The river exit is characterized by several sand-bars and by localized backshore accretion with embryo dune formation. North of this point, the low-angled beach as far as Drimore is up to 160 m wide and composed of sand with a calcium carbonate content of 42%, although the dunes and machair behind can reach up to 84% (Ritchie, 1971). Seepage of ground water from the landward surfaces seasonally affects the beach so that the higher water-tables of winter intersect the gravels of the backshore storm ridge. Such impounding of the winter water table has profound geomorphological and ecological consequences, since the low-lying parts of the machair and dunes landward remain flooded to depths of up to 0.5 m for up to five months of the year (Ritchie, 1971). The backshore ridge is affected by storm wave activity and wave-transported gravels are found up to 50 m inland flooring the erosion and deflation hollows in the dunes behind.

Two areas of the beach depart from the above pattern of sand beach, gravel ridge and backing suites of dunes and machair. To the south, near Stoneybridge, the backing dune and machair zone disappears and is replaced by a superb broad-crested coarse gravel ridge that reaches up to 10 m above mean sea level and up to 50 m wide (Ritchie, 1971). Under storm conditions the ridge is subject to roll-over of the constituent gravels that encroach into the area of marsh and lochs on the landward side. South of Ardivacher Point, at West Gerinish, about 200 m of beach is now backed by a sloping gabion wall built to protect military installations. To the north of Ardivachar Point, the island of Gualan is an arcuate but narrow ridge of low dunes that is overwashed by gravels from the upper beach over all except the northernmost part of its 2.2 km length (Figure 9.10). The lower beach on the seaward side is sandy, low-angled and only a few hundred metres wide at low tide. At the northern end of Gualan, and to a lesser extent in the south, the intertidal sands widen to about 1 km, behind which occur embryo dunes backed by well-developed dunes of up to 4 m high (Keast, 1994). The eastern beach of Gualan represents

Figure 9.9 The extensive machair lands of South Uist, looking north, with the exit of the Howmore River in the foreground, Ardivachar, Loch Bee, Gualan and North Uist in the distance at the top of the photo. (Photo: P. and A. Macdonald/SNH.)

the westernmost limit of the intertidal sands of the narrows that separate South Uist from Benbecula (the South Ford). Much of the western coastal edge of Gualan is subject to erosion and this is manifest either in low cliffs cut into the underlying machair or by gravel washover in small lobes that extend eastwards considerable distances down the dune and machair backslope.

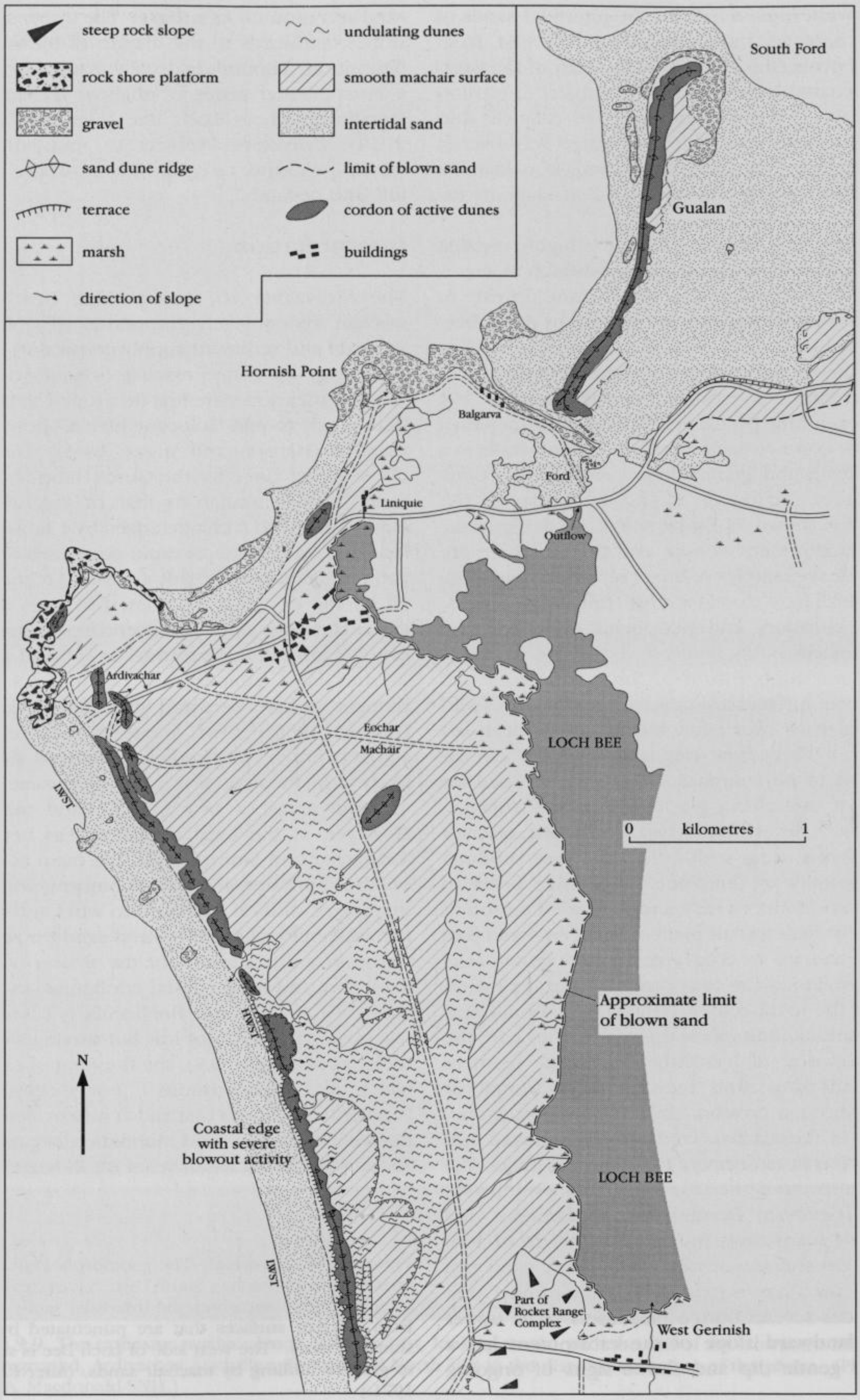
Elsewhere, the coastal edge is highly variable in elevation and morphology, although in general there is a tendency for erosion and retreat. In most places there is a steep seaward dune face, capped by a sharp crest at between 4 and 12 m OD. More complex areas of dunes occur where higher transverse ridges intersect the coast but in general the profile is relatively constant with a gentle concave backslope leading landwards to a low-lying and generally wet machair (a representative section of the northern part of the coast is shown as Figure 9.11). In some areas, for example at Drimore and Eochar, there are excellent examples of linear blowthroughs some of which have developed into fully formed deflation corridors and peripheral re-depositional hummocks.

Immediately inland of the coastal edge the machair surfaces are generally low features and rarely reach over a few metres above mean sea level. Where low ridges occur they can be shown to be composed of machair draped on top of underlying glaciogenic ridges (Ritchie, 1971). Nevertheless two distinctive machair landforms occur within the otherwise subdued topography of this zone. Extensive fields of hummocky dunes exist superimposed on top of the low flat machair plains. Between 1 and 3 m high and up to 8 m across, these hummocky dunes extend for considerable distances inland from the main coastal dune ridge. Dominated by marram *Ammophila* vegetation, they have the appearance of recently deposited features formed from sand recycled from frontal or blowthrough erosion. Inland, the most prominent of the machair landforms is a curved seaward-facing escarpment that stretches almost the entire length of the coastline. Well-developed at West Gerinish, Dremisdale and Drimore, the 16–20° scarp slope varies in height from 1 to 7 m. Several sections are under active wind erosion that has revealed a stratigraphy that includes several buried palaeosols. The upper and landward slope of the escarpment has a more gentle dip and shows signs of ongoing sand accretion on its surface. The upper surface slopes landwards to the margin of blown sand deposition, a boundary usually marked by either a coast-parallel series of shallow lochans and marshes (such as Loch Bee (Figures 9.9 and 9.10)), themselves subject to inundation of windblown sand, or by the rising surface of the hill land beyond.

Interpretation

The Ardivachar to Stoneybridge beach and machair system likely responded to Holocene sea level and sediment supply constraints in the same way as other machair systems in the Western Isles and were first developed sometime in the early to mid-Holocene before about 6500 years BP (Hansom and Angus, 2001). The relative sea-level curve for the Outer Hebrides has a form broadly similar to that of Orkney (see Figure 6.28) and is characterized by a slowing, or inflexion, in the rate of rapid rise in sea level at about 6500 years BP. This argument is supported by the existence of numerous sites in the Outer Hebrides where Holocene freshwater peat is now found in the intertidal or subtidal zones. In the Uists, submergence of up to 5 m is thought to have occurred since 8800 years BP (Ritchie, 1985). Such a rate of sea-level rise, across a pre-existing sediment covered shelf, is likely to be the main driver behind the existence of large areas of beach, dune and machair. However, at the local level, such as between Ardivachar and Stoneybridge, the main controls on the dune and machair geomorphology are the degree of local exposure to wind and wave, the availability of suitably sized sand for aeolian transport and, crucially for the timing of sand incursion, the local coastal configuration. The coast of the Uists and Benbecula is essentially composed of a series of low but varying altitude rock basins (Figure 9.9), the flooding of each of which was asynchronous. For example, at Peninerine on South Uist and at nearby Borve on Benbecula the first sand inundation occurred at about 6600 radiocarbon years BP, indicating the

Figure 9.10 (overleaf) The geomorphology of the area around Ardivachar, South Uist. A narrow cordon of active dunes separates the intertidal sandy beach from machair surfaces that are punctuated by erosional terraces. The west side of Loch Bee is subject to gradual infilling by machair sands. (After Ritchie, 1971.)


steep rock slope
rock shore platform
gravel
sand dune ridge
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direction of slope
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smooth machair surface
intertidal sand
limit of blown sand
cordon of active dunes
buildings
South Ford
Gualan
Hornish Point
Balgarva
Ford
Liniquie
Outflow
Ardivachar
Eochar
Machair
LOCH BEE
0
kilometres
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West Gerinish

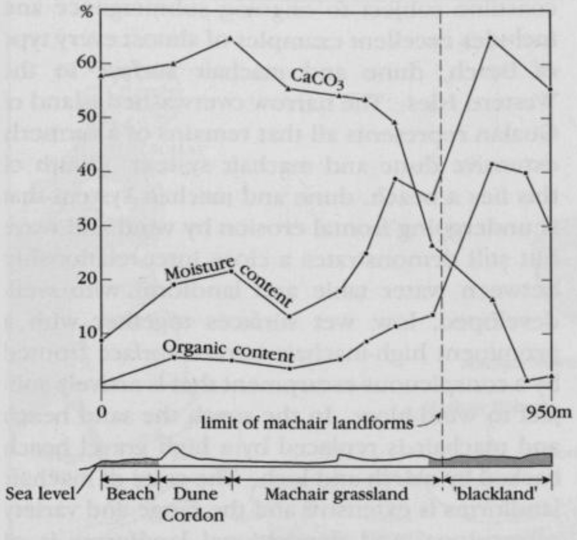

Figure 9.11 A representative cross-section over Dremisdale Machair, South Uist, showing the relationship between landforms, vegetation and soil characteristics. Note the landward decline of calcium carbonate content of the sand from high values close to the beach. Dremisdale is sited just north of the Howmore River exit (see Figure 9.9). (After Mather and Ritchie, 1977.)

proximity of the shore (Ritchie *et al.*, 2001). On the other hand, on Pabbay to the north, intertidal peat at three locations suggests that whereas one part of the island was first affected by a major sandblow event *c.* 7700 radiocarbon years BP, another part was first affected *c.* 4300 radiocarbon years BP (Ritchie and Whittington, 1994). It appears most likely that progressive inundation by sand occurred as the coastline, forced by a rising relative sea level over much of the Holocene Epoch, moved eastwards. The result was the development of beach, dune and machair complexes which themselves became subject to erosion or flooding as the coastline progressed eastwards.

For example, between South Uist and Benbecula, the low basin that now contains the South Ford became flooded during the mid-Holocene and most of the central low-lying machair cover was lost. The narrow dune ridge of Gualan, north of Ardivachar, and small lateral fragments to the north and south of the South Ford, are probably all that remains of this formerly extensive machair. Tidal access to the Gualan machair was probably first gained as the dune cordon was breached in both the north and south ends. The breaches remain, but the process has advanced to the extent that the Gualan dune cordon is now thin and low with a coastal edge that is being eroded (Figure 9.10). Almost everywhere it is threatened by washover of gravels in storm conditions that will eventually lead to loss of the remaining dune and machair and further migration eastwards into the narrows.

Ongoing relative sea-level rise coupled with reductions in the offshore sand supply has subsequently resulted in erosion of many Hebridean beaches and the frontal undercutting of the sand dune and machair systems that they support (Figure 9.3; Hansom and Angus, 2001). The mainly sandy linear beach between Ardivachar and Stoneybridge reflects this and is mostly characterized by landward retreat of the coastal edge. Nevertheless, the sloping gabions at West Gerinish appear to be stable, with limited sign of either undercutting or outflanking. It may be that the sediment supply along this part of the coast has been locally healthy in recent years. Frontal erosion of the foot of the prominent, bare dune-slope by waves and deflation of the face by wind, has resulted in progressive landward migration of the seaward escarpment into the dune cordon and machair behind. Such progressive coast-parallel frontal removal of the dune cordon and the development of bare sand slopes exposed to the west, also provides conditions conducive to the development of linear blowthroughs and deflation corridors at right angles to the coastline. Good examples of this occur at Drimore and Eochar, together with the re-depositional dune landforms that form downwind of the erosional sites. Much of the remaining area landward of the seaward dune cordon is characterized either by low-lying and wet machair surfaces or high landward-sloping machair surfaces separated from the low-lying ground seawards by a steep, wind-eroded escarpment.

The low-lying machair demonstrates a sensitive inter-relationship between landform and water table. Although the higher and drier parts both to seaward and landward of the low-lying machair are subject to deflation for most of the year, the lower and wetter surfaces do not deflate when wet yet continue to accept deposition of windblown sand. The resultant landforms are thus virtually flat and with a gentle landward gradient away from the main sand source. No detailed studies exist of the geomorphological processes involved in this windblown re-depositional system, but it seems likely that ongoing deposition onto the usually wet and gently sloping surfaces results in their progressive elevation, particularly at the seaward margin. Low-lying, flat and wet ground may be progressively replaced by higher sloping sand surfaces.

Similar processes are likely to have been responsible in the past for the initial development of the escarpment that often lies landwards of the low-lying machair, a feature prominent at West Gerinish, Dremisdale and Drimore. It is well-known that the landward slope of the high machair and wetland behind is continually elevated by the receipt of substantial quantities of blown sand deflated from both the beach and dune cordon as well as directly blown from the front of the escarpment itself. Accretion of the top surfaces of high machair appears to be both episodic and of long standing since palaeosols and archaeological remains ranging in age from the Neolithic to recent historic are exposed at several places in the deflated edges of the high machair. For example, on the South Uist machair at Kildonan (NF 725 284), south of Stoneybridge, Iron Age structures and associated palaeosols dating from 2500 to 1500 radiocarbon years BP have been exposed by subsequent deflation (Gilbertson *et al.*, 1996) and at nearby Cladh Hallan (NF 734 219), Bronze Age middens and palaeosols from 4000 radiocarbon years BP are exposed in the eroding escarpment edge of the high machair (Gilbertson *et al.*, 1999). Such palaeosols often form a layer resistant to further deflation (Ritchie, 1979a,b) although there is also evidence of periods of instability and sand-blow that extend into modern times (Gilbertson *et al.*, 1996, 1999). Hansom and Comber (1996) and Gilbertson *et al.* (1999) emphasize that although machair landforms are continually developing, they are probably more stable now than in the past. As a result it is possible that the very marked relationships that exist between the supply of fresh shell-sand, soil characteristics, vegetation and landform noted by Ritchie (1976) (Figure 9.11) may change in the future as the supply of fresh sand alters.

Conclusions

The South Uist coastline between Ardivachar Point and Stoneybridge is an exposed Atlantic coastline subject to ongoing submergence and includes excellent examples of almost every type of beach, dune and machair surface in the Western Isles. The narrow overwashed island of Gualan represents all that remains of a formerly extensive dune and machair system. South of this lies a beach, dune and machair system that is undergoing frontal erosion by wind and wave but still demonstrates a close inter-relationship between water table and landform with well-developed, low, wet surfaces together with a prominent high-machair terrace surface fronted by a conspicuous escarpment that is actively subject to wind-blow. In the south the sand beach and machair is replaced by a high gravel beach backed by marsh and loch. The suite of machair landforms is extensive and the range and variety of erosional and depositional landforms is of international geomorphological importance. Interest is further enhanced by the occurrence of several archaeological sites that provide a cultural and dating context for machair development.

It is the type site on which much of the early work on machair development was based.

HORNISH AND LINGAY STRANDS (MACHAIRS ROBACH AND NEWTON), NORTH UIST, WESTERN ISLES (NF 860 750–NF 890 777)

Introduction

The beach–dune–machair systems of Hornish and Lingay Strands include Machairs Robach and Newton, Clachan Sands, and part of Vallaquie Strand (see Figure 9.1 for general location). The area provides excellent examples of most of the machair landform and vegetation types found in the Uists. Machairs Robach and Newton provide the best sites in the Western Isles for flat and low-lying machair landforms that have been influenced by water-table effects and modified by centuries of traditional grazing and cultivation practices. They also provide the finest examples in the Western Isles of old and high machair plateau forms that have either been dissected down to the water table by deflation to produce a distinctive scarp and table land appearance or undercut by wave activity to produce a truncated sequence. Recent depositional activity has enlarged the intertidal strands, and together with saltmarsh development adds to the complexity and scientific interest of the site.

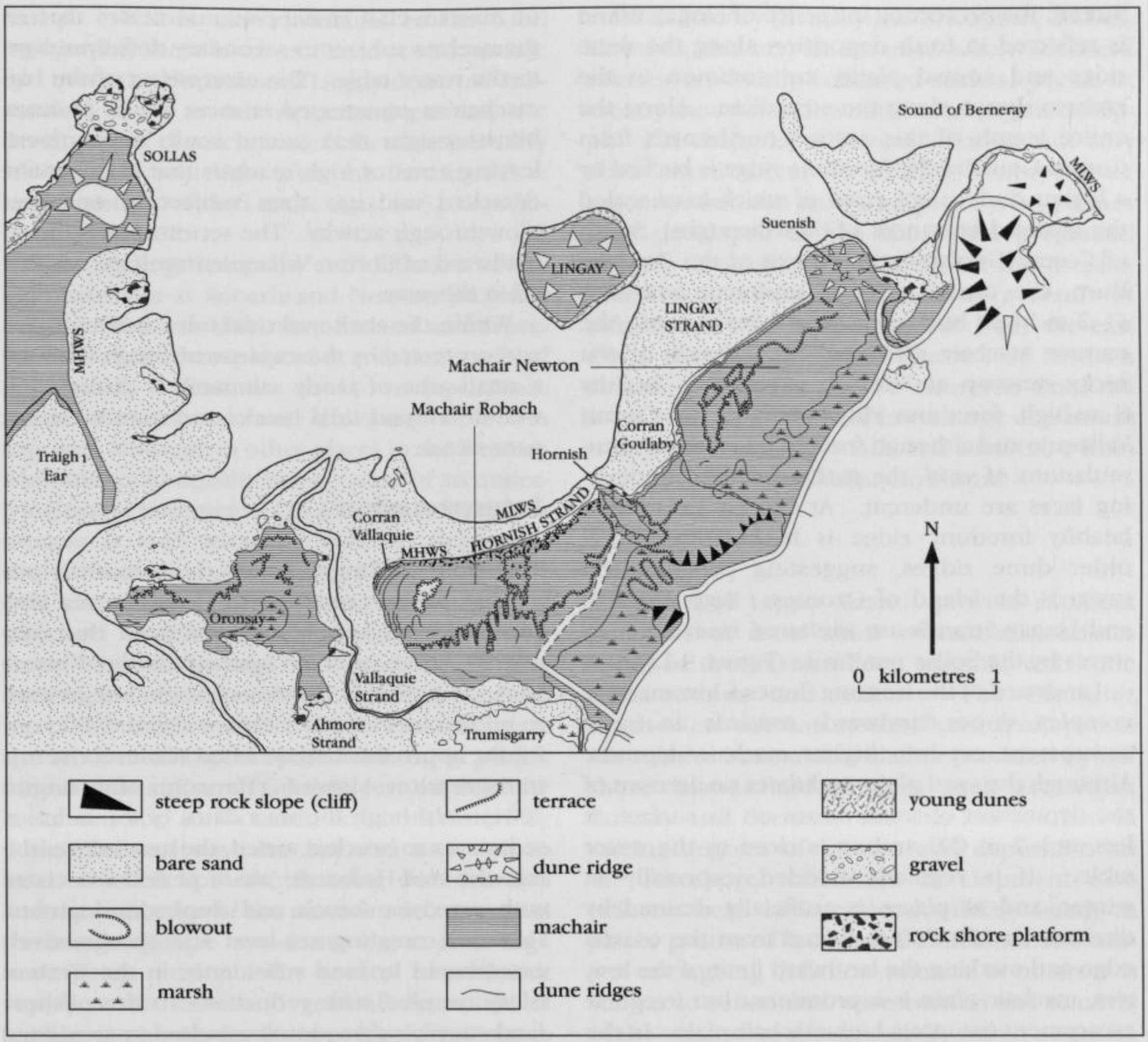

Figure 9.12 The geomorphology of Hornish and Lingay Strands including Machairs Robach and Newton. Well-developed beaches, dunes and machair have benefited from the relative protection from westerly waves offered by the headland at Sollas and the island of Lingay (see Figure 9.4). (After Ritchie, 1971.)

Description

Hornish and Lingay Strands face north-west on the north coast of North Uist. On their landward side, the beaches are backed by extensive machair surfaces that rise to the east and south and grade into hill land beyond (Figure 9.12). The northernmost part of the strand is hinged against a low rocky knoll at Suenish and the southern limit is the low island of Oronsay, itself fringed with fragments of rocky shore platform. The intervening sands stretch for 4.5 km in a gently curving bay broken only by a small rocky ridge of gneiss at Hornish where the beach narrows to only 100 m. At both extremities the beach widens to over 1 km in the north at the intertidal sand tombolo that extends to the island of Lingay and in the south at Corran Vallaquie. The beach gradient is shallow and low sand-bars are common in the fine sand. The shell content of sand at nearby Ahmore and Trumisgarry is 52% and 44% respectively. In the north of the site the coastal edge is mainly characterized by re-depositional young foredunes masking a retreating older machair edge and a narrow band of young dunes colonized by vigorous growths of marram *Ammophila arenaria* everywhere skirts the backshore. At Lingay

Strand, the protecting influence of Lingay Island is reflected in fresh deposition along the dune ridge and annual plants are common in the embryo dunes along the strandline. Along the entire length of this section northwards from Corran Goulaby, the foredune ridge is backed by a higher dune ridge, parts of which have sealed the seaward entrances of blowthroughs. South of Corran Goulaby and the exit of the Goulaby Burn, the coastal edge is undercut with low (1–2 m high) but active sand faces cut into the mature machair plain behind. South of the rocky outcrop at Hornish a relatively healthy 8 m-high foredune ridge extends to Corran Vallaquie and although fronted by seasonal accumulations of sand, the partly obscured underlying faces are undercut. At Corran Vallaquie a healthy foredune ridge is backed by several older dune ridges, suggesting progradation towards the island of Oronsay. Both Hornish and Lingay Strands are sheltered from westerly waves by the Sollas peninsula (Figure 9.12).

Landward of the fronting dunes a low machair complex slopes landwards towards an inner escarpment cut into higher machair deposits. Although the sand plain undulates on account of the deposition of small dunes on its surface, it lies at 1–2 m OD and so is close to the water table. It is regularly flooded, especially in winter, and in places is artificially drained by ditches. At 100–700 m inland from the coastal edge and marking the landward limit of the low, wet, machair plain is a prominent but irregular escarpment cut into a high machair plain. In the north the high plain lies some 3–8 m above the level of the lower surface and slopes landwards for 1.25 km to a poorly drained zone of marsh with small lochans where it meets the rising hill land beyond. Although the high machair plain is currently cultivated, it remains subject to wind-blown sand deposition that slowly infills the marsh zone behind. Just north of Hornish, the inner escarpment approaches the coastal edge and what remains of the low machair plain is actively being undercut by wave erosion. South of Hornish, Machair Robach extends up to 2.5 km inland and, although the landform sequence mirrors that of Machair Newton, the degree of deflation, especially of the higher machair surface, is more impressive and the zone that is locally eroded down to the water table widens towards the south-west. Flanking the deflated areas are eroded sandy faces cut into the surrounding machair surface and areas of marram-clad re-depositional dunes that are themselves subject to secondary deflation down to the water table. The escarpment of the high machair is punctuated in most places by linear blowthroughs that extend south or south-east leaving arms of high machair that may become detached and are then subject to enhanced blowthrough activity. The series of large dunes landward of Corran Vallaquie may have originated in this way.

Within the sheltered tidal inlet at Trumisgarry and protected by the expanse of Tràigh Vallaquie a small area of sandy saltmarsh is dissected by well-developed tidal creeks and numerous salt-pans occur.

Interpretation

The Hornish–Lingay beach–dune–machair system probably responded to Holocene sea level and sediment supply constraints in the same way as other machair systems in the Western Isles. It probably developed sometime in early to mid-Holocene times before about 6500 years BP, the approximate date when sea-level rise and transgression slowed (Hansom and Angus, 2001). Although the start dates of the influx of sediments to beaches varied, the general trend is that the mid-Holocene was a period associated with extensive beach and dune development. However, ongoing sea-level rise (progressively exacerbated by land subsidence in the Western Isles) coupled with reductions in the offshore sand supply subsequently resulted in erosion of many Hebridean beaches and the frontal undercutting of the sand dune and machair systems that they support. Gilbertson *et al.* (1999) identified several periods of sand drift in the Uists dating from 9000–8300, 7500–7000, 6900–6400 and 5800–4200 radiocarbon years BP. In North Uist, Ritchie and Whittington (1994) show that organic deposits now exposed in the intertidal zone at Cladach Mór were first subject to sand incursion at 7600 radiocarbon years BP, one of the earliest records of offshore-sourced carbonate sand incursion in the Uists (Gilbertson *et al.*, 1999). At Camas Mór on the island of Vallay, 10 km west of Hornish Strand (Figure 9.4), the first sand incursion occurred at 6925 years BP. However, Ritchie *et al.* (2001) identify the major period of sand incursion at many sites in North Uist to be after 5200 radiocarbon years BP, this date agreeing with the well-known period of strong sand drift on the coasts of north-west

Europe. Within the constraints of the local topography, there is no evidence yet to assume that events at Hornish and Lingay departed substantially from the above general pattern, the development of machair surfaces most probably taking place sometime after the first arrival of large amounts of sand at the coast at 5200 radiocarbon years BP.

The ongoing dissection and deflation of the high machairs at Robach and Newton probably began as soon as they were formed and represent excellent examples of a constant cycle of deposition, erosion and re-deposition. Deflation continued until the water table was exposed, although in other places in the Western Isles this could equally be exposure of an underlying gravel basement. On Machair Robach this process is well advanced with an impressive summit accordance of remnants of high machair that allow the reconstruction of an original tableland that is now characterized by steep sandy windward scarps and gentle and stable backslopes. Re-deposition of eroded sand on top of the deflated surface produces a secondary spread of small superimposed dunes. In places, for example at Corran Goulaby just north of the rocky outcrop at Hornish, frontal erosion by both wind and wave has been so severe as to have removed both the fronting dune cordon and the high edge of the machair surface so that the low backslope now forms the coastal edge undergoing erosion. The control of sediment supply, water table and general dynamism of aeolian processes displayed at Machairs Robach and Newton, conforms well to the model of machair development suggested by Ritchie (1979a,b) and supported recently by Gilbertson *et al.* (1999), and Machair Robach is probably one of the best examples of machair erosion and development in the Western Isles. Viewed in the context of a generally submerging coastline, recycling of beach and sand dune sediments might be expected as wave erosion progressively enhances coastal instability and produces sand surfaces susceptible to wind-blow. So too might be the progressive flooding of low-lying basins to form intertidal strands, such as at Trumisgarry and Tràigh Ear, and the associated flooding of terrestrial deposits, some of which now appear as intertidal peats.

Although the coastal edge is often obscured by newly deposited windblown sand, the general underlying status of the beaches of the Uists appears to be characterized by erosion and sediment deficiency (Ramsay and Brampton, 2000e). However, this may be reversed where sediment sources are locally enhanced such as occurs at estuary mouths or downdrift of a longshore supply. For example, at Corran Vallaquie not only does there occur a healthy embryo-dune sequence but also several ridges of young dunes have developed as the shore has prograded towards Oronsay. The wider beach and its associated dunes have developed as a result of refraction-driven longshore drift from the east along the wide intertidal expanse of Hornish Strand. Sand may also be delivered from the south-west as a result of low-energy deposition within the Trumisgarry inlet and wind-blow from the upper beach on Vallaquie Strand.

Conclusions

Hornish and Lingay Strands provide excellent examples of most kinds of machair surfaces found in the Western Isles, together with wide tidal strands and inlets. The extensive beach–dune–machair systems have developed in the relative but variable shelter provided by offshore islands and skerries such as Lingay, Boreray and Berneray and this has resulted in varying degrees of erosion and deposition on the foreshore. Machair development also reflects these topographical effects, being in places protected from wave attack but still subject to ongoing deflation whereas in others it is subject to substantial wave erosion and removal of the original landforms, all set within a context of submergence. Machairs Robach and Newton are one of the sites of the highest geomorphological interest in the Highlands and Islands. Since 66% of the world resource of machair is found in the western seaboard of Scotland, there can be little doubt about the international scientific importance of Hornish and Lingay Strands and Machairs Robach and Newton.'

PABBAY, HARRIS, WESTERN ISLES (NF 900 870)

Introduction

The island of Pabbay lies in the Sound of Harris some 8 km north of North Uist (see Figure 9.1 for general location). About 30% of the island area is covered by blown sand, most of which is located in the south-east, and the site is probably

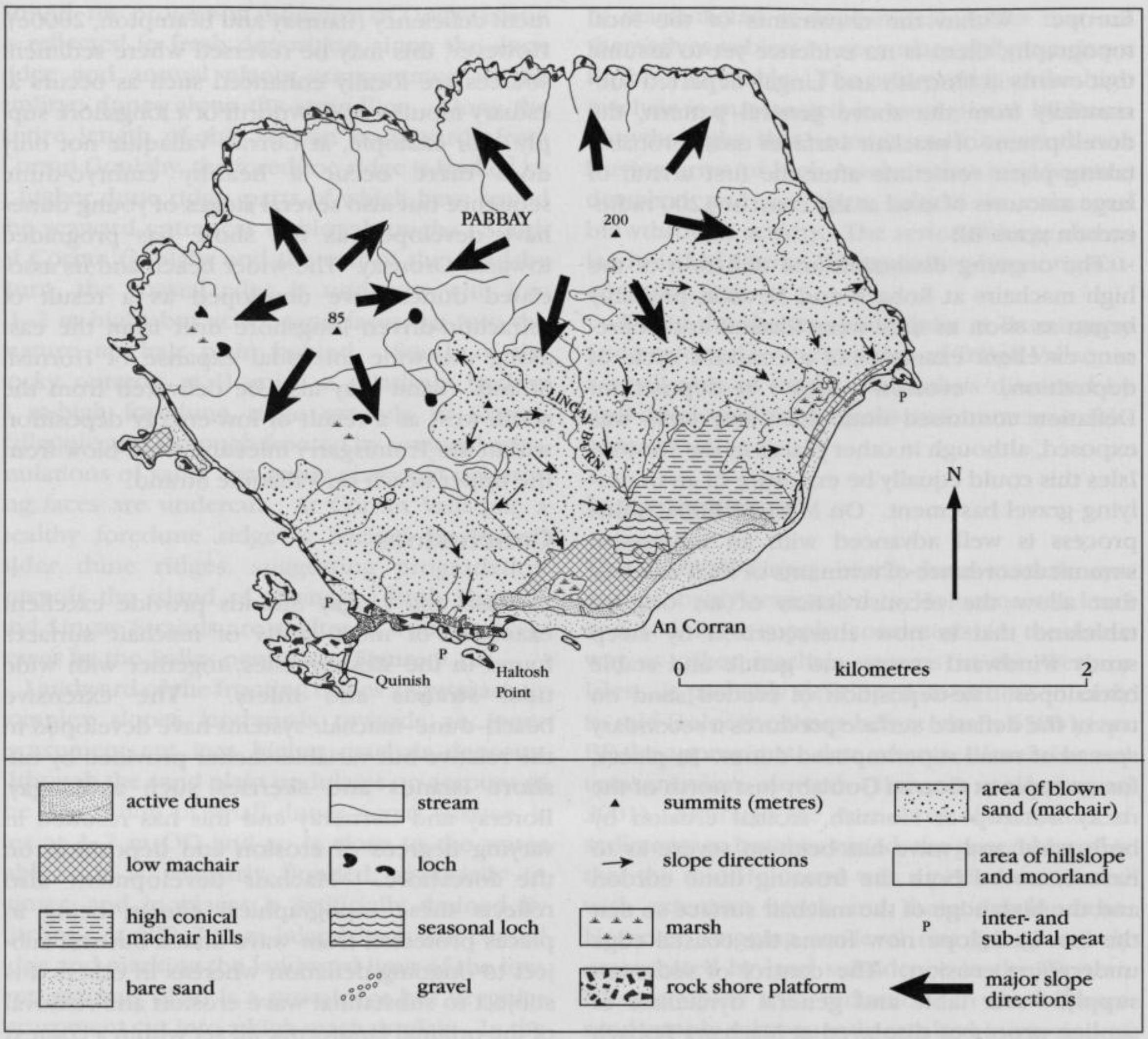

Figure 9.13 The geomorphology of Pabbay, Sound of Harris, showing the extensive area of climbing machair and the low-lying area east of Haltosh Point that has been infilled by beach and dune accretion since 1857, when it was a marine inlet. (After Ritchie, 1980.)

the best example of climbing dune habitat in the Western Isles. The machair on Pabbay is of national importance because it provides good examples of all the types of machair and dune surfaces found in the Outer Hebrides in addition to areas of unusual large conical dunes. Unusually, the machair areas face south-east rather than to the west as is the case in most of the Hebridean machair. There is no record of rabbits having reached the island, and since rabbits are thought to have had a major effect on dune and machair geomorphology, Pabbay provides a good comparative site. Several areas of intertidal and subtidal peats occur on Pabbay that may help elucidate the sequence of aeolian and sea-level events that led to machair development both on Pabbay and elsewhere in the Outer Hebrides.

Description

Pabbay is a distinctive, conical island, which has been uninhabited since the 1930s. The coastline is also distinctive being characterized by north and east coasts that are rocky, cliffed and indented with geos and inlets and south and west coasts that are low-lying and predominantly sandy (Figure 9.13). The coastal edge of the south and west coast comprises three crescentic sand embayments that have developed between low rocky skerries and platform remnants. Landwards of these embayments a beach–dune–machair complex has accumulated that has extended north to cover about 30% of the area of the island. Ritchie (1980) described the island as consisting of three main landform surfaces. The northern half of the island is characterized by ice-moulded bare rock and boulder surfaces, stripped of the original peat cover. The central–west plateau is covered by boggy moorland in the west and north and by windblown shell-sand elsewhere. The south is dominated by shallow basins filled with various types of machair and dune landforms.

The beaches along the south-west coast are mainly gravel storm ridges connecting low fragments of rock shore platform that are locally covered by a thin veneer of blown sand (MacTaggart, 1998c). Small pockets of intertidal organic deposits are occasionally visible near the offshore skerry of Quinish. Quinish is connected to Pabbay by a gravel tombolo that steepens at its landward end to obscure the machair edge. The gradient and height of the gravel ridge decline towards Haltosh Point where it is replaced by a predominantly sand beach. To the east, between Haltosh Point and the rocky cliffs of the north-east coast, lie two promontories that define three crescentic sandy embayments each composed mainly of shell-rich white sand. The first of these promontories, An Corran, is a triangular sandy foreland backed by low machair. The beach to the west is often partly covered by bars of small rounded gravels but the 1.5 km-long and 200 m-wide beach to the east is characterized by thick accumulations of sand that is subject to wind-blow (MacTaggart, 1998c). From comparison of aerial photographs the coastal edge of this promontory has retreated over the period from 1965 to present to form a steep scarp face that undercuts the seaward edge of the dune ridge, while progradation of several tens of metres has characterized the area to the east (MacTaggart, 1998c). The second promontory east of Haltosh Point (Figure 9.13) is a low rocky outcrop veneered by blown sand, beyond which is another sandy beach both shorter and narrower than the one to the west. A narrow gravel bank occurs along the coastal edge at the eastern end of this beach. Intertidal and subtidal peat deposits have been reported at the eastern end of the beach by Ritchie (1980).

Much of the coastal edge to the west of Haltosh Point is obscured by gravel beach deposits banked up against a steep and undercut machair face. Machair stratification is visible in places and displays alternating sequences of organic and sandy horizons. The coastal edge to the east of Haltosh Point is characterized mainly by localized areas of accreting and erosion-affected dune scarps that average 2–3 m high but a 15 m-high section undergoing erosion occurs in the face of a well-vegetated large dune ridge that runs inland and declines in height to the west of the first promotory. The ridge is punctuated by three shallow blowthroughs. Seawards of this large ridge lies a series of low accretional dunes that are vegetated to different degrees by primary colonizing species and marram *Ammophila arenaria*. At least two sequences of dune ridges are present, each running at a different angle from the present coast, the seaward sequence cross-cutting the landward sequence. The alignment of the large dune ridge defines a wider and more deeply indented bay centred on the outlet of Lingay Burn. Subsequent accretion has resulted in low dunes developing seawards of the large dune. The easternmost bay is characterized by a low machair edge undercut into several low hillocks, sections within which show thick accumulations of sand capped by an organic horizon that corresponds to the surface of the low machair plain behind. The organic layer is itself capped by windblown sands that have now been sectioned by coastal erosion. Ritchie (1980) reports several exposures of dune-foot organic horizons in the machair edge.

Behind the beach and dunes lies an extensive machair surface that displays three machair types: level or undulating machair, wet machair and hill-slope machair. Two large areas of wet machair occur landwards of the dunes backing the two eastern beaches. The largest of the wet machair areas was mapped by Ritchie (1980), and still remains, as a seasonal loch displaying distinctive vegetation zonation patterns dominated by bryophytes. The area of wet machair matches fairly closely with the extent of a marine inlet shown on the Admiralty Chart of 1857. To the south-west of the central wet machair lies low hummocky machair but to the north-east on the rising hillside lies a spectacular series of near-symmetrical conical sand dunes up to 8 m high and rising to 30 m OD. The dunes support machair vegetation with only small patches of marram *Ammophila arenaria*, although the intervening low-angled surfaces between the dunes contain damper habitats (Dargie, 1998). A small area of calcarenite occurs at the north end of the machair on Pabbay.

Interpretation

In common with much of Harris and the Uists, coastal development on Pabbay has been dominated by sea-level change and the availability of sediment. Throughout most of the Holocene Epoch sea-level rise has resulted in transgression of the seaboard of the Western Isles. However, since much of the coastline is characterized by undulating rocky surfaces at various altitudes and often with a variably thick veneer of glaciogenic deposits, the timing of inundation and subsequent beach and sand-dune deposition varies from site to site. Submergence of at least 2.8 m since 7700 radiocarbon years BP is indicated from the radiocarbon dating of freshwater peat from Pabbay (Ritchie, 1985), although dates elsewhere in the Uists suggest that the amount of submergence since 5100 radiocarbon years BP was of the order of 5 m. Certainly, the coastline of Pabbay was likely to have been characterized by variably drained low rocky basins at different altitudes and distances from the coast that began to fill with terrestrial peat at different times and may have been subject to the first wind-blow events at different times. Sea-level rise began to slow about 6500 years BP (see the introduction to the present chapter) but in the Outer Hebrides large amounts of sand from offshore sources had probably begun to arrive on shorelines prior to this date, resulting in wide beaches and the potential for substantial wind-blow and dune and machair development. It is thus likely that the lower levels of the first machair surfaces were formed early in the mid Holocene times, although the recycling of machair surfaces ensured that 'first wind-blow' events occurred over a wide range of dates. The abrupt change from a peat surface to a sandy upper section occurred at about 4400 radiocarbon years BP at Quinish on Pabbay (Ritchie, 1980). The former terrestrial peat deposits are now located 80 m seawards of MLWS, so it may be that much of the former low machair surface has been subsequently eroded and recycled landwards to form the higher machair, a process that continues today.

Historical records support the above reconstruction and indicate that the south-east part of Pabbay was formerly a large plain consisting of a sandy soil mixed with earth so fertile that Pabbay was known as the 'Granary of Harris' (Angus, 1997). However, in a sand storm in 1697 about 300 acres of arable land were overwhelmed by sand as well as land lost on the south-west side of the island 'where many people still alive have reaped crops of grain' (Walker (1764), cited in Angus, 1997). It is tempting to attribute the development of the climbing machair and conical dunes in the east of the island to the wind-blow events of 1697 particularly since the walls of ruined buildings have not yet been comlpetely buried by blown sand. Elton (1938) attributes this to stabilization of the higher surfaces into a closed turf resulting from a shift from predominantly arable farming before the end of the 18th century to pastoral farming thereafter. In spite of this possible stability at altitude, substantial changes at lower levels occurred as a result of sea-level rise. An early map of Pabbay in 1805 shows the coastline much as it is today yet the Admiralty Chart of 1857 shows a large tidal inlet behind the dunes. The first OS maps in 1881 show this loch sealed from the sea, presumably resulting from sand deposition (Angus, 1997). Since then, substantial accretion of dune and sand has resulted in the consolidation of the two forelands, with the high dune ridge probably marking the former position of the mean high-water springs in 1881. However, recent erosion of the west coast and accretion to the east (Angus, 2001) suggests that cycles of erosion and deposition, depending on storm approach direction, continue to influence the sand feed to the beaches and dunes of Pabbay.

Conclusions

Pabbay displays excellent examples of a range of beach–dune–machair landforms and is probably the best example of climbing dune habitat in the Western Isles (Dargie, 1998) with high conical dunes that are unique in terms of their scale and symmetry. The machair assemblage is also unusual in that it faces south-east whereas most other machair faces west. The island is also important for comparative study since there is no record of rabbits on Pabbay. The presence of several intertidal peat deposits together with an historical record of change allows the development of beach and machair to be placed in a temporal context.

LUSKENTYRE AND CORRAN SEILEBOST, HARRIS, WESTERN ISLES (NG 057 973–NB 068 004)

Introduction

Luskentyre Banks and Corran Seilebost are twin peninsulas that enclose the vast intertidal sand beach of Tràigh Luskentyre on the west coast of Harris (see Figure 9.1 for general location). They are both unusual settings for machair development but have several distinctive features and may represent the remnants of a once larger system. Luskentyre is of interest as a dynamic beach–dune–machair system with substantial dune development, whereas Seilebost incorporates a beach–dune–machair system backed by saltmarsh and extensive areas of intertidal sand. Only the seaward tip of Seilebost is a true sand-spit with identifiable growth stages and a landward curve. Together the Luskentyre and Corran Seilebost system has the appearance of being set within a structural trough that has been subject to submergence and represents a single dynamic depositional complex that is of great geomorphological interest.

Description

The Luskentyre–Corran Seilebost site extends for 3 km from the northern tip of the Luskentyre Banks to the southern extremity of the Corran Seilebost spit. At its widest it reaches a little over 1 km from mean low-water spings to the south of Tràigh Rosamol to the southernmost part of Luskentyre Dunes (east of area (1) Figure 9.14). The intertidal sandflats and saltings of Tràigh Luskentyre are an integral part of the coastal geomorphological system; they are also important for ornithological reasons.

Tràigh Luskentyre occupies an inlet that extends inland 4 km to the south-east and is characterized by intertidal sandflats crossed by a single tidal channel that is subject to lateral migration. In 1996 the channel approached close to the tip of the spit at Corran Seilebost (see Figure 9.15; MacTaggart, 1997c). Well-developed mega-ripples on the intertidal sandflats indicate that ebb velocities are an important factor in the redistribution of sediments within the embayment. Sandy saltmarsh communities have developed in the more sheltered places within the inlet, such as in the lee of the promontory of Corran Seilebost and at the mouths of several freshwater streams that drain onto the sandflat. Enclosing the seaward end of the sandflats of Tràigh Luskentyre are the twin promontories of Luskentyre Banks in the north and Corran Seilebost in the south.

Luskentyre Banks forms a bulbous triangular-shaped foreland jutting out from the steep rocky slopes of mainland Harris towards the island of Taransay (Figure 9.15). The beach of Tràigh Rosamol in the north is hinged onto the southern part of the rocky promontory of Aird Groadnish and curves west to reach 300 m wide at the point of Luskentyre Banks. The beach continues to the south-east and narrows to 50 m at a second rocky promontory close to Luskentyre settlement. The beach is composed of fine-grained sand of 0.22 mm diameter, of which some 54% is shell (Ritchie and Mather, 1970b). Outcrops of calcarenite occur at mean low-water springs along this part of the foreland (Ritchie and Mather, 1970b). The southern end of Tràigh Rosamol is backed by a single ridge of 2–3 m-high dunes. The seaward edge of the dunes increases in height to the north where several marram-clad ridges have developed, probably reflecting a sand supply from the south. The northernmost extremity of Tràigh Rosamol is marked by a locally undercut dune edge and a deep sand-floored erosion corridor across which drains a small stream (Figure 9.14). To the east of the point, the coastal edge is accretionary with low dunes developed in front of the higher, more stable dunes behind. However, towards the south-east, the low accretionary ridge narrows and the backing dunes become progressively undercut to produce dune faces of up to 20 m high. In the extreme south-east of the site, the coastal edge is rocky with a thin veneer of machair.

Ritchie and Mather (1970b) and Harris and Ritchie (1989) described the landforms of the foreland in terms of areas approximating those numbered on Figure 9.14. In the east of the site in area 1, an area of dunes is dissected by a partly stabilized blowthrough system that is now being undercut at its seaward edge. To the north-west of this in area 2, an old and stable machair surface is dissected by a series of blowthroughs of varying sizes to produce a chaotic surface surrounding a long and stable blowthrough corridor that has extended to the north. Area 3 to the north-west of area 2 consists of a series of U-shaped blowthroughs, dune

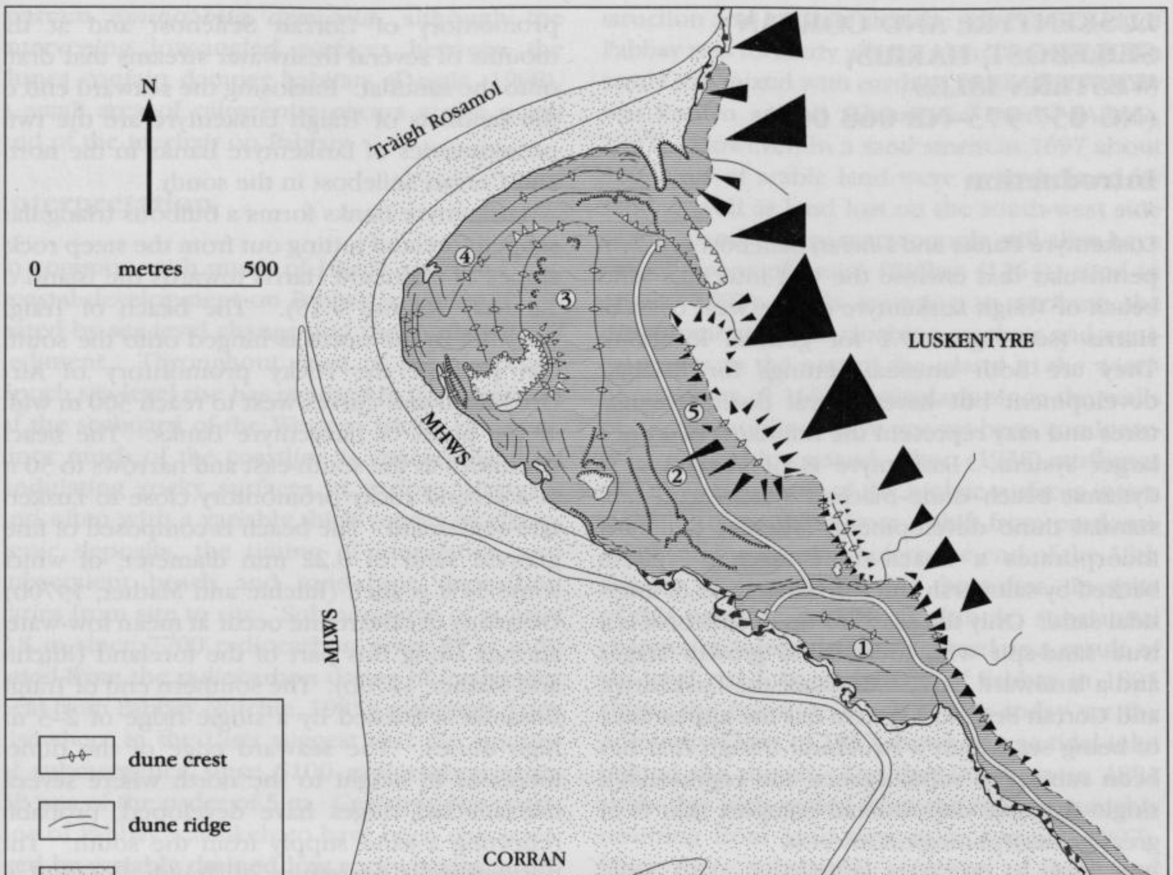

Figure 9.14 The geomorphology of Luskentyre and Corran Seilebost. Extensive intertidal sands front the dune and machair landforms of Luskentyre where several large blowthroughs occur. The dunes reach 35 m OD and are the highest free-standing dunes in Harris. Numbered locations on Luskentyre are referred to in the text. The complex of beach–dune–machair features may be the remnant of a once-larger machair that has been fragmented by submergence. (After Ritchie and Mather, 1970b.)

Figure 9.15 The rocky peninsula of Crago lies in the foreground of this aerial oblique looking north-west over Tràigh Luskentyre to the dunes and machair beyond. The western tip is highly active with clear evidence of extensive wind-blow. The free-standing spit of the tip of Corran Seilebost is also in view in the centre left. The island of Taransay (at the top) provides shelter from westerly waves. (Photo: P. and A. Macdonald/SNH.)

ridges and conical sand dunes that reach over 35 m OD, the highest free-standing dunes in Harris. The conical dunes appear to be recent re-depositional features superimposed on the top of an earlier central high ridge system. This high surface is impressively dissected in the south by both elongate and cauldron-form blowthroughs, the largest of which is a long-established feature surrounded on all sides by exposed sand escarpments of up to 35 m OD and which tower above the blowthrough floor lying at a few metres above OD (Figure 9.15; MacTaggart, 1997c). Outcrops of calcarenite occur on the floor of the blowthrough. Since Mather and Ritchie (1970) described the feature, the seaward end of the main blowthrough has been sealed by the deposition of a ridge of new dunes, although north-trending blowthroughs have subsequently developed along the advancing northern apex of the main blowthrough (MacTaggart, 1997c). In the northern part of area 3, the high sand ridge is dissected by a number of blowthroughs that have also extended northwards as a series of unvegetated sand waves with steeply sloping (30°) leading edges that inundate area 4 to the north. Area 3 is separated from the active coastal edge by area 4, an extensive, high, mature dune-plateau that reaches 20 m OD. Stable sand dunes have been superimposed on top of the older surface. The northernmost parts of areas 3 and 5 are truncated by the landward extension of the sand-floored erosion corridor at the north end of Tràigh Rosamol. The sides of this gorge-like form are cut into machair sand in the north and bedrock in the south and probably represent a fault-controlled stream incision that has become partly machair-filled. Area 5 represents a high, but gently sloping, surface of extensive hill machair that is used intensively for cultivation and grazing and that masks the underlying glacially moulded surfaces of the hill-slopes above.

Corran Seilebost is a peninsula of about 700 m wide at its root against the rocky knoll of Aird Horgabost in the south. From here it progressively narrows for 1.3 km northwards to a narrow neck of sand. On the west side, Tràigh Seilebost is a straight and gently sloping beach that extends seawards for 300 m and includes wave-built swash bars. On the east, the extremely gentle slope of the intertidal sandflats of Tràigh Luskentyre extends inland. The western coastal edge is backed by a nearly continuous foredune ridge of up to 10 m high, except in the south where the foreshore is backed by an undercut old and stable machair surface. Towards the north of the peninsula a healthy and prograding foredune ridge with extensive marram *Ammophila arenaria* cover has developed, although this becomes subject to wave undercutting towards a low sand-spit that extends north from the tip of the peninsula. The spit is highly dynamic and can lose much of the tip in a single storm, followed by a period of slow rebuilding. Where the spit begins to curve to the north-east, a few small blowthroughs have now been sealed by the development of foredunes across their seaward entrances (MacTaggart, 1997c). The dunes of the east face of the peninisula are lower than in the west but are subject to wave undercutting at high tide so that bare sand slopes characterize much of the Tràigh Luskentyre shore. Most of the central core of the peninsula is composed of dune ridges of varying sizes, some of these well-vegetated features recurving north and east where the spit has extended. In the south of the peninsula, the dunes extend to cover most of the edge of the higher machair surfaces behind. These older machair surfaces support several dune ridges and escarpments that trend west–east across the peninsula but they also occur as flat-topped features or form gentle aprons over the surrounding slopes. To the east of the machair area a small area of saltmarsh has developed with mature features such as tidal creeks and salt-pans. The seaward edge is undercut but the landward edge grades into sloping machair surfaces.

Interpretation

There seems no reason to suppose that the development of the Luskentyre–Corran Seilebost system should be substantially different in its response to Holocene sea level and sediment supply constraints than other machair systems in the Western Isles such as, for example at Mangersta or Hornish. Holocene sea-level rise slowed to a much reduced rate post-6500 years BP (Hansom and Angus, 2001). Although the start dates varied, the general trend is that the mid-Holocene was a time associated with an influx of sediments and extensive beach and dune development. However, ongoing sea-level rise (progressively exacerbated by land subsidence in the Western Isles) coupled with reductions in the offshore sand supply has subsequently resulted in erosion of many Hebridean beaches and the frontal undercutting of the sand dune and machair systems that they support.

Events at Luskentyre–Corran Seilebost appear to have followed this general trend, albeit exacerbated by two local effects. The low-gradient offshore zone resulted in a substantial and easily accessible source of beach and dune sediments, and the shelter offered by Taransay resulted in an essentially benign wave environment conducive to beach development within what had become a drowned tidal inlet. As a result the inlet became the locus of deposition with beach development at its entrance. Features of coastal deposition commonly occur where wave refraction reduces the capacity of waves to convey sediment. The swash-aligned orientation and location of Corran Seilebost can be explained in this manner. Similarly waves from both north and west influencing Luskentyre might also be expected to produce the triangular foreland of Corran Raah, on the lee shore of Taransay. In spite of the shelter afforded by Taransay, the extent and height of the dune and machair surfaces on both sides of Tràigh Luskentyre is impressive and, in the context of the inlet as a whole, Ritchie and Mather (1970b) suggested that the unusually shaped and sited twin promontories might represent fragments of a much more extensive dune and machair system. This hypothesis suggests that the original beach and dune probably developed only slightly seawards of the present location but that the machair surface may have extended over much of what is now Tràigh Luskentyre. Remnants of this machair surface fringe parts of Tràigh Luskentyre some distance inland, for example at Crago and farther east (Figure 9.14). Submergence over the later Holocene subsequently resulted in erosion of the fronting beach and dune, fragmentation of the fronting system and the submergence of Tràigh Luskentyre. The original direction of wind-blow within the enlarged system may have had a substantial westerly bias but once fragmentation occurred, the northern part of the system may have become more influenced by southerlies that drove blowthrough corridors northwards, a process that continues today. In addition, the seaward edges of the Seilebost saltmarsh are undercut and have a very similar appearance to wet machair. Submergence may have resulted in the conversion of a low-lying machair to what was reported by Dargie (1998) as a saltmarsh community with excellent examples of transitional saltmarsh–machair communities at its landward margin. Coring of the intertidal flats and saltmarshes may help resolve some of the above uncertainties. The outcrop of calcarenite below low water at Luskentyre may suggest submergence and/or retreat, since the formation of such crusts may be related to deposition or re-deposition of calcium carbonate under fluctuating water tables.

In the above scenario, the 'spit' of Corran Seilebost has not been formed by longshore drift from south–south-west, but by submergence of a more extensive dune-machair system and is not a true spit. In addition, the location of the estuarine channel will have influence on the extent and timing of erosion of both Corran Seilebost and Luskentyre.

Conclusions

Together the twin peninsulas of Luskentyre and Corran Seilebost represent a highly dynamic beach–dune–machair system that is one of the most scientifically interesting areas in the Western Isles. Not only do the sites contain the best examples in Harris of most of the features of machair landforms, but they have also formed in an unusual setting. It is possible that the present sites represent the remnants of a once more extensive beach–dune–machair system that has become fragmented by submergence. If this is the case, then the sites have added significance since they may form part of a suite of machair sites in the Western Isles that record, in the various stages of development of their landforms, a cycle of growth and decay that has affected machair over the Holocene Epoch.

MANGERSTA, LEWIS, WESTERN ISLES (NB 008 308)

Introduction

Mangersta Sands occupy a small embayment situated on the exposed west coast of Lewis, near Uig (see Figure 9.1 for general location). A 200 m-wide beach fronts a long, narrow machair that occupies a depression running inland. Mangersta is an excellent example of a beach–dune–machair complex in which much of the dune has been eroded and the machair surface has been deflated down to the water table. Little of the stripped surface has been re-colonized by vegetation and it seems likely that Mangersta represents an advanced stage in the cycle of growth and decay of beach–dune–machair complexes in exposed areas.

Description

The beach at Mangersta extends to 200 m in length and at low water is 200 m wide. It is contained within rock headlands cut into Lewisian gneiss and sits within a valley that is probably part of a pre-glacial drainage system (Ritchie and Mather, 1970b) (Figure 9.16). The low-gradient intertidal beach is composed of well-sorted, medium-grained sands (median diameter 0.39 mm), 38% of which is shell. The upper beach is characterized by a steeper-gradient arcuate storm ridge composed of subrounded gravel, through which water seeps from the surfaces behind. The gravel ridge is 100 m long and 20 m wide. A continuous cordon of frontal dunes behind the beach is lacking at Mangersta and

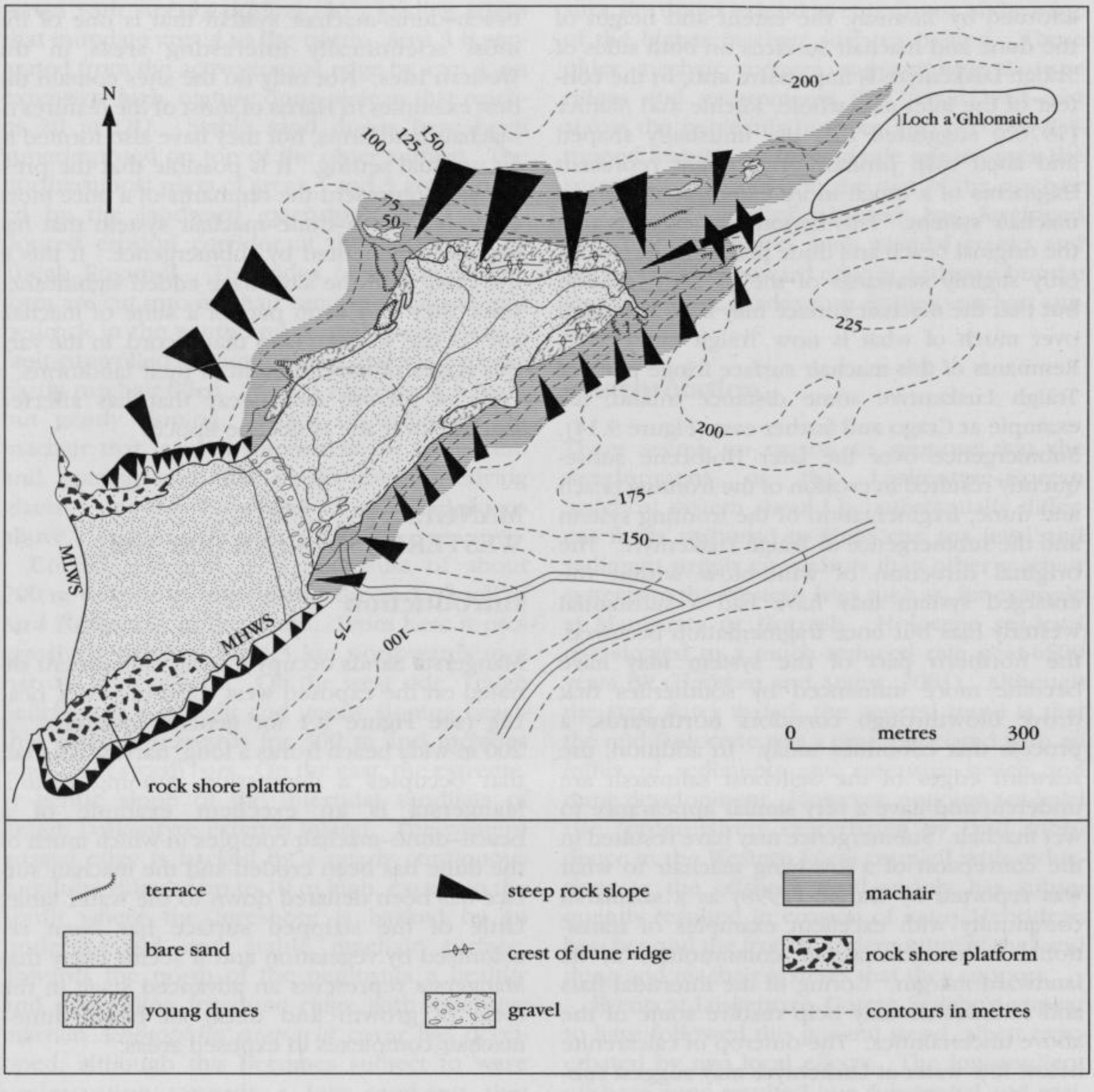

Figure 9.16 The geomorphology of the small embayment of Mangersta, Lewis. A narrow beach separates an area of low-lying sand from the sea. Mangersta is an example of a machair complex that has been eroded and deflated down to the water table. (After Ritchie and Mather, 1970b.)

only in the southern part are poorly developed and discontinuous young dunes found. Extending for at least 500 m inland of the gravel storm ridge at Mangersta, is a flat and bare sand surface that is deflated to the water table. The seaward part of the surface is littered with drift-wood and a series of small braided streams cross the low-gradient (1°) slope (Figure 9.17). The flat-floored deflation surface abuts landwards against the steep rocky slopes surrounding the depression, the abrupt change of gradient being masked by small marram-clad sand dunes. In spite of new dune development and re-vegeta-tion around the perimeter of the depression and to a limited extent around storm debris just above mean high-water spings, much of the cen-tral sand area was unvegetated in 1970 (Ritchie and Mather, 1970b) and remained so in 2001 when the photograph Figure 9.17 was taken. Most of the flanking dune orientations reflect deposition by winds from the south-west. A thin veneer of machair occurs on all of the

Figure 9.17 The central deflated surface of Mangersta viewed from the north-east. Climbing machair veneers the flanking slopes and occasional washover of the fronting beach occurs during storms. (Photo: J.D. Hansom.)

surrounding hill-slopes above the central depression. The lower parts of the machair are terraced in places indicating that they have undergone erosion in the past, although much of the contact is obscured beneath the younger flanking dunes. The thin layer of hill machair is undergoing active erosion by runoff, and in places the underlying glacial till cover is visible in stream cuttings (Figure 9.17).

Interpretation

In common with much of the Western Isles, coastal development at Mangersta has been dominated by sea-level change and the availability of sediment. Throughout most of the Holocene Epoch, sea-level rise has resulted in transgression of the seaboard of the Western Isles. Although dates vary between locations in Scotland, it is generally thought that sea-level rise slowed after 6500 years BP (Hansom and Angus, 2001). A large influx of coastal sediments is thought to have occurred in response to the slowing of sea-level rise and beaches developed with sufficient excess sand available on the upper profile to be blown into the extensive dune and machair systems that remain active today (Ritchie, 1971; Hansom and Comber, 1996). However, ongoing sea-level rise, coupled with reductions in the offshore sand supply, subsequently resulted in chronic erosion of many Hebridean beaches and the frontal undercutting of the sand dune and machair systems that they support. The events at Mangersta appear to have followed this general trend, albeit exacerbated by local effects. The wider Mangersta coastline is characterized by cliffs cut into resistant rocks and so the potential sources of beach sediment are restricted to adjacent glaciogenic deposits. Since both the onshore and offshore extent of the Mangersta valley is limited (deep water exists close inshore at Mangersta), the amount of glaciogenic sediment available from both sources was probably also very restricted. It seems likely that given an initially limited supply of sediment, any beach development would eventually suffer sediment supply problems as the supply became exhausted. In the exposed wave and wind environment of Mangersta this situation may have been achieved earlier in the cycle of machair development and erosion than has occurred elsewhere.

The extent of hill machair at Mangersta, and the occurrence of erosional terraces at lower levels of the hill machair suggests that the central area once supported a machair surface probably sited landwards of a dune cordon behind the beach. The deflation of the central depression behind the beach is likely to be attributable to a reduction in the rate of sediment supply from an already restricted offshore contributing area. Reduction of beach sand leads to starvation and eventual removal by wind erosion of the landward dune area. The flat machair surfaces behind these dunes then underwent deflation down to either an underlying gravel basement or to the water table. Since the machair at Mangersta is crossed by streams and is often wet, it appears to have deflated down to the water table. Severely deflated machair occurs at several other sites in both the Western Isles and in the north-west Highlands, but nowhere is the amount of stripping so complete as at Mangersta (Ritchie and Mather, 1970b). The emplacement of the arcuate storm ridge on the upper beach at Mangersta may be a relatively recent development, since the ridge obscures any eroded frontal edge of the central machair depression. The gravels remain relatively unrounded and so have been relatively unaffected by wave abrasion. However, it may be that the gravels are part of a poorly-developed storm beach thrown up before the build-up of sand and subsequently exhumed from beneath the dune cover. Field visits in 2001 indicated that small amounts of gravel had been artificially added to the ridge in an attempt to reduce the likelihood of washover.

Conclusions

The causes of the severe deflation at Mangersta are not known with certainty, nor are the start and end dates of stripping episodes. For example, the effect of land-use practices or of rabbit-induced erosion cannot be discounted. Whatever the reason, Mangersta is the best example of stripped machair in Scotland, and so probably in the world. It seems likely that the fundamental and underlying cause for deflation and stripping may be related to the progressive exhaustion of a locally limited sediment supply. Mangersta may thus represent an advanced stage in the cycle of growth and decay that, to varying extents depending on the local conditions, may characterize all beach–dune–machair complexes.

TRÀIGH NA BERIE, LEWIS, WESTERN ISLES (NB 103 360)

Introduction

Tràigh na Berie is one of the largest beach, dune and machair complexes on the Isle of Lewis in the Outer Hebrides of Scotland (Ritchie and Mather, 1970b; see Figure 9.1 for general location). Set in the rugged terrain of the ice-scoured Lewisian gneiss, Tràigh na Berie is relatively sheltered and contains a spectacular assemblage of soft coastal landforms including a wide beach, dunes, machair plain and hill machair. The coastal edge in the west and extreme east is now marked by erosion whereas the central part of the beach is experiencing accretion and embryo dunes characterize the coastal edge. Actively accreting dunes are unusual in Scotland and thus are of considerable geomorphological interest. The key geomorphological interest of Tràigh na Berie lies in the dynamism of the inter-relationships between the individual landform components of beach, dune, and machair.

Description

Tràigh na Berie, on the north-east side of the Valtos peninsula, is a wide 1.5 km-long sand beach extending in a long smooth curve between the rocky headlands of Sròn a'Chnip to the west and Stung to the east. Both headlands and the surrounding terrain are composed of resistant Lewisian gneiss. Behind the beach a wide dune and machair system extends inland onto steep ice-scoured slopes of gneiss. A linear depression cutting across the Valtos peninsula has been infilled with sand (Tràigh Teinish) which extends to a small beach to the south. A number of small lochs, located between the bedrock to the south and the advancing machair, are gradually being infilled by blown sand (Ritchie and Mather, 1970b; Figure 9.18). The main beach has a north-east aspect, facing into the relative shelter of Loch Roag. The adjacent coastline is highly crenulate and additional shelter is afforded to Tràigh na Berie by many small

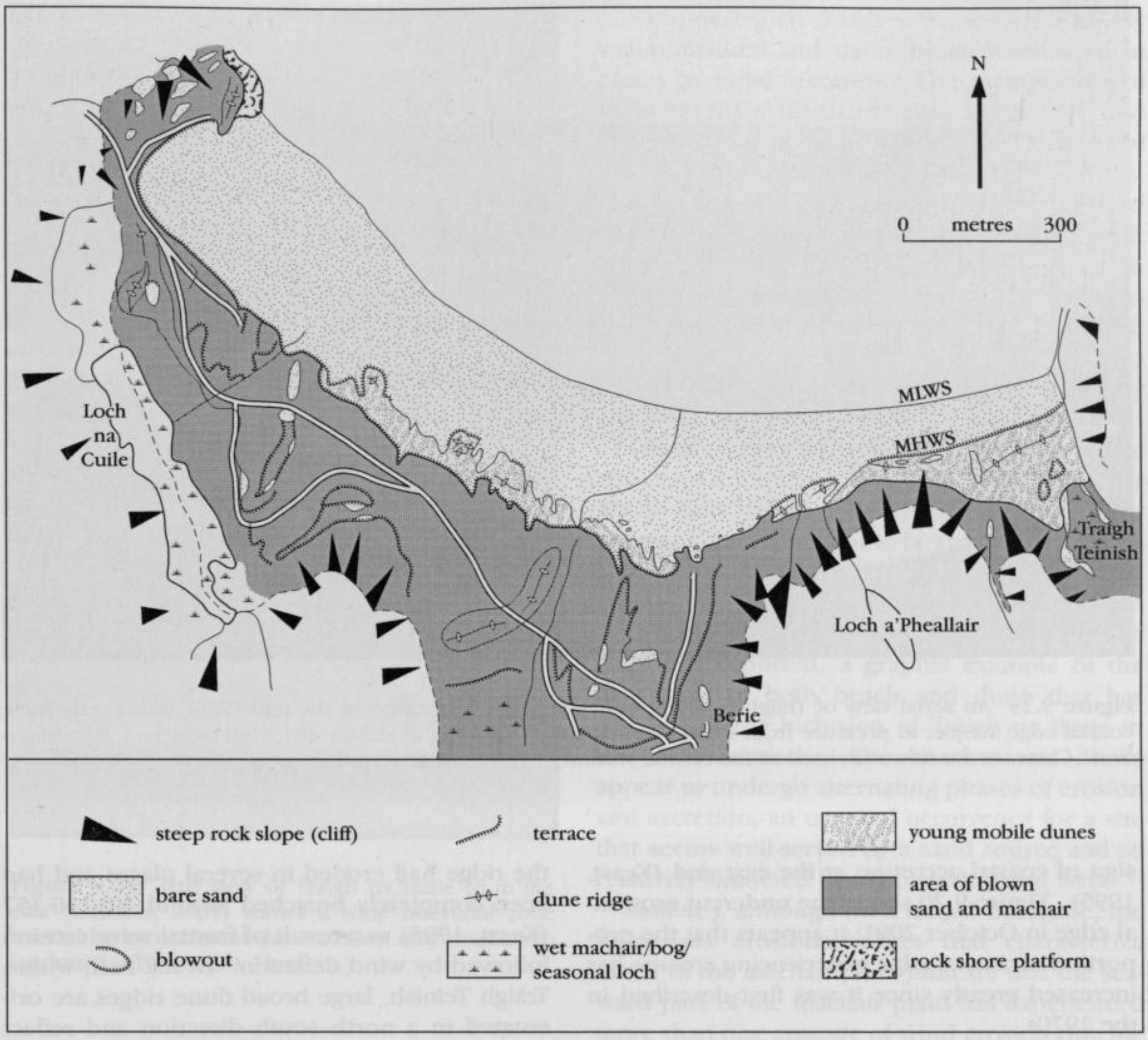

Figure 9.18 The geomorphology of Tràigh na Berie showing a mainly eroding coastal edge (see Figure 9.20). Several small lochs that lie behind the machair surfaces are subject to infill by blown sand. (Modified from Ritchie and Mather, 1970b.)

islets, the largest of which lie to the north-west and north-east (Figure 9.19). The sand at Tràigh na Berie beach is composed of fine, shell-rich sand of median diameter 0.2 mm and 47% calcium carbonate content. The upper beach, which forms the nourishment zone for the dune system, is over 50 m wide in the west but narrows to only 15 m in the east (Ritchie and Mather, 1970b). In spite of these intertidal widths, in 1970 the coastal edge in the extreme west was marked by a low sand-cliff, between 1–3 m high, eroded into machair and with no foredunes to the seaward side (Ritchie and Mather, 1970b). In contrast, the eastern end in 1970 was marked by rapid accretion with large quantities of sand accumulating in the form of broad dune ridges up to 12 m high across the mouth of the Tràigh Teinish depression. In view of this, Ritchie and Mather (1970b) suggested an easterly drift of sediment and an anticlockwise rotation of the beach arc, a view echoed by Ramsay and Brampton (2000e). However, by July 1994 most of the eastern coastal edge was undercut and showing signs of erosion. The development of embryo dunes was localized to only one central section of the beach, with little

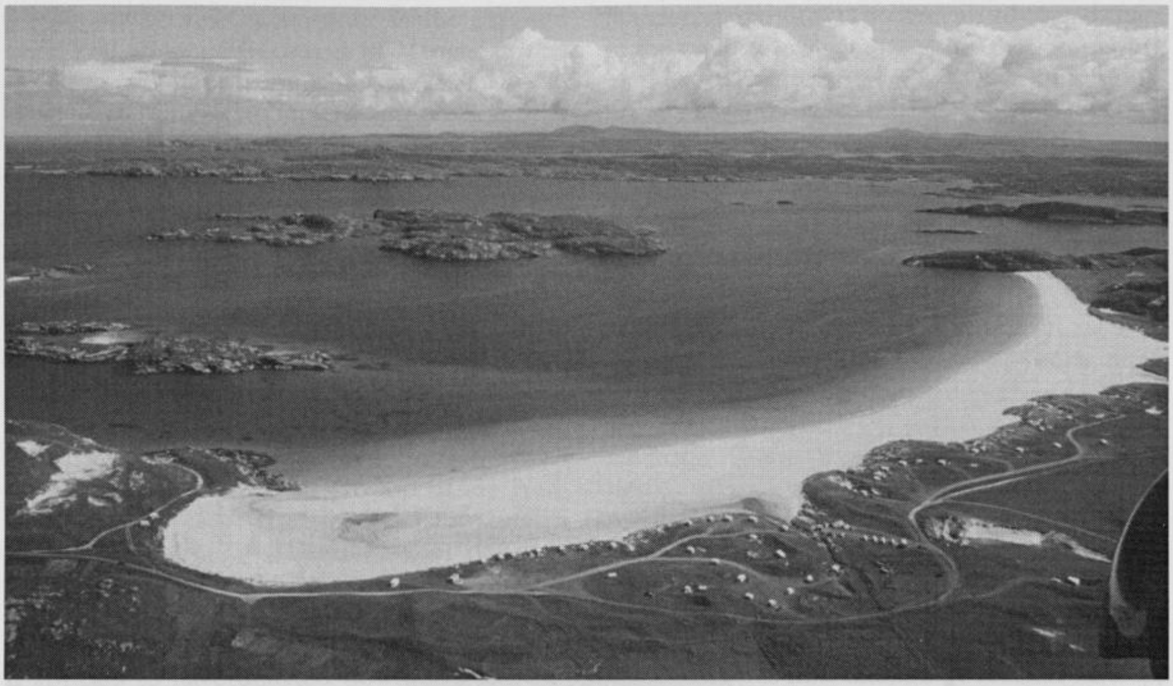

Figure 9.19 An aerial view of Tràigh na Berie from the south-west taken in the mid-1980s shows a dynamic coastal edge subject to pressure from tourist caravans and resulting in substantial wind-blow and destabilization. Caravans are now restricted to the central section of the dune and machair area. (Photo: S. Angus.)

sign of coastal accretion at the east end (Keast, 1995). Figure 9.20 shows the undercut erosional edge in October 2001; it appears that the proportion of coastal edge experiencing erosion has increased greatly since it was first described in the 1970s.

Dune forms are best developed in the central–eastern part of the site (Figures 9.18 and 9.20) where the coastal edge is characterized by low mobile dunes, up to 5 m high but which increase in height towards the east (Keast, 1995). Along parts of this foredune ridge, wave undercutting has exposed parts of the dune face that are now subject to wind erosion and deflation. In 1970 the dune face in the central part of the beach was accreting with embryo dunes developing into short north–south-trending dune ridges separated by stretches of bare sand that coalesce in places to form continuous, coast-parallel foredune ridges (Ritchie and Mather, 1970b). In 1970 these embryo and foredunes abutted discontinuously against an abandoned machair edge, suggesting that the period of rapid foredune accretion observed in 1970 post-dates a previous period of machair erosion (Ritchie and Mather, 1970b). However, by 1995 the ridge had eroded in several places and had been completely breached around NB 110 357 (Keast, 1995) as a result of frontal wave erosion followed by wind deflation. In the east, within Tràigh Teinish, large broad dune ridges are orientated in a north–south direction and reflect the topographical channelling of winds.

Seawards of the beach and dune zone a wide machair plain, characterized by numerous erosional edges most of which are now healed, extends inland to the steep, ice-scoured gneiss slopes. The machair impounds several small lochs, which are gradually being infilled by blown sand to form marshy depressions. A major erosional terrace lies over 400 m landward of the high-water mark and separates the machair into two major units (Figure 9.18). The larger area of machair lying to the seaward side of the scarp is flat and scarred by numerous small and low erosional edges. The smaller machair unit to landward of the edge slopes gently landwards and grades into the wet machair, marshes and impounded lochs. Farther inland considerable areas of hill machair have developed on the steep gneiss slopes. In places the hill machair is eroded and blowthroughs and

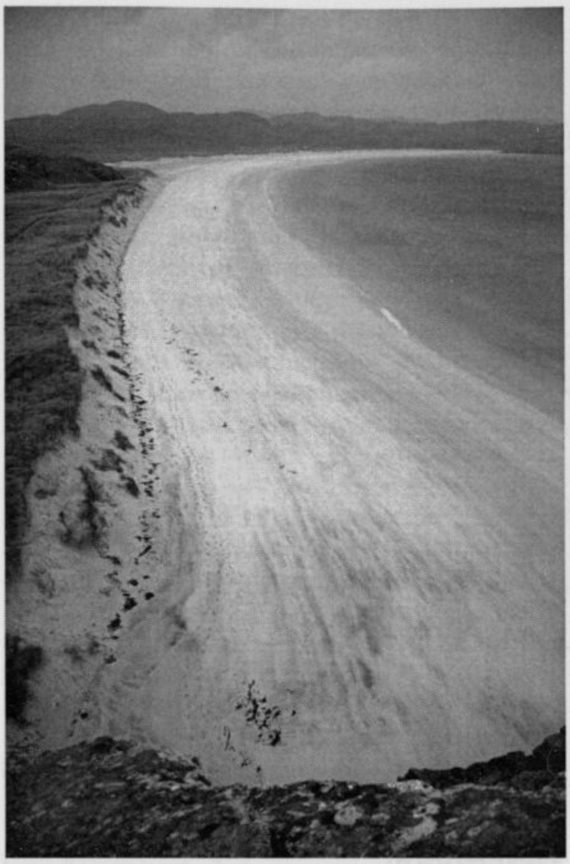

Figure 9.20 This view of Tràigh na Berie from the east (October, 2001) shows a wide intertidal zone backed by an undercut dune cordon and machair to landward. (Photo: J.D. Hansom.)

exposed sand cliffs are present. At the extreme east end of the site, behind the coastal dune cordon, a level area of machair lies close to the water table.

Interpretation

Tràigh na Berie is a small basin that has become infilled with sand driven onshore by a rising sea level during the late Holocene. Since there is no evidence that gravel ridges underlie the beach, it can be assumed either that gravels were not a major constituent of the source materials or that gravel ridge development failed to occur, probably on account of the low levels of wave energy within the bay. It may also be the case that if the sand budget at Tràigh na Berie has been positive until recently, any gravel ridges still remain to be sectioned and exposed. Ritchie and Mather (1970b) described Tràigh na Berie as a relatively well-nourished and stable beach dominated in places by rapid accretion. The main source of sediment to the beach and dune system was, and still is, derived from the sand-covered seabed of West Loch Roag (Ritchie and Mather, 1970b). The high proportion of shell-derived beach sand suggests a significant offshore sand source but it is unknown whether the supply of sand at Tràigh na Berie has diminished recently. There is morphological evidence to suggest that the beach undergoes temporary changes from accretion to erosion and that the beach is currently mainly erosional (Figure 9.20).

The erosion of the machair edge in the west and rapid dune accretion in the east observed by Ritchie and Mather (1970b) led them to suggest that the beach appeared to be rotating in an anticlockwise direction. However, when re-examined in 1995 and 2001, this tendency was not obvious and erosion of the east and west ends was reported, a graphic example of the dynamism of both beach and dune that has resulted in the inclusion of Tràigh na Berie in the GCR network. The beaches and dunes appear to undergo alternating phases of erosion and accretion, an unusual occurrence for a site that seems well-served by a sand source and so relatively sheltered from both wind and wave.

Similarly, although on a longer timescale, the numerous erosional edges that characterize much of the machair plain indicate that the seaward part of the machair plain has experienced more than one episode of wind erosion (Ritchie and Mather, 1970b). The eroded machair scarp in the centre of the beach, which was fronted by actively accreting foredunes in 1970, may be the most recent expression of an erosional system that involves not only short cycles of alternate wind-generated scarp erosion and machair deflation down to the water table, but also of wave-generated frontal erosion of the seaward edge. The relative shelter of the site, plus its apparently healthy sand source may be the main reason why this beach–dune–machair system has not yet undergone the chronic frontal erosion found elsewhere on the more exposed shores of the west coast of the Hebrides. In this respect, Tràigh na Berie conforms with the model proposed in Figure 9.3 of the introduction to this chapter, with its dune cordon undergoing erosion but still largely intact. The sand removed from the dunes and machair edges is deposited elsewhere within the system. Although it remains to be fully investigated, the evidence of past erosional episodes within the machair is of great importance in the understanding of the way in which machair systems evolve over time.

It is possible that a contributory cause of the present instability in the central section of Tràigh na Berie is related to the impact of tourists using the beach (Angus and Elliott, 1992; Ramsay and Brampton, 2000e). Access through the dunes and machair to the beach certainly exacerbates erosion of the low machair faces at the western end of the beach. Wind erosion and re-deposition in the central section of the dune is also exacerbated by the presence of caravans within the dunes and the high density of pedestrian tracks over the dunes. However, the main cause of instability appears to be frontal erosion by waves and its subsequent effect on blowthrough development. The main drivers behind this situation are more likely to be sea-level rise and sediment supply than human impact.

Conclusions

Tràigh na Berie is a large spectacular beach–dune–machair unit set in an area of rugged gneiss upland, a very different setting from the open machair plains typical of the Uists. The geomorphology is controlled by a complex of inter-related marine and aeolian processes resulting in an extremely dynamic and variable system. The complexity of inter-relationships and vigour of processes is of very high geomorphological importance. Tràigh na Berie is of particular interest because it contains evidence of several stages of dune development as well as evidence of past erosional episodes in the machair plain. Tràigh na Berie is of outstanding importance in the context of elucidating machair evolution.

BALNAKEIL, SUTHERLAND (NC 390 700)

Introduction

The *c*. 3 km-long peninsula of An Fharaid encloses Balnakeil Bay and lies at the entrance to the Kyle of Durness, 15 km east of Cape Wrath on the extreme north-west tip of the Scottish mainland (see Figure 9.1 for general location). It contains a magnificent and spectacular array of beach and dune erosional and depositional landforms ranging from undercut dune faces to large and active dune blowthroughs. Large blowthrough corridors and transgressive sand waves carry windblown sand across the An Fharaid peninsula from the beaches on the west coast to cascade over a prominent cliff on the east, a landform assemblage unique in Britain if not in Europe. The wide, steep-sided, blowthrough corridors are up to *c*. 25 m deep and up to *c*. 400 m long (Figure 9.21). Mature machair vegetation has stabilized much of the higher blown sand deposits in the north and east of the peninsula leading to a marked contrast between these stable machair slopes and the lower altitude, highly active dunes and blowthrough corridors. The dunes of Balnakeil are some of the most active in Scotland and display important interactions between wave erosion and undercutting of the dune-toe and the effect of high velocity winds in driving the eroded dune sand inland and uphill. However, in spite of the clear geomorphological interest and importance of this site, it has attracted only limited scientific research, and much of the following description and interpretation is drawn from Ritchie and Mather (1969) and Hansom (1998).

Description

Balnakeil beach occupies the west side of the isthmus that connects the An Fharaid headland with the mainland to the north of Durness (Figure 9.21). The *c*. 3 km-long peninsula of An Fharaid consists of a block of gneiss tilted towards the south-west and connected at its southern margin to a similarly tilted block composed of schist beyond which the Durness limestones crop out (Ritchie and Mather, 1969). The blocks provide an inclined plane up which large quantities of sand are blown in a north-easterly direction from the beach and from frontal dunes undergoing erosion. The peninsula is up to 1.5 km wide close to the headland in the north, but narrows to *c*. 400 m in its central section at NC 390 700. The west coast is cliffed from NC 385 708 north to An Fharaid headland while the east coast is entirely cliffed with only a few small pocket beaches. The sand has a mean diameter of 0.292 mm with 52% of this being composed of calcium carbonate derived from shells (Ritchie and Mather, 1969). The spectacular assemblage of cliff, beach, dune and machair forms of the peninsula can best be described in two sections.

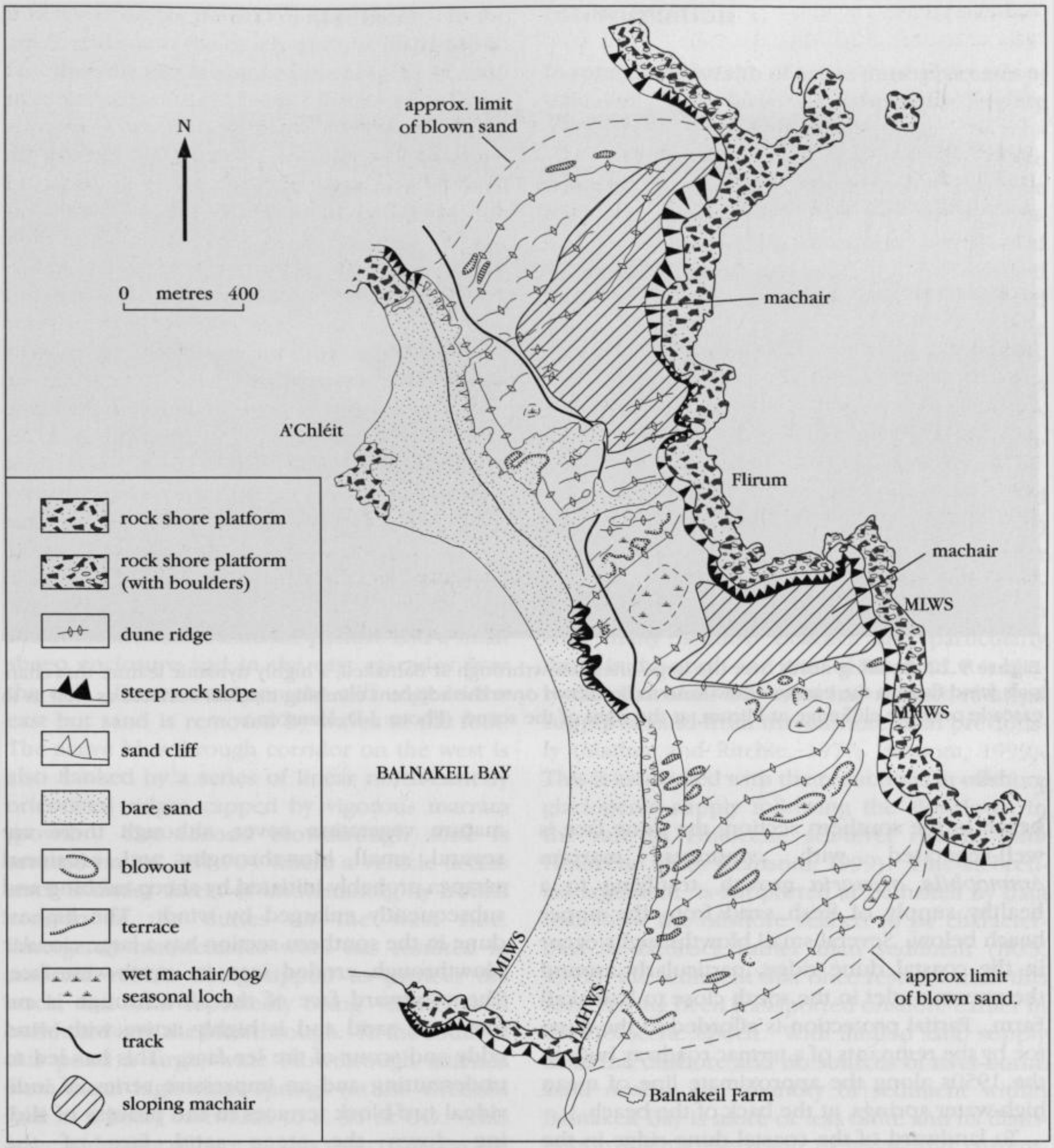

Figure 9.21 The geomorphology of Balnakeil–An Fharaid is dominated by the easterly transport of blown sand from the beaches of Balnakeil Bay into dune and machair surfaces that climb the slopes of the An Fharaid peninsula. Some of the larger linear blowthroughs channel sand to cascade over the cliff on the eastern edge of the peninsula. (After Hansom, 1998.)

The southern section includes the wide intertidal sand beach of south Balnakeil Bay and the mature dune system that extends across the peninsula to cliffs on the east coast. A broad, *c.* 10–15 m-high, coast-parallel dune ridge backs the 220 m-wide sandy beach and is erosional over much of its length. Although there is evidence of past wave-undercutting and basal slumping of the dune toe, the erosional contact is often covered by a small ramp of windblown sand to give the appearance of relative stability (Hansom, 1998). Higher up, to the rear of the

Figure 9.22 Looking north over the large linear blowthrough at Balnakeil, a highly dynamic feature that channels wind flow to the east to allow sand to be blown onto the adjacent climbing machair surfaces as well as to cascade over the cliff edge at Flirum, at the right of the scene. (Photo: J.D. Hansom.)

beach in the southern section, the dune face is well-vegetated with vigorous marram *Ammophila arenaria* growth, testifying to a healthy supply of fresh sand from the upper beach below. Several small blowthroughs occur in the coastal dune ridge, particularly around the stream outlet in the south close to Balnakeil Farm. Partial protection is afforded to the dune toe by the remnants of a tarmac roadway built in the 1950s along the approximate line of mean high-water springs, at the back of the beach.

To landward of the coastal dune ridge in the southern section, the undulating mature dunes are low in the west but increase in height as the system extends eastwards across the peninsula to climb An Fharaid headland as a thin machair cover. Damp dune slacks are common within the lower parts of the dune system and support wet machair vegetation communities. The bedrock surface is low in the west where it is veneered by sand but rises in the east to substantial cliffs of *c*. 30 m OD. The dune ridges trend in a north-easterly direction and reach heights of up to *c*. 20 m in places. They are mainly stable at present and support a mature vegetation cover, although there are several small blowthroughs and erosional scrapes probably initiated by sheep-rubbing and subsequently enlarged by wind. The highest dune in the southern section has a large circular blowthrough eroded into its north-west face. The windward face of the blowthrough is cut into bare sand and is highly active with wind eddy and scour of the lee face. This has led to undercutting and an impressive series of individual turf-block terraces in the process of sliding down the steep sand face of the blowthrough.

The northern section is the narrowest part of the peninsula and extends from Flirum on the east and the rock protuberance on the west coast, which separates Balnakeil Bay beach into a southern and northern section, to the rocky slopes north-east of the intertidal skerry of A'Chléit (Figure 9.21). The geological structure of this section consists of a low rocky slope rising from sea level in the west to up to 50 m-high cliffs near Flirum in the east. The skerry of A'Chléit is connected to the mainland by an intertidal sand tombolo, and acts as an intertidal pinning point for the 200 m-wide beach. To the north and south the beach width is restricted to less than 50 m. In spite of the volume of sand that has accumulated in the shelter of A'Chléit, the upper beach is erosional in this central section, with only a narrow beach at high tide. Exposure to north-westerly waves has resulted in undercutting and destabilization of the *c*. 15 m-high mature dunes that back the narrow beach, linear erosion of the dune toe–upper beach interface and the development of steep erosional faces in the bare sand of the dunes. The associated removal of dune-face vegetation has resulted in blowthrough activity in two main areas. One of these, centred on NC 390 702, continues through the peninsula east to Flirum and comprises large, steep-sided, linear blowthrough corridors that rise from sea level on the west shore to *c*. 30 m OD on the east shore (Figure 9.22). The presently unvegetated blowthrough feeds sands directly from Balnakeil Bay into a large transgressive sand wave that in the north inundates machair pasture and a small sheep enclosure and in the east cascades over the cliff. Dunes occur on the cliff edge in the east but sand is removed by waves at the foot. The active blowthrough corridor on the west is also flanked by a series of linear north-easterly orientated ridges capped by vigorous marram growth. The second blowthrough zone is centred on NC 387 704 where a vehicle access track is under threat of undermining by frontal erosion of the dunes on the west side. Emergency maintenance work has resulted in assorted rubble being tipped to protect the track, and sand repeatedly being cleared and bulldozed into the blowthrough. To the south of this point a large, wide blowthrough extends from mean high-water springs (at the wrecked hull of a boat) eastwards to *c*. 30 m OD. This large wide area of bare sand is punctuated at the western end by the upstanding remnants of old fixed dunes, complete with vegetation cap that are now eroded on all sides to produce pinnacles ranging in height from 3 m to 15 m. Landwards of the blowthrough vigorous marram growth has led to stabilization of the dune surfaces. A distinct boundary exists between the lower surfaces stabilized by marram *Ammophila arenaria* and the higher surfaces to the east charcterized by machair grassland. This boundary is likely to be mobile with rapid sand inundation favouring marram encroachment of machair.

Interpretation

In spite of the wealth of active dune processes at Balnakeil, with large blowthroughs feeding transgressive sand waves that allow sand to travel from the beaches on the west coast across the peninsula to cascade down the high cliffs on the east coast, the site has attracted surprisingly limited geomorphological research. Ritchie and Mather (1969) and Hansom (1998) described the geomorphology of the site and highlighted the importance of aeolian processes in both the past and present geomorphological development and evolution of the site, particularly in the central section. However, further geomorphological research at this spectacular and highly active site is clearly warranted.

Based on both theoretical considerations and field observations, Ritchie and Mather (1969) suggested a clockwise rotation of the beach over time with the erosion in the north being balanced by accretion in the south. In common with many Scottish beaches and particularly those in the north and west of Scotland, it is likely that Balnakeil Bay now has a much-reduced supply of sand from the offshore than previously (Mather and Ritchie, 1977; Hansom, 1999). This is associated with the reductions in offshore glaciogenic supply following the slowdown in the rate of Holocene sea-level rise in mid-Holocene times (Hansom, 1999). This theoretical argument is supported at Balnakeil by data that show the offshore seabed to be characterized by bedrock rather than sediment (BGS, 1991), the sediment that once rested within this zone having been transported onshore earlier in the Holocene Epoch. With limited sand supply from the offshore and no sources of river-borne sand nearby, the quantity of sediment within Balnakeil Bay is more or less finite and its distribution mainly the result of wave- and current-transport processes within the bay. The field observations that support the above view relate to the predominantly unidirectional waves that impinge on the beaches from the north-west and produce a southwards transport of sand. Some 20 years after the beach rotation suggestion of Mather and Ritchie (1977), similar landforms and processes were recorded by Hansom (1998) and so are clearly long-lived.

The northern beach remains narrow and waves access the base of the dunes regularly giving rise to chronic frontal erosion and slumping of the dunes above. Given the wave refraction patterns within Balnakeil Bay, much of the sand-loss is to the south but significant amounts of sand are also lost by wind-blow to the backing dunes via blowthrough corridors. The northern part of Balnakeil Bay is likely to operate at a budgetary loss in terms of sand input and output. However, in spite of an apparently rapid rate of erosion and dune-toe recession in the north, there is also some evidence suggesting that wave attack of the dune face may not be as rapid as supposed. In-situ timbers from the hull of a boat wrecked on the northern beach over 100 years ago are still exposed at MHWS, although the dune toe has receded a few metres beyond this (K. MacRea, pers. comm., 1996.).

In contrast, Mather and Ritchie (1977) noted accretion in the southern part of Balnakeil Bay, where both the intertidal zone and the upper beach are wider. Refracted waves break on the shore more or less simultaneously, and although longshore transport out of Balnakeil Bay into the Kyle of Durness to the south occurs, it is probably limited. This may not have been the case earlier in the Holocene Epoch, and there is evidence that the sand budget in the south of the Kyle of Durness was sufficient to feed wind-blown sand to South Balnakeil via the now-stabilized sand sheets on top of the intervening peninsula to the west of Balnakeil Farm. As a result, it is likely that the southern part of Balnakeil Bay is a partial sediment-trap, although the amount of sand transported to and from the southern part of the bay is unknown. Storm wave activity on the south beach probably results in onshore–offshore sediment exchanges, and this is the likely reason why there is evidence of not only accretion but also erosion on the south beach. The eroded remnants of a tarmac access road built by the Ministry of Defence in the 1950s runs along the back of the beach. Within a year of construction, the roadway was undermined by wave erosion and abandoned (K. MacRea, pers. comm., 1996). Since then, rather than being buried by sand accretion, its foundations remain exposed and in places subject to minor undermining by waves. The presence of the foundations now provide protection to the dune toe from wave undercutting, although vigorous marram growth on the seaward faces of the well-vegetated dunes above indicate a healthy blown-sand supply from the beach below (Hansom, 1998).

Wave-induced frontal erosion of the dune toe creates the conditions for wind-induced point erosion and blowthrough activity, since wave undercutting of the mature dunes backing the northern beach removes vegetation and allows unrestricted wind access to the bare sand surfaces. Wind deflation and sand transport has resulted in large areas of bare sand and massive blowthrough corridors that extend over *c.* 400 m from the west coast of the peninsula to cascade in sandfalls over the eastern cliffs. The range of large- and small-scale wind erosional and re-depositional features within this system is spectacular and of immense scientific interest. The stabilized linear dune-ridges that flank the active, steep-sided blowthroughs provide evidence that until recently the ridges were the sides of large active blowthrough corridors which are now naturally stabilized by vegetation. This suggests a long-lived process that undergoes small shifts in location leading to time-transgressive zones of alternating erosional activity and vegetational stability.

Conclusions

Balnakeil Bay contains some of the most dynamic dune forms in Scotland. The rock-floored peninsula tilts towards the south-west, providing an inclined plane up which large quantities of blown sand progress in a north-easterly direction. Large, steep-sided and highly active blowthrough corridors feed transgressive sand waves that transport sand across the peninsula from the beaches on the west to cliffs on the east. It is possible that an earlier transgressive sand- wave system operated on the rocky peninsula between the Kyle of Durness and southern Balnakeil Bay. Sand cascades down the eastern cliffs and is effectively lost from the Balnakeil system. Mature machair vegetation has stabilized the blown sand veneer at higher altitudes, and the juxtaposition between this and the marram-dominated highly active ridges associated with the blowthrough corridors is striking and of great geomorphological interest. Balnakeil Bay is characterized by the juxtaposition of a range of dune erosional processes and landforms within a setting that is unparalleled in Britain, if not in Europe.