



## Sea level, climate change and coastal evolution in Morar, northwest Scotland\*

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### Abstract

Analyses of geomorphologically contrasting sites in Morar, NW Scotland, describe the forcing mechanisms of coastal change. Isolation basins (i.e. basins behind rock sills and now isolated from the sea following isostatic uplift) accumulated continuous marine and freshwater sediments from c.12 to 2 ka BP. Raised dune, marsh and wetland sites register breaching, migration and stability of dunes from c. 9 to 2 ka BP. High-resolution methods designed to address issues of macroscale and microscale sea-level changes and patterns of storminess include 1-mm sampling for pollen, dinocyst and diatom analyses, infra-red photography, X-ray photography and thin-section analysis. The data enhance the record of relative sea-level change for the area. Major phases of landward migration of the coast occurred during the period of low sea-level rise in the mid-Holocene as the rate of rise decreased from c. 3 to < 1 mm/year. Relative sea-level change controls the broad pattern of coastal evolution at each site; local site-specific factors contribute to short-term process change. There is no record of extreme events such as tsunami.

Within a system of dynamic metastable equilibrium, the Holocene records show that site-specific factors determine the exact timing of system breakdown, e.g. dune breaching, superimposed on regional sea-level rise. The global average sea-level rise of 3 to 6 mm/yr by AD 2050 predicted by IPCC would only partly be offset in the Morar area by isostatic uplift of about 1 mm/yr. A change from relative sea-level fall to sea-level rise, in areas where the regional rate of uplift no longer offsets global processes, is a critical factor in the management of coastal resources.

### Introduction

Recent investigations of isolation basins (i.e. basins behind rock sills and now isolated from the sea following isostatic uplift) and wetland sites in north-western Scotland between Loch Morar and Kentra Moss (Figure 1) provide a record of relative sea-level change and coastal evolution from c. 12 ka BP to the present (Shennan et al. 1993, 1994, 1995a, b, 1996a, b). Sediments accumulated in wetland environments landward of sand-dune systems at Mointeach Mhor

and Glenancross. These sediments record phases of breaching, migration and stability of dunes. Mointeach Mhor and Glenancross are significant sediment sinks on a coastline characterised by sea-lochs and rocky headlands exposed to westerly storms. Isolation basins are also significant sediment sinks, incorporating autochthonous biogenic, and allochthonous minerogenic sediments. The latter include both terrestrial sediments from the freshwater catchment and marine sediments transported across a sill into the basin. Analysis of isolation-basin sediments (e.g. Shennan et al. 1994, 1995a) shows continuous sedimentation during

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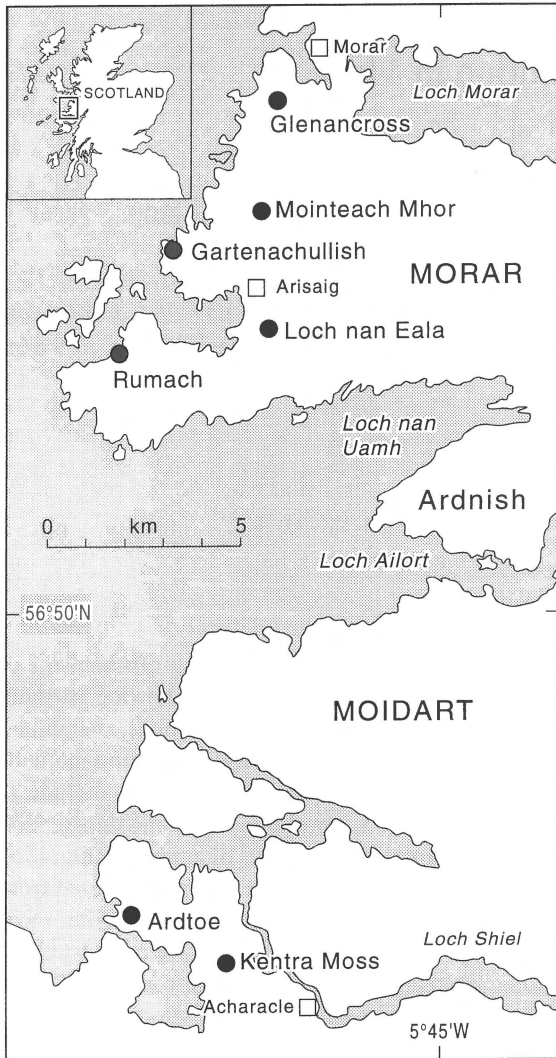


Figure 1. Isolation basins and wetland sites (all shown by ●; settlements shown by □) in northwest Scotland between Loch Morar and Kentra Moss.

marine and freshwater phases and through the transitions between each phase. Sediments and microfossils within the isolation basins contain records of climate, environment and relative sea-level changes. The record of relative sea-level change through the Holocene provides a baseline for investigation of the forcing mechanisms of coastal change at nearby wetland sites that register breaching, migration and stability of dunes. Major geomorphological and sedimentological changes occurred in wetlands at Mointeach Mhor and Glenancross during the mid-Holocene but the sea-level record from isolation basins is poorly defined during that period (Shennan et al. 1995a). We selec-

ted two new sites, Gartenachullish and Rumach VI, to investigate further the forcing mechanisms of coastal change. The results have a wider application within the project 'Climate Change and Coastal Evolution in Europe' (De Groot & Orford this issue).

## Aims

The project 'Climate Change and Coastal Evolution in Europe' has five aims: to identify the relative effects of short-term sea-level changes, patterns of storminess and extreme flooding events on coastal processes; to identify the impact of changes in relative sea level and in patterns of storminess upon sediment delivery to the coastal systems; to investigate the links and relationships between the rates of long-term (century to millennium scale) and short-term (year, decade to century scale) coastal processes; to develop new techniques in the investigation of coastal sequences; and to assess the implications of the results for coastal management. We address these aims by combining the results of investigations at two new sites, Gartenachullish and Rumach VI, with data from previous investigations (Shennan et al. 1993, 1994, 1995a, b, 1996a). At Gartenachullish biogenic and minerogenic sediments accumulated behind a raised sandy dune or beach ridge. Analysis of the sediments provides an explanation for the major coastal changes at the site, relating climate and sea-level change to dune, beach and wetland development. At Rumach VI there are over 10 m of fine-grained minerogenic and biogenic, marine and freshwater sediments in a basin landward of a rock sill at 4.8 m OD. Shennan et al. (1993, 1995a, 1996a) present the results of investigations from the other five basins at Rumach.

## Techniques

Lithostratigraphic data were collected using a hand-gouge, and described using the scheme of Troëls-Smith (1955). All cores are levelled to OD (national datum), with a closing error of  $\pm 0.01$  m. Following completion of the transects a 50 mm diameter piston corer was used to collect all samples for laboratory analyses. Preparation of samples for pollen, diatom and radiocarbon analyses followed standard procedures, including modifications to give microfossil concentration estimates (Battarbee & Kneen 1982, Palmer & Abbott 1986, Moore et al. 1991). Frequencies of

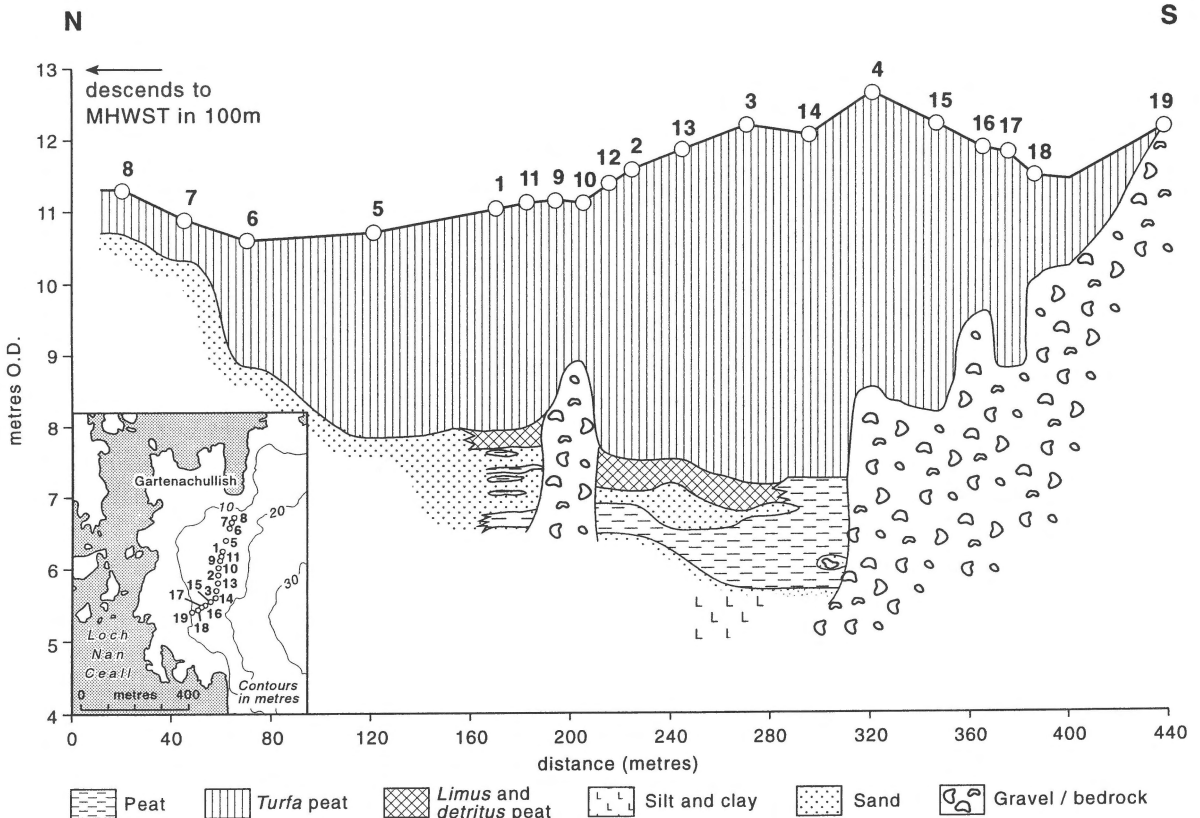


Figure 2. Gartenachullish generalised stratigraphy, simplified from field notes recorded with Troëls-Smith (1955) descriptions. North of core GA95-8 the sand surface, with an organic topsoil, descends to the present shoreline within 100 m. Southwest of core GA95-19, which is the lowest exposed point of the gravel ridge, the ground surface descends to the present shoreline within 200 m.

pollen and diatoms are expressed as percentages of total land pollen (% TLP) and total diatom valves (% TDV), respectively, based on a minimum count of 200. Diatom salinity groups follow the halobian classification system (Vos & de Wolf 1993). The raw data are available from the first author. High-resolution pollen and diatom sampling (1 mm scale) was completed over selected intervals of the Rumach VI cores together with infra-red photography, X-ray photography and thin-section analyses. For each thin section, point counts from an eye-piece grid give percentage estimates of sediment composition based on counts of 300 per level. Conventional and AMS (Accelerator Mass Spectrometry) radiocarbon ages supported by pollen data provide the chronology. All ages refer to radiocarbon years before present unless stated otherwise.

## Gartenachullish

### Lithostratigraphy

The generalised stratigraphy of this wetland site (Figure 2) comprises a series of minerogenic and organic layers between a gravel ridge at the southern end of the section and a sand beach or dune ridge at the northern end. The deepest core, GA95-13, ended in a blue to grey clay (lithologically similar to Lateglacial deposits from other sites in this area) while other cores ended in sand or gravel. The deepest organic unit is a black to brown herbaceous peat, recorded between GA95-14 and GA95-1. The peat is overlain by sand. The thickest sand recorded is in core GA95-1 where it contains a series of thin sandy peat layers. The base of the sand was not reached in any cores north of GA95-1 so it is unknown how far the thin sandy peat layers extend. A scanning electron microscope (JSM-IC 848) was used to analyse the surface morphologies of the sand grains in core GA95-1. The conchoidal fractures of the

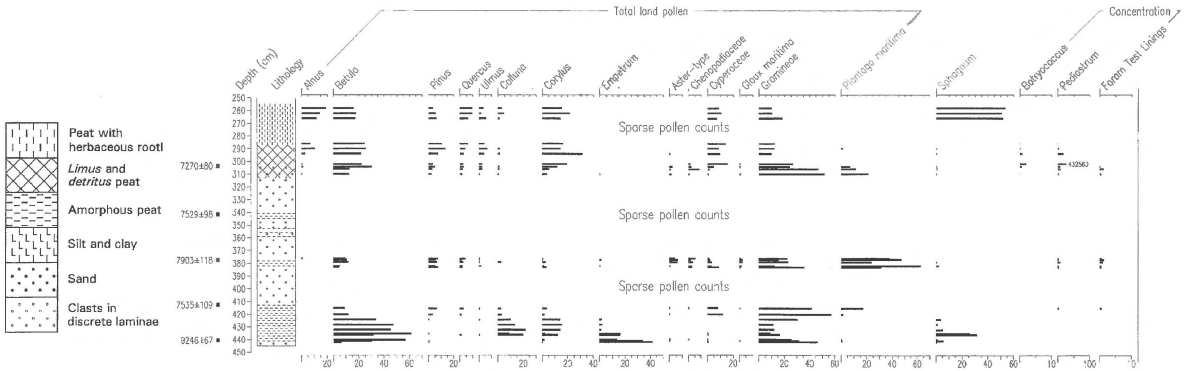


Figure 3. a. Pollen diagram from Gartenachullish core GA-95-1. Only major taxa are shown, full data are available from the first author. Total land pollen are shown as % TLP counts. *Botryococcus* and foraminiferal test linings are shown as concentrations of grains ( $10^4 \text{ cm}^{-3}$ ). *Pediastrum* is shown as concentration of grains ( $10^3 \text{ cm}^{-3}$ ). At level 302 cm, the *Pediastrum* concentration is shown numerically. Radiocarbon dates as in Table 1. The lithology section contains detail not shown on Figure 2; symbols follow Troëls-Smith (1955). b) Lithology key for microfossil diagrams (Figures 3a, 4, 6, 7, 10, 11).

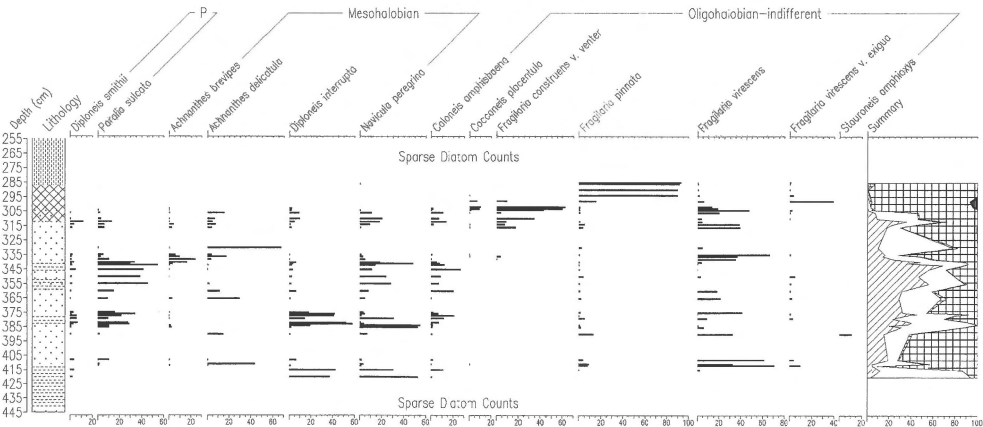


Figure 4. Diatom diagram (% TDV, total diatom valves) from Gartenachullish core GA95-1. Lithology section as in Figures 3a, b. Only those diatom species >10% TDV are shown; full data are available from the first author. Radiocarbon dates as in Table 1. Key for summary graph of halobian groups on right edge of diagram: diagonal lines =  $\Sigma$  polyhalobian (P) species, white =  $\Sigma$  mesohalobian (M) species, horizontal lines =  $\Sigma$  oligohalobian-halophile (O-H) species, cross-hatch =  $\Sigma$  oligohalobian-indifferent (O-I) species, solid =  $\Sigma$  halophobe (H) species.

grains, together with their stratigraphic position, indicate a subaequous depositional environment (personal communication, R.J. Allison). Above the sand there is a ‘limus’ (microscopic organic particles or colloids sedimented in water, Troëls-Smith, 1955) and then an herbaceous and bryophyte ‘turfa’ peat (peat with roots and stems, Troëls-Smith, 1955) which grades into the present raised bog community.

Core GA95-1 was selected for laboratory analyses because the multiple sand and peat layers provided the best opportunity to study a series of coastal changes.

*Biostratigraphy and chronostratigraphy*

The pollen assemblage in the lower peat of core GA95-1 (445–410 cm) is dominated by *Betula*, *Empetrum* and Gramineae (Figures 3a, b). This assemblage is consistent with the early Holocene radiocarbon age (Table 1). In the middle of the lower peat *Calluna*, *Corylus* and *Sphagnum* rise. Within the top 10 cm of this peat *Pinus* and *Quercus* rise, along with Cyperaceae, Gramineae and *Plantago maritima*. The latter are good evidence for development of a salt-marsh environment. This is corroborated by the diatom assemblage in the upper part of the lower peat which is dominated by *Diploneis interrupta* and *Navicula peregrina* (Figure 4). Both of these species are

Table 1. Radiocarbon dates from Gartenachullish, core GA95-1

Laboratory code	Depth cm	Altitude m OD	$^{14}\text{C}$ yr BP $\pm 1\sigma$	cal. BP $\pm 2\sigma$ (probability of date within range)	Comment
UB-4031	302–304	7.99–7.97	7270 $\pm$ 80	7900–8180 (1.00)	Transition from salt-marsh to freshwater limus at c. 20 cm above MHWST* $\pm 20$ cm. Negative sea-level tendency.
UB-4032	340–342	7.61–7.59	7529 $\pm$ 98	8110–8440 (0.98)	Intra-sand peat, probably reworked.
UB-4033	376–378	7.25–7.23	7903 $\pm$ 118	8420–8990 (1.00)	Intra-sand peat, probably reworked.
UB-4034	411–413	6.90–6.88	7535 $\pm$ 109	8110–8440 (0.98)	Salt marsh peat, forming c. 20 cm below MHWST, but altitude lowered by overburden of sand. Positive sea-level tendency.
UB-4035	439–441	6.62–6.60	9246 $\pm$ 67	10040–10360 (1.00)	Base of lowest peat in section. Formed above the limit of highest tides.

\* MHWST = Mean High Water of Spring Tides.

typical salt-marsh diatoms. Foraminiferal test linings are also recorded. The assemblages indicate a positive sea-level tendency within the upper part of the peat, dated  $7535 \pm 109$  BP.

The sand lies above the lower peat with a sharp boundary. There is no recovery of significant numbers of pollen from the lower sand unit (410–385 cm). Diatoms show a mixed assemblage of oligohalobian (e.g. *Fragilaria virescens*), mesohalobian (e.g. *Achnanthes delicatula*) and polyhalobian (e.g. *Paralia sulcata*) species. The thin intra-sand peat at 383–376 cm yields a pollen assemblage very similar to that from the upper part of the lower peat, but dominated by salt-marsh taxa such as *Plantago maritima*, with abundant foraminiferal test linings. Between 390 and 325 cm the diatom assemblages in all the thin sand and peaty units are mixed although the summary graph shows an increase in polyhalobian species in the middle of the section. *Paralia sulcata* and the mesohalobian benthic taxa *Diploneis interrupta* and *Navicula peregrina* indicate regular tidal inundation and nearby salt-marsh environments. The presence of *Fragilaria virescens* indicates standing fresh or low-salinity water. Overall we interpret the sand unit, together with the thin peaty layers, as indicating mobilisation of sand into a shallow embayment. The entrance to the embayment,

from the north, was probably choked with sand, with a shallow body of water landward. The thin peaty layers are probably reworked from the basal peat during the transgression of the sea into the shallow embayment. This would explain the microfossil assemblages and radiocarbon ages for the layers between 383 and 340 cm.

From the upper part of the sand unit, above 316 cm, into the overlying limus, the mixed diatom assemblage gives way to a freshwater assemblage dominated by *Fragilaria* species. This represents a negative sea-level tendency that is corroborated by a decline in the abundance of *Plantago maritima* pollen and foraminiferal test linings and a rise in Gramineae, tree pollen and the freshwater alga *Pediastrum*. The freshwater limus, the base of which is dated  $7270 \pm 80$  BP, indicates a body of shallow water behind a sand body now large enough to exclude inundation by tides and storm waves. A transition through the herbaceous peat to a *Sphagnum*-dominated pollen assemblage (285–265 cm) reveals the development of a raised bog community.

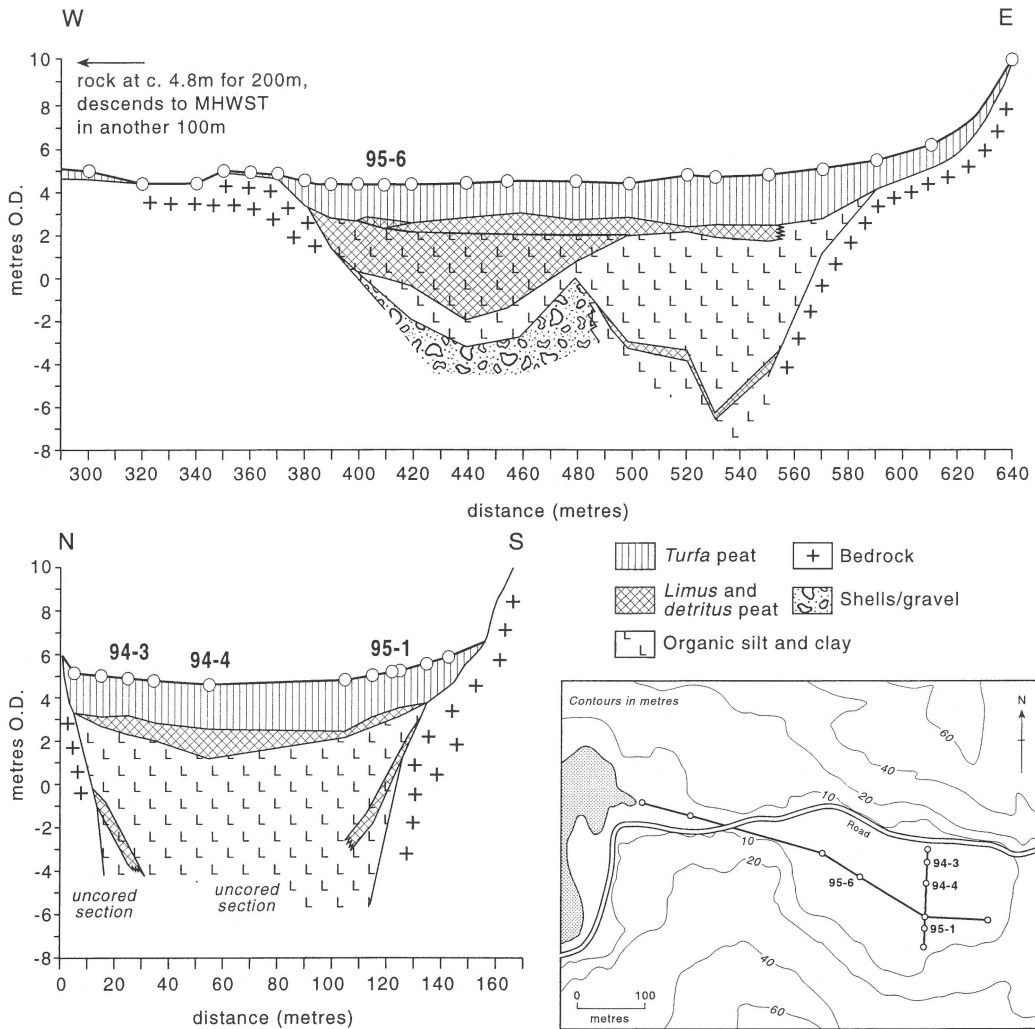


Figure 5. Rumach VI stratigraphy. The site map shows only the location of the boreholes used for laboratory analyses and those marking the orientation of the two sections illustrated. Over 200 boreholes were used to describe the stratigraphy and morphology of the basin.

**Rumach VI**

*Lithostratigraphy*

The general lithostratigraphy of the basin is summarised on Figure 5. The section from the long axis of the basin shows the broad rock sill at 4.8 m OD. Basal sediments near the rock sill consist of shelly gravels. They are overlain by an organic grey silty clay that grades up into an olive-green limus. In the deeper, eastern part of the basin there is a lower limus and a lower, less organic silty clay. These lower units are not identified nearer the rock sill, because either they lie too deep to be sampled or, in the case of the cores nearest the rock sill, they are absent. The transect from

north to south clearly shows the lower limus getting deeper away from the margins of the basin, and rapidly becoming too deep to be reached with the hand coring equipment used. The lower limus grades upwards into the organic silty clay present throughout the basin. Most cores then record the gradual transition from this thick silty clay to an upper olive-green limus which is overlain by ‘turfa’ peat.

The lithostratigraphy and sill altitude suggest that Rumach VI should provide a record of sea-level and environmental change comparable to the main basin at Loch nan Eala, 4 km to the east (Shennan et al. 1994; Figure 1). The sill of the latter basin was disturbed by engineering works during the last century



Table 2. Radiocarbon dates for sea-level index points from Rumach VI

Core RVI-	Laboratory code	Depth cm	$^{14}\text{C}$ yr BP $\pm 1\sigma$	cal. BP $\pm 2\sigma$ (probability of cal. date within range)	RWL m OD	IR m	Comment
95-1	Beta-91307	390	10290 $\pm$ 60	11720–12390 (1.00)	1.2	0.5	Isolation contact
94-3	SRR-5489	842–845	9005 $\pm$ 55	9890–10040 (1.00)	1.8	0.5	Positive sea-level tendency within lower limus
94-3	SRR-5488	821–824	8790 $\pm$ 70	9540–9920 (1.00)	1.2	0.5	Positive sea-level tendency near top of lower limus
94-4	Beta-91306	585	5690 $\pm$ 50	6401–6637 (0.96) 6345–6371 (0.03)	–1.5	0.4	Start of the final isolation
94-4	Beta-91305	420	4760 $\pm$ 40	5448–5589 (0.80) 5329–5378 (0.17) 5384–5401 (0.03)	–1.0	0.4	Stage within the final isolation
94-3	SRR-5487	287–289	3350 $\pm$ 70	3400–3720 (0.99)	1.2	0.4	Stage within the final isolation
94-4	Beta-91304	210	2670 $\pm$ 50	2732–2863 (1.00)	2.0	0.4	End of the final isolation

AMS samples have Beta laboratory codes; RWL estimated present altitude of the reference water level (m OD) of the sea-level index point; IR indicative range of the sea-level index point (m). For further discussion of reference water levels and indicative ranges see Shennan et al. (1995a). It is possible that different reference water levels and indicative ranges would apply to basins significantly smaller than Rumach VI.

around 3350  $\pm$  70 BP. Occasional mesohalobian diatoms within an otherwise freshwater assemblage show that only rare high tides, and probably storm surges, entered the basin by 2670  $\pm$  50 BP. Later text sections describe the results of high-resolution studies of selected sections of the transition from the fully marine to freshwater phases.

### Relative sea-level change

All the radiocarbon-dated samples from Rumach VI fulfil the criteria for sea-level index points. The indicative meaning of a sea-level index point consists of the 'reference water level' (i.e. the palaeo-tide level

represented by the dated sample) and the indicative range (i.e. the vertical error term in estimating the reference water level). The series of dates and microfossil assemblages from the final isolation, between 5690  $\pm$  50 and 2670  $\pm$  50 BP, record different positions in the tidal cycle as the basin is gradually cut off from the sea. Earlier work recognised this but gave no quantitative values, e.g. Kjemperud (1986). Also, Kjemperud studied sites in an area where the present mean spring tidal range is 1 to 2 m, compared to over 4 m on the Morar coast. Shennan et al. (1995a) suggested that individual index points from isolation basins may have reference water levels as different as highest astronomic tides (+2.9 m OD) and mean high water of neap tides (+1.2 m OD). With the data from

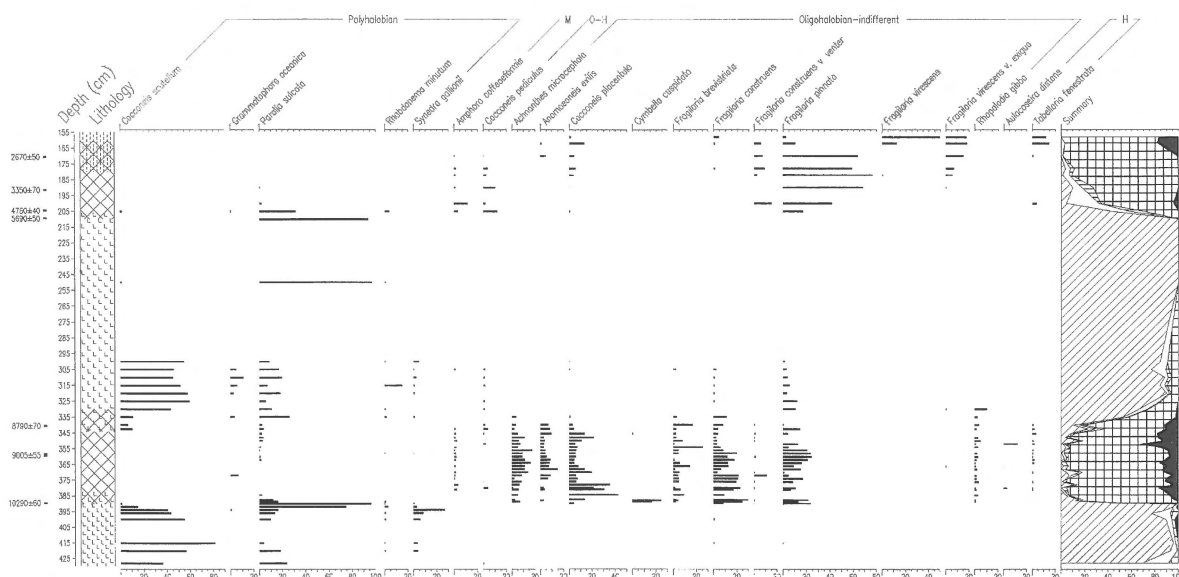
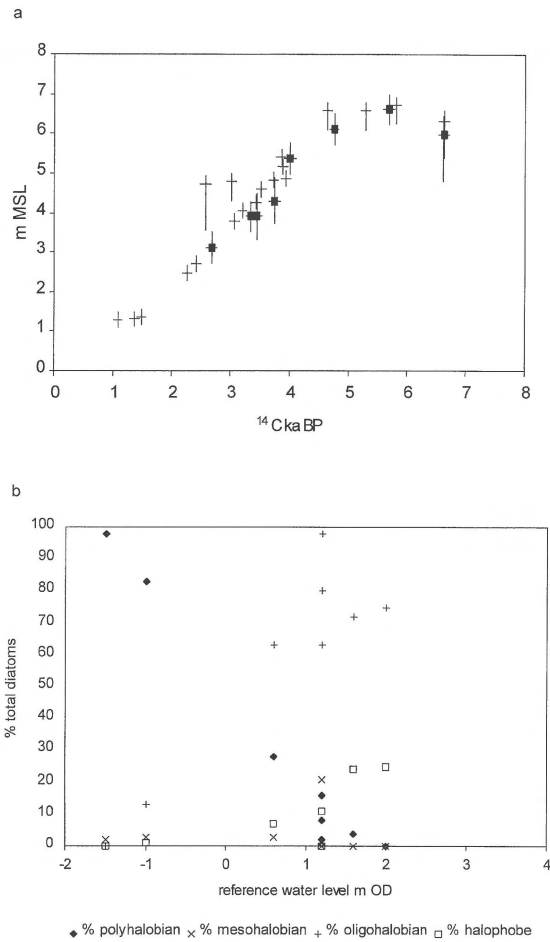


Figure 7. Diatom diagram (% TDV) from the section 155–427 cm of Rumach VI core RVI95-1 containing the upper and lower limus. The lithology section contains detail not shown on Figure 5; for legend see Figure 3b. Only those diatom species >10% TDV are shown; full data are available from the first author. Key for summary graph of halobian groups on right edge of diagram, and abbreviations, as for Figure 4.

Rumach VI we now suggest that the differences are greater (Figure 8; Table 2). Shennan et al. (1995a) noted the range of factors that influences salinity in the basin during an isolation, or connection, process. They stress the need for additional work on isolation basins in macrotidal environments, especially studies of present-day examples and hydrological modelling in order to quantify the indicative meanings of different samples. There is some, but not sufficient, progress on these issues. In the present study we estimate the indicative meanings for different stages of the isolation and connection processes by calibrating the reconstructed palaeo-sea levels at Rumach VI and Loch nan Eala (Shennan et al. 1994) against independent calculations of palaeo-sea level obtained from other sites. Comparable contemporary environments present at Kentra Bay (Shennan et al. 1995b) provide precise estimates of relative sea-level change from raised tidal marshes at the adjacent Kentra Moss (location on Figure 1). Modelling studies show that the pattern and magnitude of relative sea-level changes in the Kentra Moss area are very similar to those at Morar (e.g. Lambeck 1995). A final constraint is the stratigraphic order of the index points from the same core and associated changes in microfossil assemblages. In combination these data suggest reference water levels between approximately mean low water of neap tides to a few decimetres below mean high water of spring

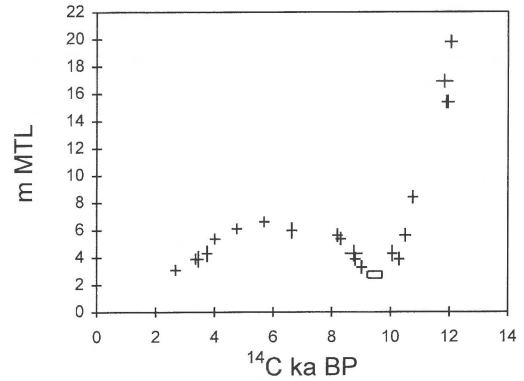
tides. Diatom salinity-class frequencies show a clear relationship with reference water level (Figure 8b). We make new estimates for reference water levels for previously published index points based on diatom frequencies. These estimates produce sea-level index points consistent with independent reconstructions of sea-level change (Figure 8a), constrained by the assumption that palaeotidal ranges were similar to present. Radiocarbon-dated samples in previous studies consisted of 3 to 5 cm sections of sediment. Where these samples contain large changes in diatom salinity class frequencies the indicative range of the sea-level index point increases.

The isolation basin data provide a summary of relative sea-level changes from 12 to 2 ka BP (Figure 9). From 12 to 10 ka BP relative sea-level fell at c. 9 mm/ $^{14}\text{C}$  yr (c. 8 mm/cal. yr). The apparent reversal of the two index points just before 10 ka BP is a result of using conventional radiocarbon techniques on a 4 cm thick sample of sediment (Shennan et al. 1994) to date the isolation of the main basin at Loch nan Eala compared to an AMS date on < 1 cm of sediment to date the isolation of Rumach VI. The Rumach VI index point is the more reliable due to both the use of a smaller sample for dating and the difficulty of identifying the sill of the main basin at Loch nan Eala (Shennan et al. 1994).



**Figure 8.** Calibration of reference water levels for sea-level index points from isolation basins at Loch nan Eala (Shennan et al. 1994, 1995a) and Rumach VI. Data from other basins, for pre-7 ka BP, are not used because of the lack of index points from tidal marsh environments. a) Sea-level index points from isolation basins (■) using the reference water levels and indicative ranges shown in Table 2, plotted against sea-level index points from raised tidal marshes and wetlands (Shennan et al. 1995a). b) Diatom salinity-class percentages for sea-level index points from isolation basins plotted against reference water level (present Mean High Water Spring Tides = 2.4 m OD; Mean High Water Neap Tides = 1.2 m OD; Mean Tide Level = 0.3 m OD; Mean Low Water Neap Tides = -0.5 m OD; Mean Low Water Spring Tides = -1.9 m OD). It is possible that different reference water levels and indicative ranges would apply to basins significantly smaller than Loch nan Eala and Rumach VI.

The dinocyst and diatom evidence from the lower limus at Rumach VI, described above, show that highest tides and surges crossed the sill throughout the accumulation of this layer. This constrains the altitude of the early Holocene relative sea-level minimum, corrected to mean tide level, to c. 2.5 to 3.0 m OD, assuming a palaeotidal range similar to today. The



**Figure 9.** Sea-level index points from isolation basin data in Morar. All data relative to Mean Tide Level (for reference water levels see Figure 8 and Table 2). Microfossil data from the lower limus at Rumach VI (see text) constrain the altitude of the early Holocene minimum to c. 2.5 to 3.0 m (shown by the open rectangle). Error bars include  $\pm 2\sigma$  for the radiocarbon age and the sum of the altitudinal errors associated with individual index points. Those data which plot above 8 m are from relatively small isolation basins and their reference water levels and indicative ranges cannot be independently calibrated at present (cf. Figure 8). Reference water levels could be up to 1 m higher than those in Table 2 and Figure 8.

age and altitude of the early Holocene minimum vary spatially and the variation is a major parameter for validating regional scale models linking earth rheology, ice sheets and sea-level change.

Sea level then rises at a rate of c. 3 mm/ $^{14}\text{C yr}$  between 9 and 8 ka BP (for this and all subsequent rates the calibrated rates are the same as the uncalibrated rates, within the  $\pm 2\sigma$  limits). From 8 ka BP to no later than 5.7 ka BP the rate of rise is very low, less than 0.5 mm/yr on average. Evidence from the upper basin at Loch nan Eala shows that relative sea level continues to rise after a small oscillation at 6.6 ka BP (Shennan et al. 1994) and the first indication of a fall in sea level is from Rumach VI at  $5690 \pm 50$  BP. Sea level falls at about 1.5 mm/yr to c. 2 ka BP and afterwards, according to data from Kentra Moss (Shennan et al. 1995b), at around 1 mm/yr.

### Evidence of short-term changes

Cores in the deepest parts of Rumach VI, with continuous sedimentation in a low-energy sub-aqueous environment throughout most of the Holocene, provide an opportunity to document long chronologies of storminess and extreme flooding events if such short-term processes leave a trace in the sedimentary record. During the final isolation the average sedimentation rate

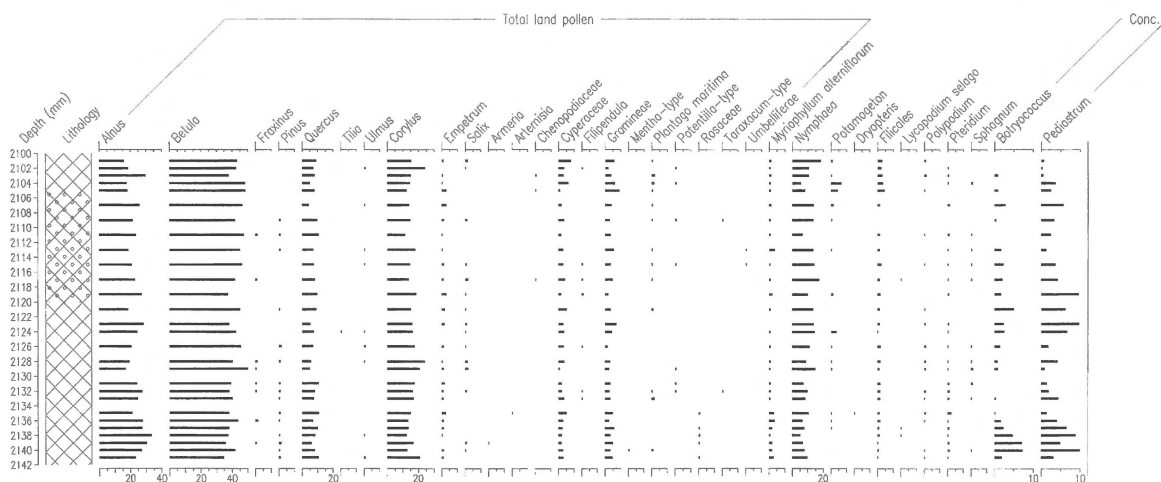


Figure 10. Pollen diagram (% TLP) from 2101–2141 mm in Rumach VI core RVI94-4 using 1 mm samples. The lithology column (legend in Figure 3b) highlights the concentrations of clasts (open circles), identified in X-ray photographs, within a silt clay limus (cross-hatching). Only those taxa >5% TLP are shown; full data are available from the first author. Algal taxa are represented as concentration of grains ( $10^4$  per gram of sediment).

at RVI94-4 (between the samples dated  $5690 \pm 50$  and  $2670 \pm 50$  BP) was c. 1.2 mm/yr. Therefore, it is possible to evaluate a record at an approximately annual resolution. Results from five experimental investigations follow, each designed to test whether an annual resolution records variations in storminess and flooding.

The first experiment encompasses a section towards the end of the isolation process when freshwater conditions prevail, with incursions of saline water only during rare extreme tides or intermittent storm surges. The pollen (Figure 10, 40 mm of sediment, equivalent to c. 50 yr) and diatom (Figure 11, 73 mm, c. 90 yr) data show a predictable trend from a weak basal marine influence (*Synedra pulchella*) to a strong freshwater influence (*Nymphaea* and *Potamogeton* pollen, oligohalobian and halophobe diatoms) towards the top of the section as the basin becomes completely isolated. There is little direct evidence for separate marine incursions from storm surges throughout this section. The origin of the cyclicity in the diatom record (2153–2105 mm, c. 60 yr) between benthic forms (e.g. *Anomoeonisis exilis*) and planktic forms (e.g. *Fragilaria virescens* v. *exigua*) is unknown. It may indicate variations in water depth, caused by changes in climate, hydrology or sea level. The cycles do not correspond to peaks in mesohalobian or polyhalobian diatoms. Between 2105 and 2120 mm, X-ray photographs reveal a concentration of clasts (Figures 10, 11); this interval corresponds with a slight increase in

mesohalobian diatoms (*Navicula digitoradiata*) suggesting a possible marine origin. Analysis of thin sections shows a small peak in the frequency of marine coralline red algae within the same interval but they show much greater peaks elsewhere, e.g. 2135–2160 mm, where there is neither X-ray evidence of concentrations of clasts nor peaks of mesohalobian or polyhalobian diatoms. Overall the X-ray, thin-section and high-resolution, 1 mm, biostratigraphic data do not provide comparable records of short-term marine incursions, of whatever origin or pattern, during the final stage of isolation.

Two further experiments on core RVI94-4, in the middle (2630–2730 mm) and at the beginning of the isolation process (5750–5850 mm, radiocarbon dates in Table 2), also failed to show objective evidence for either individual or grouped surges. Weak laminations, revealed in the X-ray photographs, result from concentrations of *Laminaria* spp. (seaweeds) fragments.

X-ray photographs of core RVI95-6, which is closer to the sill, reveal numerous discrete laminae. Analysis of thin sections shows that the clasts producing these laminations are composed mainly of quartz grains. Microfossil data show no significant changes at these levels (Figure 12). Therefore, there is no objective evidence to relate the formation of such laminae to storm activity. Other possible explanations include changes in sediment supply and tidal dynamics around the sill of the basin.



The conclusion from the series of experiments based on 1 mm sampling for pollen, dinocysts and diatoms, analysis of thin sections, X-ray and infrared photographs is that such methods fail to provide replicatable and consistent criteria for identifying either individual surge or extreme flooding events or groups of events.

### Origin of sediments at Rumach VI

Field investigations reveal evidence of slopewash at the edges of the Rumach basin, input from streams, and lag deposits close to the sill. However, the origin of the bulk of the sediments within similar basins during periods when they are connected to the sea is poorly known from previous investigations (Shennan et al. 1993, 1994, 1995a, 1996a) except that the presence of chains of some diatom species indicates growth *in situ* in the basin. Analysis of the thin sections, loss on ignition (% LOI) and microfossil-concentration data provide new information on the sources of sediment which infill the basins. Estimates from the thin-section analyses show that during the marine phase over 95% of the bulk sediment consists of clay, silt and amorphous organic material; LOI is c. 20%. The proportion of sediment composed of diatoms increases from < 5% during the marine phase to a peak of c. 20% midway during the isolation process, when LOI is 40%. At the end of the isolation process diatoms comprise 5 to 10%, and clay, silt and amorphous organic material 90 to 95% of the bulk sediment, with 55 to 60% LOI. There is little coarse minerogenic input into the basin, apart from lag deposits close to the sill and clastic laminae, identified in X-ray photographs, in limited sections of the cores. Fine-grained minerogenic input decreases during the isolation process.

### Discussion

The results of our studies in relation to the five aims mentioned above are discussed below.

#### *Short-term sea-level changes, patterns of storminess and extreme flooding events*

Isolation basins, including Rumach VI described here and those analysed previously (Shennan et al. 1995a, 1996a, b), register the macroscale and megascale records of sea-level change with minimal influence from

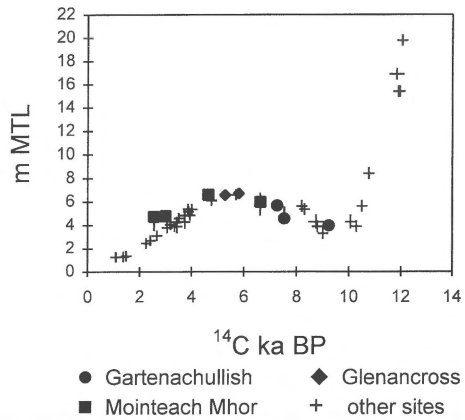


Figure 13. Radiocarbon-dated samples recording sea-level and coastal changes at Gartenachullish, Glenancross and Mointeach Mhor compared to relative sea-level changes (corrected to Mean Tide Level) derived from all sites shown in Figure 1. Error bars include  $\pm 2\sigma$  for the radiocarbon age and for the sum of the altitudinal errors associated with individual data points.

storms and surges. We find no record of extreme events such as tsunamis. The effects of short-term sea-level changes, such as individual storm events or periods of enhanced storminess that would alter the sedimentary regime within a basin, exhibit no clear biostratigraphic or lithological signal. Isolation basins reflect quiet-water deposition, with sedimentation rates frequently 1 to 2 mm/yr towards the centre of the basin (Rumach VI; Loch nan Eala main basin, Shennan et al. 1994), and register sea-level changes identifiable at different stages of connection and isolation.

Gartenachullish records a range of sea-level changes and coastal processes. Peat initiation at  $9246 \pm 67$  BP occurs during the early Holocene relative sea-level minimum (Figure 13). Sporadic occurrences of *Aster*-type, *Chenopodiaceae* and *Plantago maritima* pollen indicate the close proximity of salt-marsh but this is followed by a period characterised by *Calluna*, *Corylus* and *Sphagnum* when raised bog developed above the direct influence of sea level. The first unequivocal evidence for sea level controlling sedimentation is the replacement of these bog communities by first freshwater and then salt-marsh. Rising sea level is the forcing mechanism that controls this sequence. The burial by sand marks a significant change in sedimentation; this is coincident with a change in diatom assemblage. This suggests a sudden event, such as a storm, during which remobilised intertidal sand inundates the developing salt-marsh. The altitude of the dated sample from the top of the salt-marsh peat,

7535 ± 109 BP, plots below the trend of rising sea level (Figure 13) probably due to consolidation by the weight of the overlying sediment. Cleaned exposures in drainage ditches at Mointeach Mhor revealed many loading and dewatering structures in peat below as little as 20 cm of sand (Shennan et al. 1995a). Similar consolidation would operate at Gartenachullish; the sand is > 1m thick at GA95-1. Therefore the sample from the base of the organic sediments above the sand sequence is a more reliable sea-level index point, dated at 7270 ± 80 BP. The c. 1 m difference in altitude is not a record of rapid sea-level rise, but is caused by rapid loading of peat by sand. The isolation basin data reveal a slow sea-level rise at this time, less than 1 mm/yr.

Inundation at Gartenachullish occurs during the period of relatively slow relative sea-level rise (after 8 ka BP), not during the preceding period (8–9 ka BP) when rates of rise reach 3 mm/yr. Similarly Mointeach Mhor records a major phase of wetland inundation starting no earlier than 6625 ± 45 BP (Shennan et al. 1995a).

Rapid burial requires a short-term coastal process, such as a storm, barrier breaching, or overwash, overprinting on the longer-term coastal process of sea-level change. The impact of a disturbance, such as a storm event, imposed on a longer-term rise in mean sea level may result in the breakdown of the sedimentological system, followed by system recovery, i.e. renewed peat growth, once equilibrium becomes re-established (Shennan 1995). As the rate of sea-level rise slows down, the barrier re-establishes stability, allowing organic accumulation to re-commence at the back-barrier site. This occurs first and rapidly at the small system at Gartenachullish, but takes longer at Mointeach Mhor. Glenancross records only the stabilisation phase (Shennan et al. 1995a). The precise timing of any morpho-sedimentary change is also dependent upon the sediment supply to the coastal system.

#### *Relative sea-level changes, patterns of storminess and sediment delivery*

The relative sea-level curve (Figure 9) shows that there was no long period of relative sea-level rise leading to marine transgression across a large area of the present offshore zone around Morar. This contrasts with the majority of the Atlantic coasts of Europe and the USA for which transgression of the continental shelf characterises most of the Holocene epoch. Around Morar, sea level did not fall below the present level at any

time during the Holocene. Therefore no new major sources of sediment enter the system other than an increase from eroded terrestrial environments following deforestation (e.g. Tipping 1994).

Isolation basins are important sinks for two suites of allochthonous sediment in addition to the primary biogenic productivity within the basin. First, they intercept sediments from the drainage basin, thus depriving the coastal zone. Second, they remove fine-grain minerogenic sediments transported from the coastal system into the basin. In combination, these factors explain in part the very restricted occurrence of muddy salt-marshes in the area.

Dune and beach systems, with associated wetlands to their landward, at Gartenachullish, Mointeach Mhor and Glenancross (Shennan et al. 1995a), each record a phase of major rapid landward migration of the coast, followed by relative stabilisation and regression. These changes are not synchronous but all occur within the period of lower sea-level rise, <1 mm/yr, in the mid-Holocene (Figure 13). Although sea-level rise is a forcing parameter, factors such as sediment supply and coastline morphology combine with individual major storms to trigger the breakdown of the dune and beach systems within a system of dynamic metastable equilibrium (Shennan, 1995). During the preceding period, 9 to 8 ka BP, faster relative sea level rise, c. 3 mm/yr, created unstable conditions for persistent dune and beach systems, leading to their landward migration. Afterwards, during the period of reducing rates of relative sea-level rise, the barrier system re-establishes equilibrium, and marine minerogenic sediment delivery landward of the barrier ceases. Organic deposition starts within brackish and salt-marsh environments, grading to freshwater marsh, and finally raised bog independent of sea level. Relative sea-level fall during the late Holocene isolates the coastal sand ridges from sediment supplied by tides and waves. They become a sediment store, at least until possible future sea-level rise leads to their remobilisation.

#### *Links and relationships between the rates of long-term and short-term coastal processes*

Our investigations of the isolation basins and dune, beach and wetland sites illustrate the interaction of long-term (century to millennium scale) and short-term processes (year, decade to century scale). Relative sea-level change controls the broad pattern of coastal evolution at each site, but the particular de-

tails result from short-term processes and site-specific factors. Millennium-scale processes, e.g. eustasy and glacio- and hydro-isostasy, control the pattern of relative sea-level change shown in Figures 9 and 13. Dominance of relative sea-level fall limits input of new sources of clastic sediments to the coastal zone. Short-term processes, probably single events such as a storm surge, superimposed on long-term relative sea-level rise trigger morpho-sedimentary responses. The resolution of the radiocarbon data fails to distinguish whether the phase of sand deposition at Gartenachullish was in the order of a few decades rather than a few centuries. These coastal systems, controlled by links between long-term and short-term processes, portray a state of dynamic metastable equilibrium (Chorley & Kennedy 1971, Shennan 1995).

#### *New techniques in the investigation of coastal sequences*

The original element in this part of the project is the combination of techniques rather than any single new technique. Of the range of techniques used the most valuable data for providing new information on both short-term changes and sediment origin are: pollen, dinocyst and diatom analysis at 1 mm intervals, infrared colour photography, X-ray photography and thin sections. These show that faint laminations and clast-rich layers seen in X-rays result from, respectively, concentrations of detrital macrophytic algae (sea-weeds) and mixtures of shell fragments, foraminifera and detrital minerals. Such layers are common near the sill and infrequent in the middle of the Rumach VI basin. Despite the presence of clast-rich layers a distinct storm-surge signal is not identified. The diatom, dinocyst and pollen analyses reveal a detailed, internally consistent record of a short-term, climate-driven environment and sea-level change. The record is not obscured by bioturbation. This provides a high-resolution record of changes in local and regional vegetation, of the origin of biogenic and minerogenic sediments, and of changes in water quality driven by climate and sea-level change.

#### *Implications for coastal management*

Dune and beach systems, with associated wetlands to their landward, at Gartenachullish, Mointeach Mhor and Glenacross, each record a major phase of rapid landward migration of the coast. Though not synchronous all occur within the period of lower sea-level rise in the mid-Holocene, as the rate of rise drops

from c. 3 to 6 mm/yr to < 1 mm/yr. Many other dune systems in the United Kingdom were mobile during periods of similarly low rates of sea-level rise (Tooley 1990). The scenarios of the Intergovernmental Panel on Climate Change (Houghton et al. 1996) suggest a global average rise of c. 3 mm/yr by AD 2050. This will be partly offset in Morar by about 1 mm/yr isostatic uplift. Any change from the relative sea-level fall experienced over the past few thousand years to a rise is likely to result in coastal morpho-sedimentary response of a magnitude not experienced for over 5000 years. The Holocene records show that site-specific factors determine the exact timing of the breakdown and migration of dune and beach systems superimposed on a regional sea-level rise. In particular, systems away from sediment sources, e.g. rivers, are under an increasing threat.

Numerous studies illustrate the coastal management issues posed by the threats from future sea-level rise to agricultural, urban, industrial and commercial areas (e.g. Doornkamp 1990, Tooley & Jelgersma 1992, Warrick et al. 1993). Coastal management is less of an issue to coastal and wetland environments while sea-level is falling. Coastal and wetland environments contain a valuable record of environmental change, of archaeological, landscape and cultural history, and of contemporary habitats. Some of these sites have a recognised status, such as Sites of Special Scientific Interest, Geological Conservation Review Sites or notified archaeological sites. Many have no formal recognition or protection. In those areas of Great Britain undergoing present land uplift (Shennan 1989) a recent review identified 205 sites of cultural or environmental interest which will be under threat if relative sea-level fall changes to relative sea-level rise (Shennan et al. 1995c). In areas outside the zone of land uplift, the rest of Great Britain and most of the European Union except Scandinavia, coastal management has addressed the threat of rising sea level for some time. Sea-level rise will become a new factor in areas where the rate of land uplift no longer offsets its effects.

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