Transactions of the Royal Society of Edinburgh: Earth Sciences, **92**, 121–136, 2001

Holocene changes in the physiography and vegetation of the Atlantic littoral of the Uists, Outer Hebrides, Scotland

William Ritchie, Graeme Whittington and Kevin J. Edwards

ABSTRACT: Immediately W of the islands of Uist in the Outer Hebrides is a wide, low-gradient submarine shelf on which glacifluvial deposits of Devensian age and calcareous sand accumulated. Following moulding by Devensian ice, the Lateglacial landscape of the littoral zone of the Uists became a series of low-lying bedrock ridges and basins. The analysis of sub-tidal organic deposits has shown that in the early Holocene this landscape supported water bodies, marshes and a vegetation mosaic of *Betula–Corylus* woodland and *Calluna vulgaris*–herbaceous taxa open ground. The submergence of this littoral area during the Holocene Marine Transgression, together with wave action typical of the position on the Atlantic margin, led to the transfer onshore of submarine shelf deposits, so creating machair (sand plain) landscapes. This brought about vegetational changes, eventually creating calcareous grasslands. The timing of these events was asynchronous, being location- and site-specific due to variations in the configuration of the littoral zone. Although the date of the initial transfer of sand is unknown, evidence from the sub-tidal deposits indicates that a major incursion of sand, in North Uist, occurred *c.* 7600 BP (8450–8340 cal BP). The same source also suggests that a further major sand movement took place during the period 5800–4200 cal BP, a period of widespread sand drift in NW Europe. The analyses of the sub-tidal deposits have also reinforced the current theory of machair evolution.

KEY WORDS: coastal submergence, inter-tidal deposits, machair, pollen analysis, radiocarbon dating, sand incursion, vegetation history.

Since the mid 1960s there has been an increasing number of multi-disciplinary investigations, including geomorphology, palynology and archaeology (e.g. Boyd 1979; Armit 1996; Edwards *et al.* 1995; Gilbertson *et al.* 1996; Angus 1997; Mulder 1999), into the Holocene landscape evolution of the Uists (used here as a collective term for the islands of North and South Uist and those lying in between; Fig. 1). The Atlantic coastal areas have undergone most investigation, whereas the E coast, which slopes steeply down to relatively deep water and is similar in its littoral configuration to the sea lochs on the W coast of mainland Scotland, has not been studied other than on a superficial basis.

The sand-fringed coastlands which, with one exceptional area in NE Benbecula and SE Grimsay, border the Atlantic Ocean have been the focus for most field- and laboratory-based research, especially in relation to the landform known as machair (Ritchie 1976). A further element of the coastline, the shallow channels which separate the islands of North Uist, Benbecula and South Uist, has also been examined as part of the evolution of the Atlantic Ocean coastlines (Whittington & Ritchie 1988). Similar but more extensive shallow channels also separate the Uists from Harris to the N and Barra to the S. All five channels are of considerable importance as a consequence of having been opened up in the mid-Holocene, thereby providing connections between the open Atlantic on the W and the sheltered Sea of the Hebrides to the E. These changes profoundly altered the spatial geography of the Outer Hebrides and, in particular, transformed tidal exchanges and coastal sediment dynamics.

This paper is focused on the W littoral of the Uists and, by integrating established information with new findings from the examination of additional coastal sites, provides a fuller understanding of the environmental changes which have occurred over the last 10,000 years. The new evidence is mostly derived from five hitherto unexplored sites of inter-tidal, intercalated organic and blown-sand deposits which occur in association with mature machair landforms. The locations of these pollen sites and other names in the text are given in Figure 1.

1. Laboratory analyses and the presentation of results

Stratigraphic interpretation has been undertaken and palynological data and radiocarbon dates have been obtained from the inter-tidal deposits. Material for pollen analysis was prepared using standard NaOH, HF and acetolysis methods (Faegri & Iversen 1989). Resulting pollen samples were mounted in silicone fluid and a minimum counting sum of 300 total land pollen (TLP) was obtained. Pollen and plant nomenclature follow Bennett (1994) and Stace (1997), respectively. Pollen diagrams were drawn with the TILIA and TILIA·GRAPH computer programs (Grimm 1991) and are displayed in Figures 3–8. The major taxa, within their local pollen assemblage zones and their TLP percentage representation, are summarised in Figure 2.

Radiocarbon (^{14}C) dates, expressed in years before present (BP), used in this study are shown in Table 1, with calendar year calibration (cal BP) at the two sigma level using the highest probability distribution in Method B from the program CALIB REV 4.2 (Stuiver & Reimer 1993; Stuiver *et al.* 1998) and rounded to the nearest ten years.

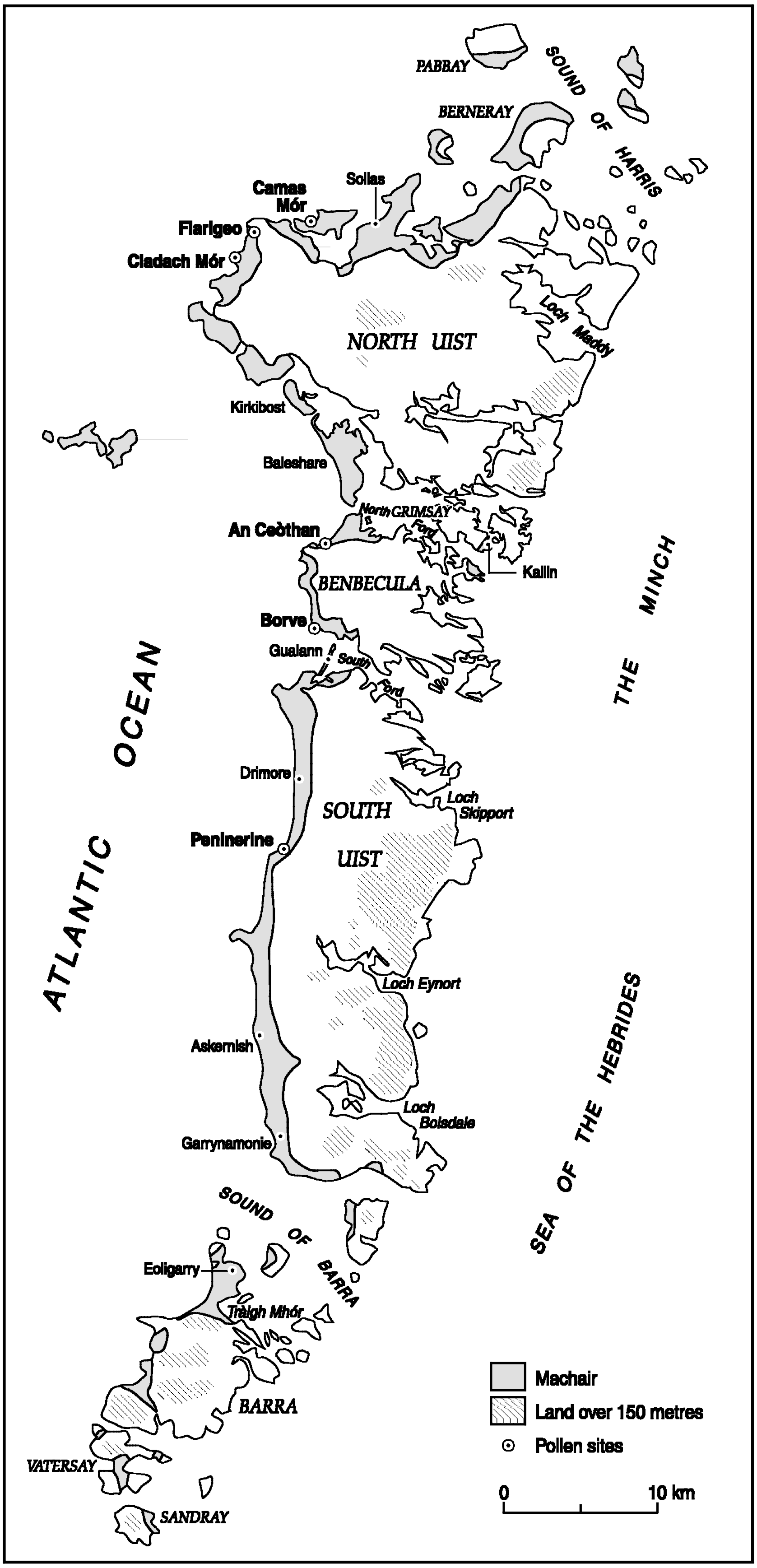

Figure 1 The Outer Hebrides from North Uist to Sandray showing the pollen sites and the location of names used in the text.

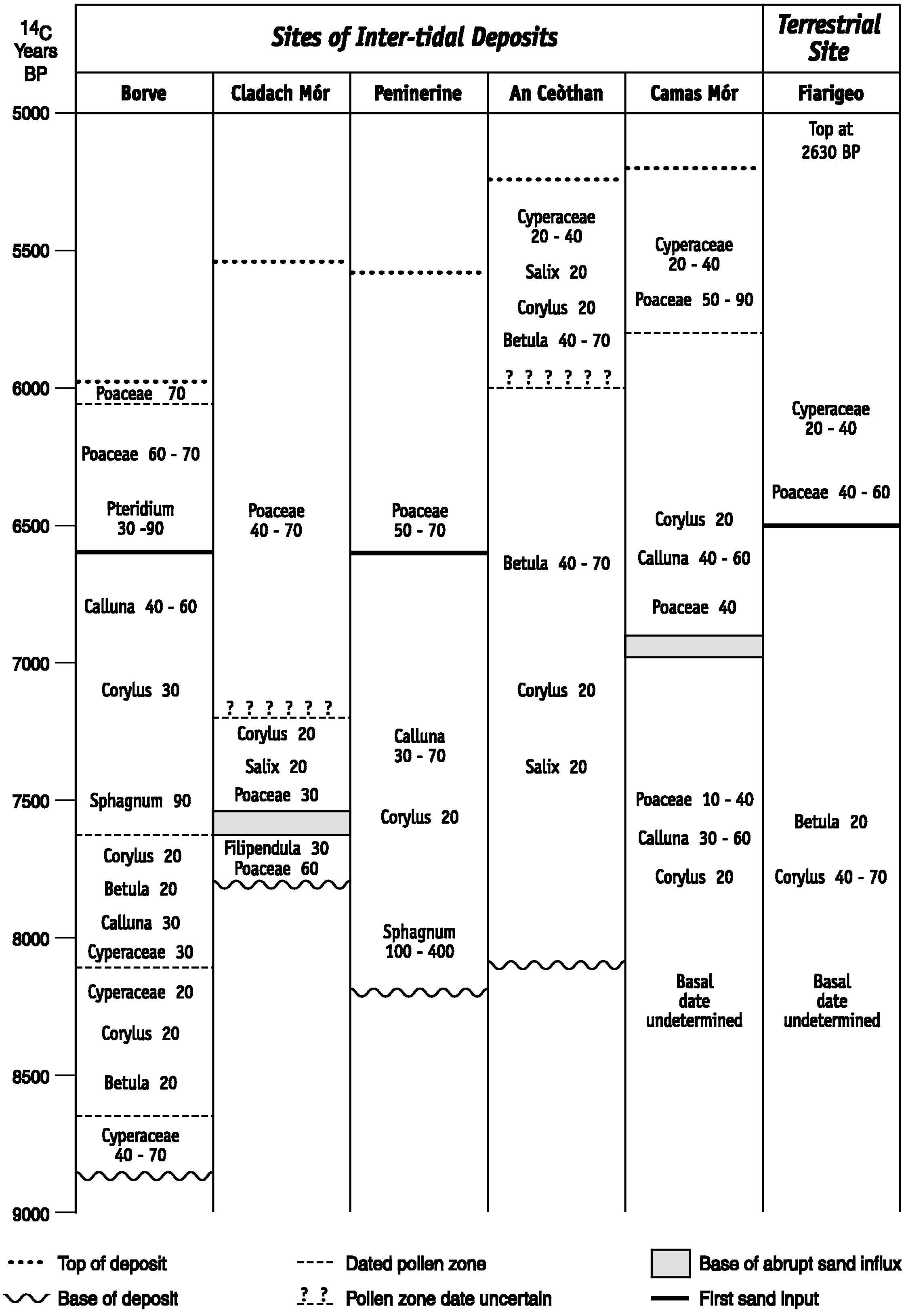

Figure 2 Dated (^{14}C yr BP) summary of the main pollen and spore taxa percentages and the sand incursions at the six coastal sites.

Table 1 Radiocarbon dates from An Ceóthan, Borve, Camas Mór, Cladach Mór, Fiarigeo and Peninerine

Site	*Depth (cm)*	*Lab. no*	*^{14}C age (yr BP)*	*cal BP (2σ)*
An Ceóthan	0·0–0·3	SRR-4912	5255 ± 45	6110–5930
	36·2–36·5	SRR-4911	8080 ± 45	9130–8970
Borve	0·0–0·1	SRR-5075	5535 ± 80	6490–6170
	42·0–42·1	SRR-4913	5980 ± 50	6940–6710
	50·0–50·1	SRR-4914	6050 ± 50	7010–6750
	54·0–54·1	SRR-4915	6605 ± 45	7520–7430
	58·0–58·1	SRR-4916	7640 ± 45	8490–8360
	64·0–64·1	SRR-4917	8110 ± 45	9140–8980
	69·0–69·1	SRR-4918	8675 ± 45	9780–9540
	73·0–73·1	SRR-4919	8855 ± 60	10170–9710
Camas Mór	9·0–9·4	SRR-3932	5195 ± 45	6000–5890
	18·0–18·4	SRR-3933	5765 ± 40	6660–6460
	30·0–30·4	SRR-3934	5835 ± 40	6740–6540
	38·0–38·4	SRR-3935	6925 ± 30	7790–7670
Cladach Mór	0·0–0·1	GU-1761	5565 ± 110	6640–6170
	97·5–98·5	GU-1762	7810 ± 140	9010–8380
Fiarigeo	50·0–50·5	Beta-127961	2630 ± 40	2790–2710
	85·5–86·0	Beta-127960	6890 ± 60	7790–7660
Peninerine	0·0–0·4	I-17121	5560 ± 110	6570–6170
	16·0–16·4	I-17122	6500 ± 120	7610–7200
	33·0–33·5	I-17124	8010 ± 130	9280–8450
	60·6-61·0	I-17123	8140 ± 130	9430–8690

2. The postglacial coastal landscape

2.1. The physical basis

The physiography of the Uists is strongly asymmetric. There is a wide, low-gradient (the average distance to the 10 fathoms (18 m) depth contour is 5·2 km, a gradient of 0·2°), submarine shelf to the W which is normally more than 100 km wide. This platform extends inland to the break of slope at approximately 50 to 100 m OD on W-facing slopes of the line of mountains which form the E-coast spine of the Uists. To the E there is a precipitous descent to the deeper waters of the Sea of the Hebrides and The Minch. This E-coast spine corresponds to the plane of the Outer Hebrides Thrust Zone which is a major geological feature stretching the whole length of the Outer Hebrides (Stoker *et al.* 1993).

Until the Holocene, most aspects of the geomorphological evolution can only be matters for speculation. Attempts have been made to detect various planation surfaces or, more correctly, areas of strong minimum slope which have been ascribed to differential emergence, modified by zones of glacial excavation. The most extensive surface is the Atlantic coastal plain (Halstead 1979) which, in its flatness and extension seawards, has no hypsographic equivalent elsewhere in Scotland.

During the Quaternary, glaciation modified these ancient geological surfaces and the patterns of iceflow and consequent glacial landforms have been progressively defined by Geikie (1873, 1878), von Weymarn (1979) and Peacock (1984), and summarised by Hall (1996). In general, the earlier assumption that the Uists were crossed by mainland ice which flowed from E to W and extended approximately 80 km W of the islands remains accepted, although the detailed patterns of these earlier iceflows are still uncertain. The thickness and extent of ice sheets are of considerable importance since this knowledge would help with the assessment of the isostatic factor in determining the amount and rate of sea-level changes in the postglacial period. As discussed later, the question of a possible forebulge effect (Clark 1980), could affect the shape of the sea-level curve over the last 10,000 years, but this aspect of the study of the post-glacial evolution of the Outer Hebrides has yet to be addressed.

In relation to the coastal zone, the last local movement of ice (Flinn 1978; Hall 1996) scoured the lower surfaces into a series of closely spaced ridges and basins. Inland, most of the depressions have been transformed into water bodies, while offshore a similar topography can be detected in the bathymetric contours as consisting of depressions separated by reefs and rises (Ritchie 1966; Pantin 1991). Lines of weakness, such as secondary fault lines, run transversely to the main Outer Hebrides Thrust Zone, and have been exploited to give strong lineations, such as the sea lochs and other inlets which have a general NW to SE orientation.

The combination of geological structures and the effects of glaciation can be summarised as providing a long chain of islands with extensive, low-altitude, ice-roughened surfaces, which are, in effect, part of the wide Atlantic continental shelf, interrupted on the E side by the discontinuous line of mountains. Most of the sea lochs and the sounds have been overdeepened by ice flows irrespective of their direction of movement and almost all the larger sea lochs, (e.g. Loch Maddy, Loch Eynort, Loch Skipport, Loch Boisdale), penetrate through the E coast mountain chain to reach the low Atlantic coastal platform.

2.2. Sources of coastal sediments

Although glacigenic materials, mainly of local till, occur on land in a few discrete broad zones (Peacock 1984), the cover is not extensive and there is an almost complete absence of glacifluvial sands and gravels. Information on glacial and fluvioglacial deposition on the Atlantic Hebrides Shelf is sparse, but it has been assumed that a substantial volume of sediment must have been emplaced on the low-gradient platform to the W of the Uists.

Substantial amounts of calcareous sediment occur on the nearshore continental shelf of W Scotland (Farrow *et al.* 1978). With the exception of the sheltered Traígh Mhór in Barra, all the sites investigated occur in high-energy locations off the Inner Hebrides and W mainland Scotland. By analogy, the shelf W of the Uists should be a prolific area for the production of high-energy carbonate deposits, mainly of fragmented molluscs. Farrow *et al.* (1978) also distinguished between more recent deposits, which resemble existing nearshore fauna, and those offshore, where many deposits are relict. Of particular importance are storm events, which not only move large volumes of shell fragments landwards but also disturb encrusted cobbles and break the *Laminaria* holdfasts. These are frequent events which result in maximum production of calcareous sediments and their transport to the nearshore zone.

High shell production also occurs in sheltered strands, beaches and sandflats but the species involved are different and in the Uists are significant sources of fragile shells. Such shell fragments are of lower density and have different grain shapes from other sand grains which are of non-biogenic origin. Although this is not something which has been researched, it is likely that the greater surface area, concave shapes and lower densities of the shell fragments might increase their ease of transport, at first by waves and, subsequently, by wind.

In general, machair sand varies from 50% to 80% calcium carbonate which is equated with its shell sand content. The remaining percentages represent large volumes of non-biogenic sand which, S of the Sound of Harris, cannot be derived from either cliff erosion or rivers since neither source exists now or was available in the past. Thus there are no realistic, alternative sources of non-shell sand other than glacigenic deposits which have been termed the 'glacial legacy' (Ritchie 1966). Given the position of the ice-sheet margins in the Quaternary, large quantities of glacial and, later, meltwater-derived materials must have been deposited on what is now the shallow Hebridean continental shelf. There may also have been a phase of Late Devensian aeolian deposition perhaps associated with ice-sheet margins (Gilbertson *et al.* 1999). It is not possible to quantify the extent or nature of the glacially-derived continental shelf deposits, although the eroding cliffs of glacial till which occur further N on the W coast of Lewis may be taken as indicative of the types of material which would have been available (von Weymarn 1974). Thus, in combination, the extensive Atlantic shelf did offer a source of siliceous and calcareous material, in vast quantities, to be swept onshore by powerful ocean waves.

Modern beach, dune and machair sands may show a preponderance, in ratios of 2:1 or 5:1, of shell to siliceous sand, but the reworked glacial sources are also very significant and, although not discussed here, also provide the materials which are characteristic of many shorelines in the Uists. There is unresolved discussion as to continuity in the supply of shell-derived sand (Mate 1991) and the possible loss of volume through leaching of calcium carbonate. Nevertheless, there appears to be agreement that the 'glacial legacy' to Holocene shorelines was massive but finite, both here and elsewhere along the Scottish coast (Hansom 1999).

2.3. The vegetation cover

The scattered exposures of inter-tidal organic deposits on the beaches of the Atlantic coasts of the Uists (Fig. 1) have made it possible to establish the nature of the earliest vegetation of the present coastal zone. Evidence for this for the island of Benbecula, which lies between North and South Uist, has been published (Whittington & Edwards 1997) and, with the extension of similar investigations to other locations, it is now possible to make an evaluation on a wider spatial scale. A vegetation history at four new sites, Camas Mór, Cladach Mór, An Ceǒthan and Peninerine (Fig. 1), has now been established. A terrestrial site, Fiarigeo (Fig. 1), just above high water mark on the NW coast of North Uist, supplements the information from the former sites.

For the sites shown in Figure 2, it is possible to state the nature of the vegetation that once existed. Polleniferous sediments first accumulated at the sites at different dates, the earliest being at Borve (Fig. 3) on Benbecula *c.* 8900 BP (10190–9790 cal BP). At Cladach Mór (Fig. 4) they were present by 7810 ± 140 BP (9010–8380 cal BP), at Peninerine (Fig. 5) by 8140 ± 130 BP (9430–8690 cal BP) and at An Ceǒthan (Fig. 6) by 8080 ± 45 BP (9130–8970 cal BP). The bases of the deposits at Camas Mór (Fig. 7) and Fiarigeo (Fig. 8) are undated.

At all of these sites, apart from the earliest deposits at Borve, and even there by *c.* 8640 BP (9710–9530 cal BP), *Corylus avellana*-type (cf. hazel) is represented in the pollen spectra. Its most striking presence is at Fiarigeo where it provides 39% TLP at the base of the diagram, rising to 70%, before it declines with dramatic suddenness. Throughout this period it is accompanied by *Betula* (birch) with percentage values dominantly between 10% and 30% TLP. The situation at An Ceǒthan is just as striking although the taxa are reversed in importance. There, by 8080 ± 45 BP (9130–8970 cal BP), *Betula* provided 35% TLP and that value rarely fell below this level until the termination of the pollen record; the taxon also peaks on numerous occasions at over 60%. *Corylus* maintains a presence on average of 15% TLP. At Borve, by 8675 ± 45 BP (9780–9540 cal BP), *Betula* and *Corylus* had become the dominant taxa, although by 8110 ± 45 BP (9140–8980 cal BP) the former went into decline while *Corylus* maintained a steady presence of over 20% TLP until 7640 ± 45 BP (8490–8360 cal BP). Camas Mór, Cladach Mór and Peninerine reveal a different story. The Cladach Mór deposits are dominated by Poaceae (*c.* 50% TLP) throughout their accumulation, with *Betula* hardly represented and *Corylus* always present but at insignificant levels, except in zone CM-2 where it reaches 20%. At Camas Mór from the beginning of pollen accumulation until *c.* 5835 BP (6740–6540 cal BP), *Calluna vulgaris* (heather), at about 40%, is the most important taxon. That situation is paralleled at Peninerine to a certain extent; *Calluna* dominates until *c.* 6500 BP (7610–7200 cal BP) and, although *Betula* is generally < 10%, *Corylus* exceeds 20% TLP at some levels.

Thus it appears that the vegetation of the western littoral, and probably of the land area to the immediate E, was one in which woodland, especially of *Betula* and *Corylus*, played an important part. Birch–hazel woodland did not apparently provide a complete cover but occurred in a mosaic with Poaceae and *Calluna*, along with other herbaceous and open land taxa (e.g. Cyperaceae [sedge family], *Filipendula* [meadowsweet], *Potentilla*-type [tormentil/cinquefoil], *Ophioglossum* [adder's tongue] and *Sphagnum* [bog moss]).

Changes in Holocene sea levels and the presence and movements of sediments, specifically of wave- and wind-transported sand, from the continental shelf were, however, to cause profound alterations to the physical nature and vegetation cover of the littoral zone. This can be identified clearly in the changing strata and pollen content at each of these sites, as well as in those described in previous publications, and indicates the extent to which local sequential changes can be associated with the site-specific evolution of the local coastal area.

3. The importance of sea-level changes

3.1. The Holocene Marine Transgression

During the Late Devensian, according to Stoker *et al.* (1993) and Lambeck (1995), sea level was substantially lower (by at least 100 m) than at present and, on the shelf W of the Outer Hebrides, this could equate to a shoreline 20 to 40 km W of its present position. As sea level rose, and this platform became progressively inundated, its suitability for shell production would be substantial. The rising sea would also come into contact with the glacial deposits which must have existed on this shelf. There is no direct, local evidence for this rise in sea level. Nevertheless, it is a recognised world-wide event with

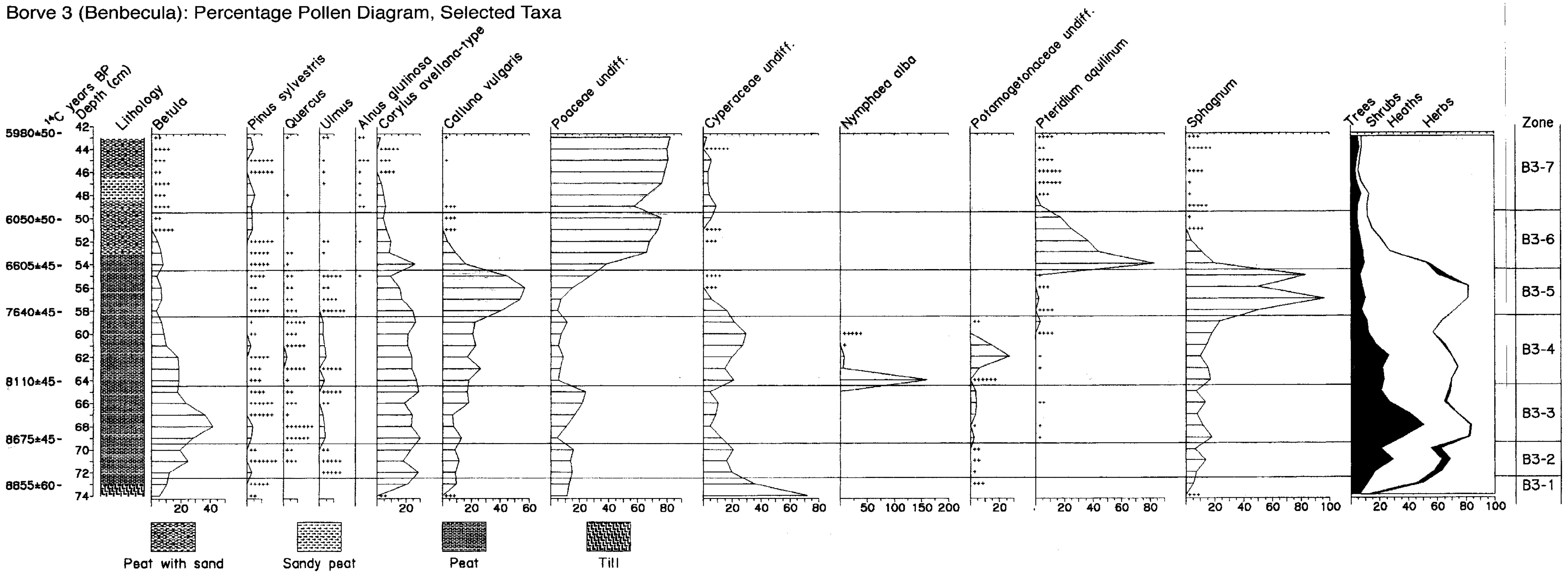

Figure 3 Percentage pollen diagram for selected pollen and spore taxa from Borve 3; percentages <2 are shown by crosses with each cross equal to one pollen grain.

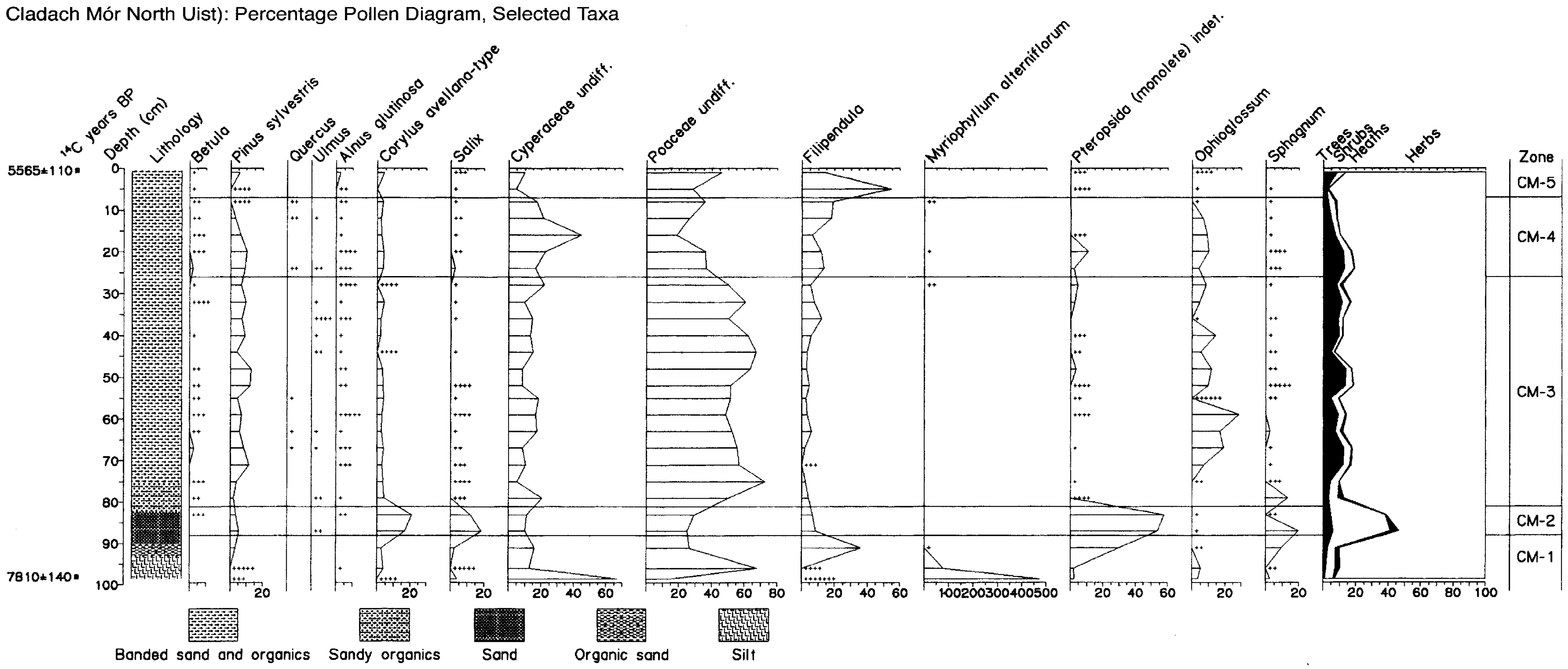

Figure 4 Percentage pollen diagram for selected pollen and spore taxa from Cladach Mór; percentages <2 are shown by crosses with each cross equal to one pollen grain.

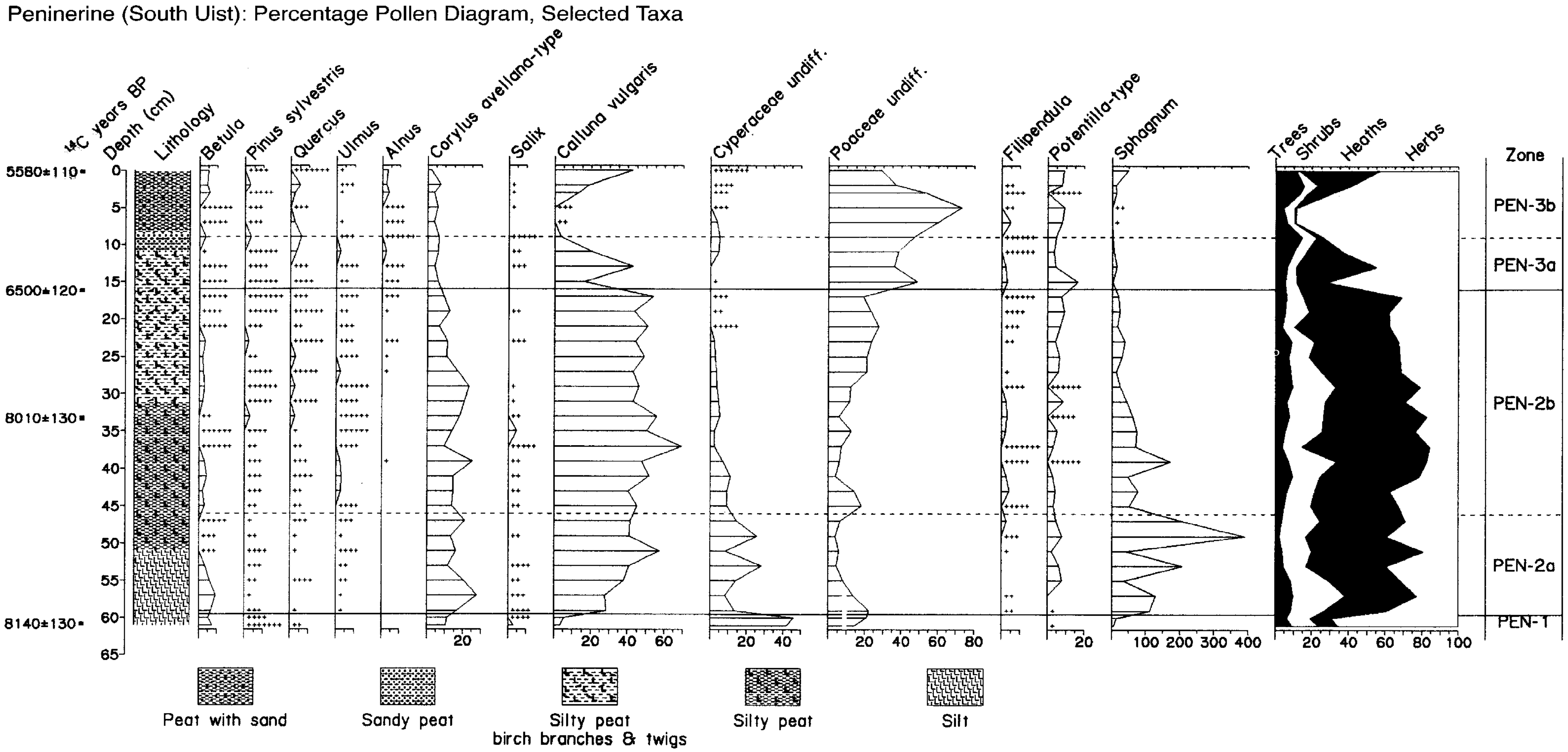

Figure 5 Percentage pollen diagram for selected pollen and spore taxa from Peninerine; percentages <2 are shown by crosses with each cross equal to one pollen grain.

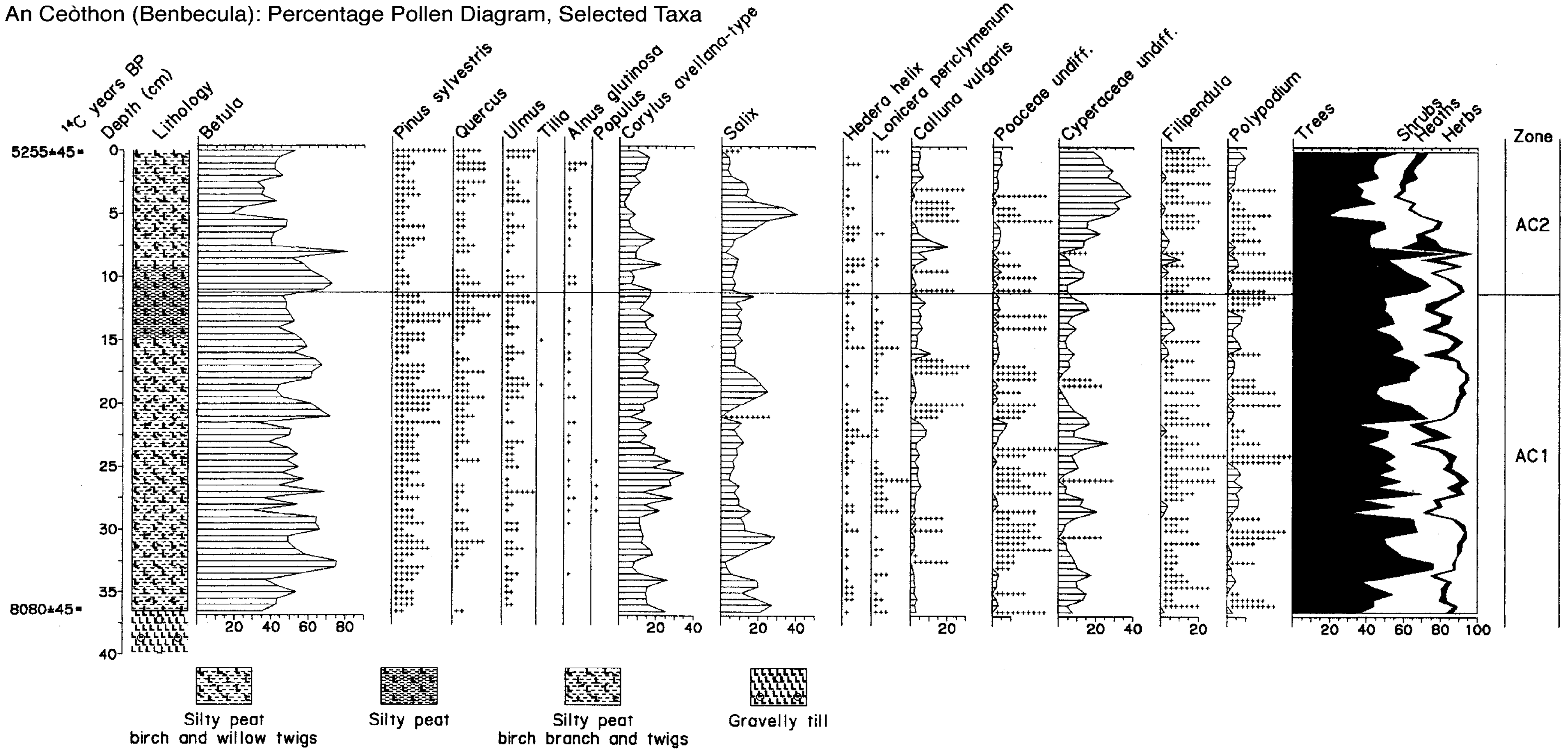

Figure 6 Percentage pollen diagram for selected pollen and spore taxa from An Ceòthan; percentages <2 are shown by crosses with each cross equal to one pollen grain.

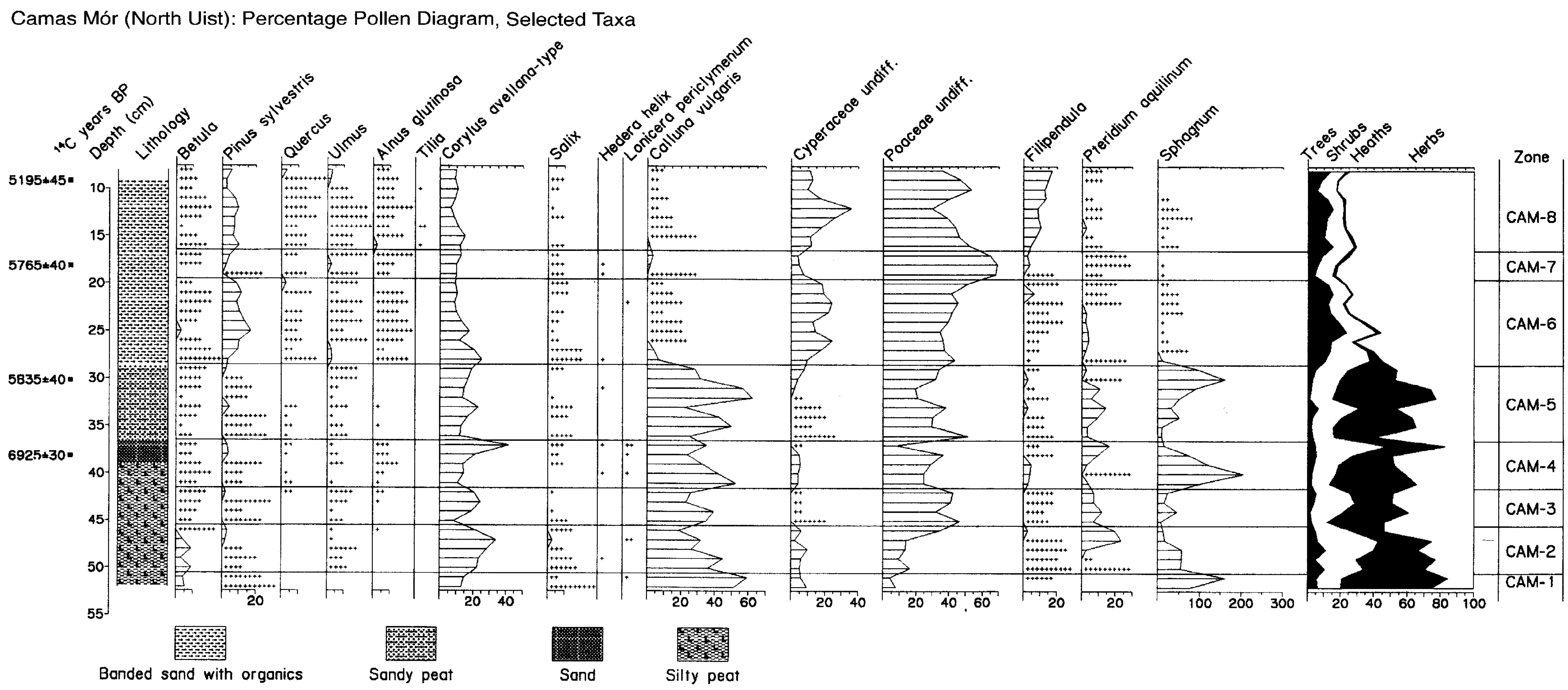

Figure 7 Percentage pollen diagram for selected pollen and spore taxa from Camas Mór; percentages <2 are shown by crosses with each cross equal to one pollen grain.

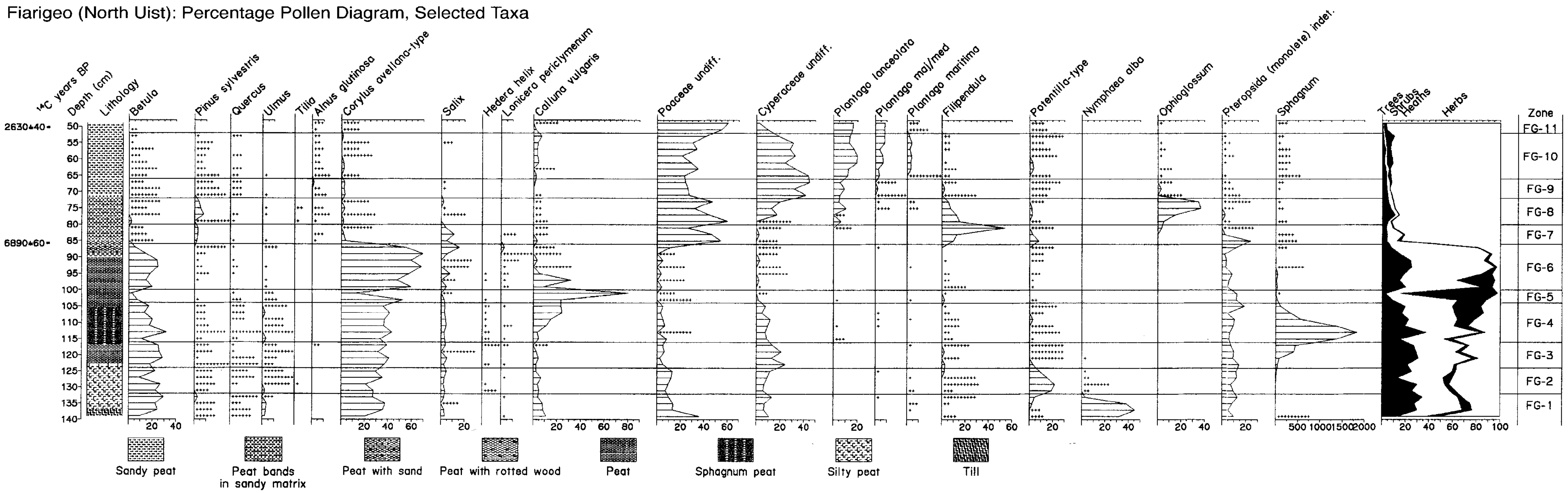

Figure 8 Percentage pollen diagram for selected pollen and spore taxa from Fiarigeo; percentages <2 are shown by crosses with each cross equal to one pollen grain.

encrusted cobbles and break the *Laminaria* holdfasts. These are frequent events which result in maximum production of calcareous sediments and their transport to the nearshore zone.

High shell production also occurs in sheltered strands, beaches and sandflats but the species involved are different and in the Uists are significant sources of fragile shells. Such shell fragments are of lower density and have different grain shapes from other sand grains which are of non-biogenic origin. Although this is not something which has been researched, it is likely that the greater surface area, concave shapes and lower densities of the shell fragments might increase their ease of transport, at first by waves and, subsequently, by wind.

In general, machair sand varies from 50% to 80% calcium carbonate which is equated with its shell sand content. The remaining percentages represent large volumes of non-biogenic sand which, S of the Sound of Harris, cannot be derived from either cliff erosion or rivers since neither source exists now or was available in the past. Thus there are no realistic, alternative sources of non-shell sand other than glacigenic deposits which have been termed the ‘glacial legacy’ (Ritchie 1966). Given the position of the ice-sheet margins in the Quaternary, large quantities of glacial and, later, meltwater-derived materials must have been deposited on what is now the shallow Hebridean continental shelf. There may also have been a phase of Late Devensian aeolian deposition perhaps associated with ice-sheet margins (Gilbertson *et al.* 1999). It is not possible to quantify the extent or nature of the glacially-derived continental shelf deposits, although the eroding cliffs of glacial till which occur further N on the W coast of Lewis may be taken as indicative of the types of material which would have been available (von Weymarn 1974). Thus, in combination, the extensive Atlantic shelf did offer a source of siliceous and calcareous material, in vast quantities, to be swept onshore by powerful ocean waves.

Modern beach, dune and machair sands may show a preponderance, in ratios of 2:1 or 5:1, of shell to siliceous sand, but the reworked glacial sources are also very significant and, although not discussed here, also provide the materials which are characteristic of many shorelines in the Uists. There is unresolved discussion as to continuity in the supply of shell-derived sand (Mate 1991) and the possible loss of volume through leaching of calcium carbonate. Nevertheless, there appears to be agreement that the ‘glacial legacy’ to Holocene shorelines was massive but finite, both here and elsewhere along the Scottish coast (Hansom 1999).

2.3. The vegetation cover

The scattered exposures of inter-tidal organic deposits on the beaches of the Atlantic coasts of the Uists (Fig. 1) have made it possible to establish the nature of the earliest vegetation of the present coastal zone. Evidence for this for the island of Benbecula, which lies between North and South Uist, has been published (Whittington & Edwards 1997) and, with the extension of similar investigations to other locations, it is now possible to make an evaluation on a wider spatial scale. A vegetation history at four new sites, Camas Mór, Cladach Mór, An Ceòthan and Peninerine (Fig. 1), has now been established. A terrestrial site, Fiarigeo (Fig. 1), just above high water mark on the NW coast of North Uist, supplements the information from the former sites.

For the sites shown in Figure 2, it is possible to state the nature of the vegetation that once existed. Polleniferous sediments first accumulated at the sites at different dates, the earliest being at Borve (Fig. 3) on Benbecula *c.* 8900 BP (10190–9790 cal BP). At Cladach Mór (Fig. 4) they were present by 7810 ± 140 BP (9010–8380 cal BP), at Peninerine (Fig. 5) by 8140 ± 130 BP (9430–8690 cal BP) and at An Ceòthan (Fig. 6) by 8080 ± 45 BP (9130–8970 cal BP). The bases of the deposits at Camas Mór (Fig. 7) and Fiarigeo (Fig. 8) are undated.

At all of these sites, apart from the earliest deposits at Borve, and even there by *c.* 8640 BP (9710–9530 cal BP), *Corylus avellana*-type (cf. hazel) is represented in the pollen spectra. Its most striking presence is at Fiarigeo where it provides 39% TLP at the base of the diagram, rising to 70%, before it declines with dramatic suddenness. Throughout this period it is accompanied by *Betula* (birch) with percentage values dominantly between 10% and 30% TLP. The situation at An Ceòthan is just as striking although the taxa are reversed in importance. There, by 8080 ± 45 BP (9130–8970 cal BP), *Betula* provided 35% TLP and that value rarely fell below this level until the termination of the pollen record; the taxon also peaks on numerous occasions at over 60%. *Corylus* maintains a presence on average of 15% TLP. At Borve, by 8675 ± 45 BP (9780–9540 cal BP), *Betula* and *Corylus* had become the dominant taxa, although by 8110 ± 45 BP (9140–8980 cal BP) the former went into decline while *Corylus* maintained a steady presence of over 20% TLP until 7640 ± 45 BP (8490–8360 cal BP). Camas Mór, Cladach Mór and Peninerine reveal a different story. The Cladach Mór deposits are dominated by Poaceae (*c.* 50% TLP) throughout their accumulation, with *Betula* hardly represented and *Corylus* always present but at insignificant levels, except in zone CM-2 where it reaches 20%. At Camas Mór from the beginning of pollen accumulation until *c.* 5835 BP (6740–6540 cal BP), *Calluna vulgaris* (heather), at about 40%, is the most important taxon. That situation is paralleled at Peninerine to a certain extent; *Calluna* dominates until *c.* 6500 BP (7610–7200 cal BP) and, although *Betula* is generally < 10%, *Corylus* exceeds 20% TLP at some levels.

Thus it appears that the vegetation of the western littoral, and probably of the land area to the immediate E, was one in which woodland, especially of *Betula* and *Corylus*, played an important part. Birch–hazel woodland did not apparently provide a complete cover but occurred in a mosaic with Poaceae and *Calluna*, along with other herbaceous and open land taxa (e.g. Cyperaceae [sedge family], *Filipendula* [meadowsweet], *Potentilla*-type [tormentil/cinquefoil], *Ophioglossum* [adder’s tongue] and *Sphagnum* [bog moss]).

Changes in Holocene sea levels and the presence and movements of sediments, specifically of wave- and wind-transported sand, from the continental shelf were, however, to cause profound alterations to the physical nature and vegetation cover of the littoral zone. This can be identified clearly in the changing strata and pollen content at each of these sites, as well as in those described in previous publications, and indicates the extent to which local sequential changes can be associated with the site-specific evolution of the local coastal area.

3. The importance of sea-level changes

3.1. The Holocene Marine Transgression

During the Late Devensian, according to Stoker *et al.* (1993) and Lambeck (1995), sea level was substantially lower (by at least 100 m) than at present and, on the shelf W of the Outer Hebrides, this could equate to a shoreline 20 to 40 km W of its present position. As sea level rose, and this platform became progressively inundated, its suitability for shell production would be substantial. The rising sea would also come into contact with the glacial deposits which must have existed on this shelf. There is no direct, local evidence for this rise in sea level. Nevertheless, it is a recognised world-wide event with different rates and absolute amounts of rise in different regions (Fairbridge 1961; Mörner 1976, 1980; Dawson 1992; Pirazzoli 1996). For NW Europe, it is generally accepted that the previously rapid eustatic rise in sea level came to an end at an altitude slightly below that of the present day (Pirazzoli 1996). The precise date of this 'levelling-off' and its relative altitude vary regionally according to local factors, including isostatic adjustments (Smith & Dawson 1983), but the eustatic sea-level curve, corrected for glacio-hydro-isostatic effects, shows the first stage of slowing at 7000 BP and near-cessation at 5000 BP at a level a few metres below present sea level (Lambeck 1995).

To the W of the Uists, the very low, seawards gradient would ensure rapid lateral marine incursion across the shelf, leading eventually to the breaking of the linkage of Harris, the Uists and Barra. With the rate of sea level rise slowing and levelling-off towards the end of this period, as it did elsewhere in W Europe, the rapid E-ward shift in the coastline would slow dramatically, or possibly prograde in response to excess sediment accumulation in the littoral zone. Since the rate and amount of the submergence of the coastline of the Uists are critical to the understanding of geomorphological and vegetational changes, some attention needs to be given to the theory of these changes, especially in relation to isostatic and eustatic components. As there is no evidence for higher Late Devensian sea levels, in spite of the known presence of a local icecap at this time over the Outer Hebrides, it is necessary to consider this region in relation to other areas which were marginal to the main Late Devensian ice sheets.

Reference to Clark (1980) raises the question as to the importance of the proximity of the coastline of the Uists to the former margin of the most recent ice sheet. Detailed assessment of this complex topic (see Smith & Dawson 1983) is beyond the scope of this paper, which uses the hypothesis that the marginal position of the Uists and the likely absence of a forebulge effect would be to produce a continuously rising sea level over approximately the last 10,000 years, i.e. similar to curves in Figure 9 which are based on the Atlantic coasts of N France (Clark 1980) and Scotland (Lambeck 1995), and the curves produced by Jelgersma (1966, 1980) and by Fairbridge (1961). The evidence for substantially lower sea levels has always been entirely circumstantial and in the earliest theories of machair evolution (Ritchie 1966) it was stated that the model of development would be facilitated if there had been a steadily rising sea level throughout the Holocene. However, the evolution of the machair landforms, other coastal types and the occurrence of sub-tidal, terrestrial, organic deposits could be explained solely by very small amounts of late submergence and, more importantly, a change from a positive to a negative coastal sediment budget. It is doubtful if unambiguous evidence of lower sea levels can be found on the Atlantic shelf or associated with the adjacent coastlines, but what is common to most

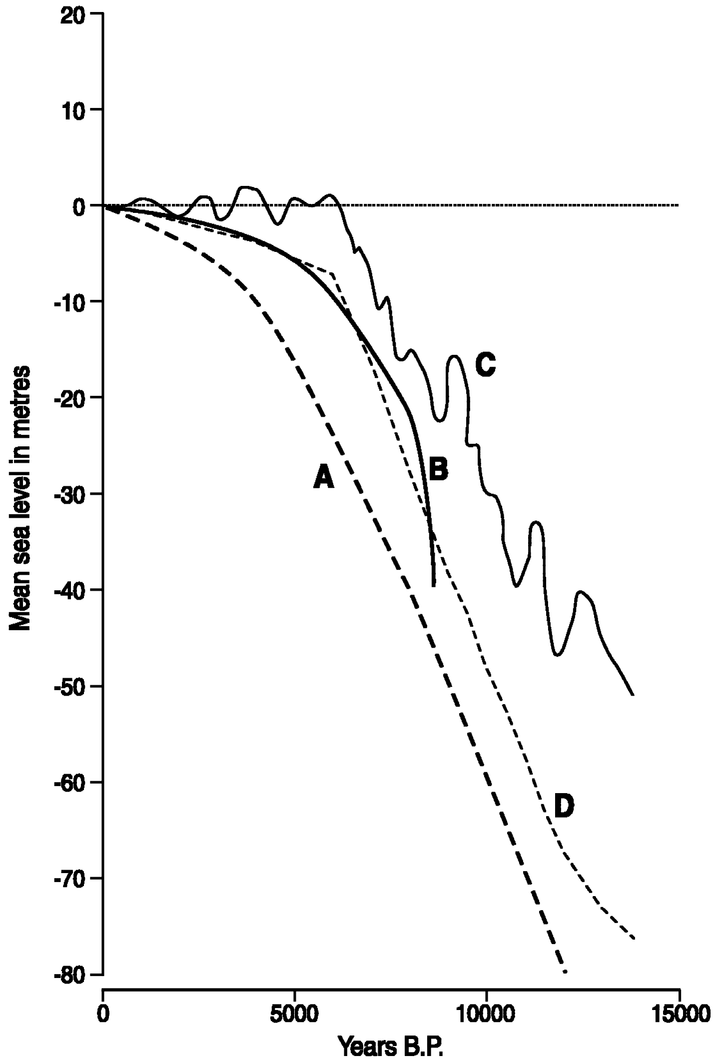

Figure 9 Estimates of sea level change during the Holocene marine transgression; curve A adapted from Clark (1980), B from Jelgersma (1980), C from Fairbridge (1961) and D from Lambeck (1995).

curves, which are likely to have been unaffected by isostatic or forebulge effects, is that at some period between 5000 and 7000 BP there was a significant slowing down in the rate of eustatic submergence, and it is this element which is critical to the evolution of the Atlantic coastline of the Uists.

The basic hypothesis which is used to model the evolution of the W coast of the Uists is furthered if there had been a steep rate of submergence with a distinctive slowing-down about 5000–7000 years ago. The latter date accords better with the time of the first sand incursions into the various inter-tidal sites. Thus at the time of inflexion of this postulated curve of sea-level rise, any sediment brought to contemporary shorelines by the earlier rapid rise would 'pause' and accumulate in sand banks, beaches and similar constructive shoreline features which would become ready sources for beach and dune building. Without further submergence, coastal processes could be expected to use these vast sediment banks to create prograding coastlines which, for a time, would reverse the process of shoreline retreat. Later, however, a negative sediment budget, accompanied by massive aeolian transport on to the land, would see a reversal to coastal erosion such as occurs everywhere in the Uists today.

This model of Holocene coastline evolution is dependent on two factors: the availability of large quantities of sediment on the Atlantic platform, and the extrapolation of the generally accepted rate of the Holocene Marine Transgression to this particular part of Britain. The supporting evidence for such a sweeping landwards of banks of sediment from the shelf comes from Admiralty Charts and British Geological Surveys (1:250,000 Map Sheets 1988; Stoker *et al.* 1993; Pantin 1991), which show that the sea bed of the Outer Hebrides is now relatively free of surface sediments other than in patches between rocky outcrops. This contrasts with most sea areas around the British Isles which tend to be covered by glacial and glacigenic deposits. Thus the absence of sediment on the shelf and the present abundance of sand onshore are powerful, albeit circumstantial, supports for the theory of translation from the shelf on to the land, but there is no direct evidence which provides a date for the initial massive transfer of this siliceous- and shell-sand from the shelf to the coastal margin. As with the process of transferring sand further inland, it is more likely to have been a continuous but uneven series of events within a particular, and possibly regionally, variable length of time. Dates are available for the first occurrence of sand in the inter-tidal organic deposits, and at some machair sites, but these blown sand incursions would be separated by some unknown timespan from the period when the main coastal beach and dune systems were first formed to seawards.

3.2. The transformation of the littoral zone

To understand the evolution of the machair and related Atlantic coastlines of the Uists during the Holocene, inductively derived models were produced by Ritchie (1979; Fig. 10). Subsequent investigations (Ritchie & Whittington 1994; Whittington & Edwards 1997) have led to the refinement of one of these models (Fig. 11) and also confirmed the importance of the inter-tidal organic deposits, preserved on the beaches of the Uists, as sources of evidence for machair development. Furthermore, the investigation at Borve on Benbecula (Whittington & Edwards 1997), because it embraced both space and time, permitted an examination of a machair cycle. The models which are summarised in Figures 10 and 11 have received support from recent palaeoecological and archaeological surveys of machair which used sediment micromorphology and optically stimulated luminescence dating programmes (Gilbertson *et al.* 1999), based mainly in southern South Uist, Barra, Vatersay and Sandray (Fig. 1). Evidence coming from the interpretation of the inter-tidal deposits at Camas Mór and Cladach Mór in North Uist, together with that from An Ceǿthan and Borve in Benbecula, the South Uist site of Peninerine and the terrestrial site of Fiarigeo, North Uist (Fig. 1), allows some correlation to be made between the periods of significant sand drift over an extensive area of the coastline of the Uists. The palynological examinations of these deposits have also allowed an assessment of the changes wrought to the vegetational cover by the sand incursions which, until now, have not been demonstrated.

The majority of the stratigraphic columns accompanying the pollen diagrams (Figs 3–8) reveal changes from the predominantly basal peat to a lithology which is either dominated, at first, by sand and then by sandy organics, or exclusively by the latter. The pollen diagrams also reveal the changes to the vegetation that occurred once the substrate took on these characteristics. The main features of these changes are shown in Figure 2. At Cladach Mór (Fig. 4) and Camas Mór (Fig. 7), established vegetation patterns managed initially to survive the addition of sand to the substrate, albeit with slight modifications. At Borve (Fig. 3), Peninerine (Fig. 5) and Fiarigeo (Fig. 8), despite there being no abrupt sand incursions, but an onset of a continuous sand input into organic sediments, there were severe and abrupt changes, with Poaceae becoming the dominant taxon. The only site where the pollen taxa do not change is at An Ceǿthan and there is no evidence for a sand incursion having ever happened at that location (Fig. 6). Apart from that site, by the time that the pollen records cease, all the sites are dominated by Poaceae, showing that not only did the incursion of the calcareous machair sand drastically alter the configuration and nature of the land surface but it also appears to have completely changed the existing vegetation mosaic of woodland and open areas, the latter having been originally dominated mainly by the acidophile *Calluna*.

Only the two northerly sites of Camas Mór and Cladach Mór record an abrupt sand incursion, at 6925 ± 30 BP (7790–7670 cal BP) and *c*. 7600 BP (8450–8340 cal BP), respectively. At Fiarigeo, the one terrestrial site, sand began to be deposited at *c*. 6480 BP (7540–7100 cal BP), while at Borve and at Peninerine that event occurred at 6605 ± 45 BP (7520–7430 cal BP) and *c*. 6500 BP (7610–7200 cal BP), respectively. Thus the suggestion, first mooted from the investigation at Cladach Mór (Ritchie & Whittington 1994) and substantiated from Borve (Whittington & Edwards 1997), that the sand incursions were asynchronous appears to be borne out. From these dates, it also appears that there was a N to S chronological progression in the sand incursions, but the fact that by 5255 ± 45 BP (6110–5930 cal BP) there had been no incursion at An Ceǿthan, lying between Cladach Mór and Borve, requires explanation. It is likely that this area round An Ceǿthan may have escaped a period of sand deposition as a result of its position, in the complex sub-system of strands and channels associated with the Atlantic islands of Baleshare and Kirkibost, which may well have been further inland than the other sites until marine erosion brought it into the current tidal zone. It is impossible to establish whether a younger sand incursion did occur at An Ceǿthan as the stratigraphy at the site, in common with all the other sites apart from Fiarigeo, is terminated by the truncation of the deposits to the depth they had achieved by 5195 ± 45 BP (6000–5890 cal BP; see Fig. 2).

4. Discussion

4.1. Changes in the woodland cover of the W coast

The established view of the Postglacial vegetational landscape

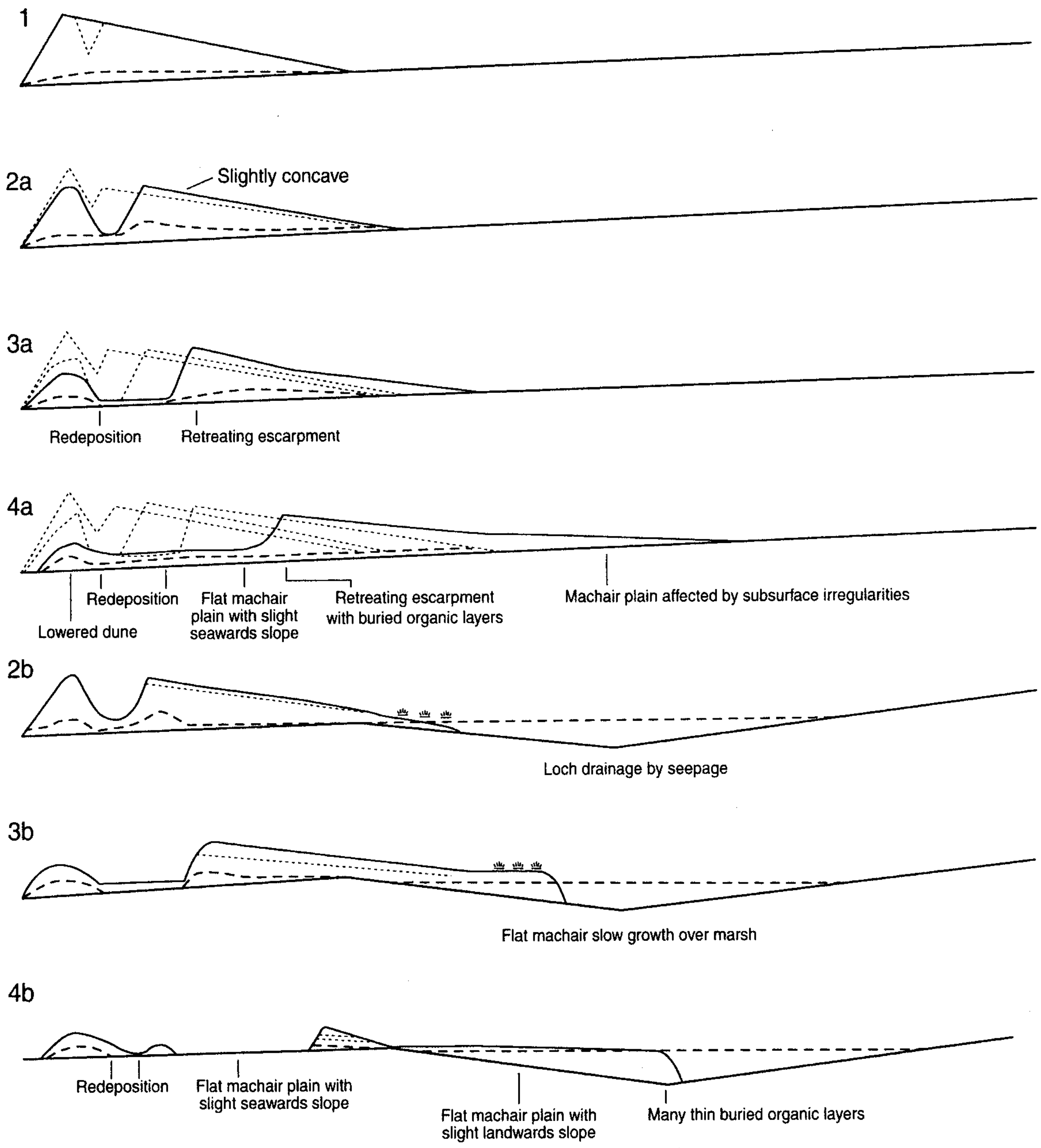

Figure 10 Two models of machair plain development: stage 1 is the initial build up of sand at the littoral; stages 2A–4A show the extension of the machair plain as a result of sequences of erosion by deflation and aeolian redeposition; stages 2B–4B show extension not by erosion but by sand encroachment into a pre-existing mire or loch basin.

of the Uists since the last glaciation had been that colonisation by woodland species would not have occurred and that the islands would have been devoid of a woodland cover probably since the last Interglacial. This view stemmed from two main sources. Firstly, today the islands are virtually treeless, they are drenched in salt spray and suffer from almost continuous strong winds with a W component. As a result, present-day perceptions have tended to prevent an objective appreciation of past conditions. The second source came from pioneering palynological studies, one from Barra (Blackburn 1946) which emphasised the non-arboreal components of the pollen record, and a further one, from the first major, modern palynological study of an Outer Hebridean site, that of the mire at Little Loch Roag, Lewis (Birks & Madsen 1979) which revealed no sign of a strong woodland presence for a period exceeding 9000 years.

Much early literature (e.g. Martin 1703; MacGillivray 1830; Lewis 1906, 1907; Samuelsson 1910; Beveridge 1911, 1926) had reported the presence of wood remains in peat deposits. More recently, Wilkins (1984) pointed to the existence of sub-fossil tree stumps on Lewis. A map illustrating the status of woodland in Scotland (McVean & Ratcliffe 1962), prior to human interference in the landscape, showed the Outer Hebrides to be wooded in the eastern half with a minor scattering of trees elsewhere, usually away from the W coast. Examination of polleniferous deposits located on the E of South Uist (Bennett *et al.* 1990) showed not only that there had been Holocene woodland colonisation, but the distinct likelihood that it included, among the dominant *Corylus* and *Betula,* some examples of thermophilous arboreal species, e.g *Alnus*, *Quercus* and *Ulmus*. Those findings provided the stimulus, in the mapping of the distribution of forest types in Britain at 5000 BP

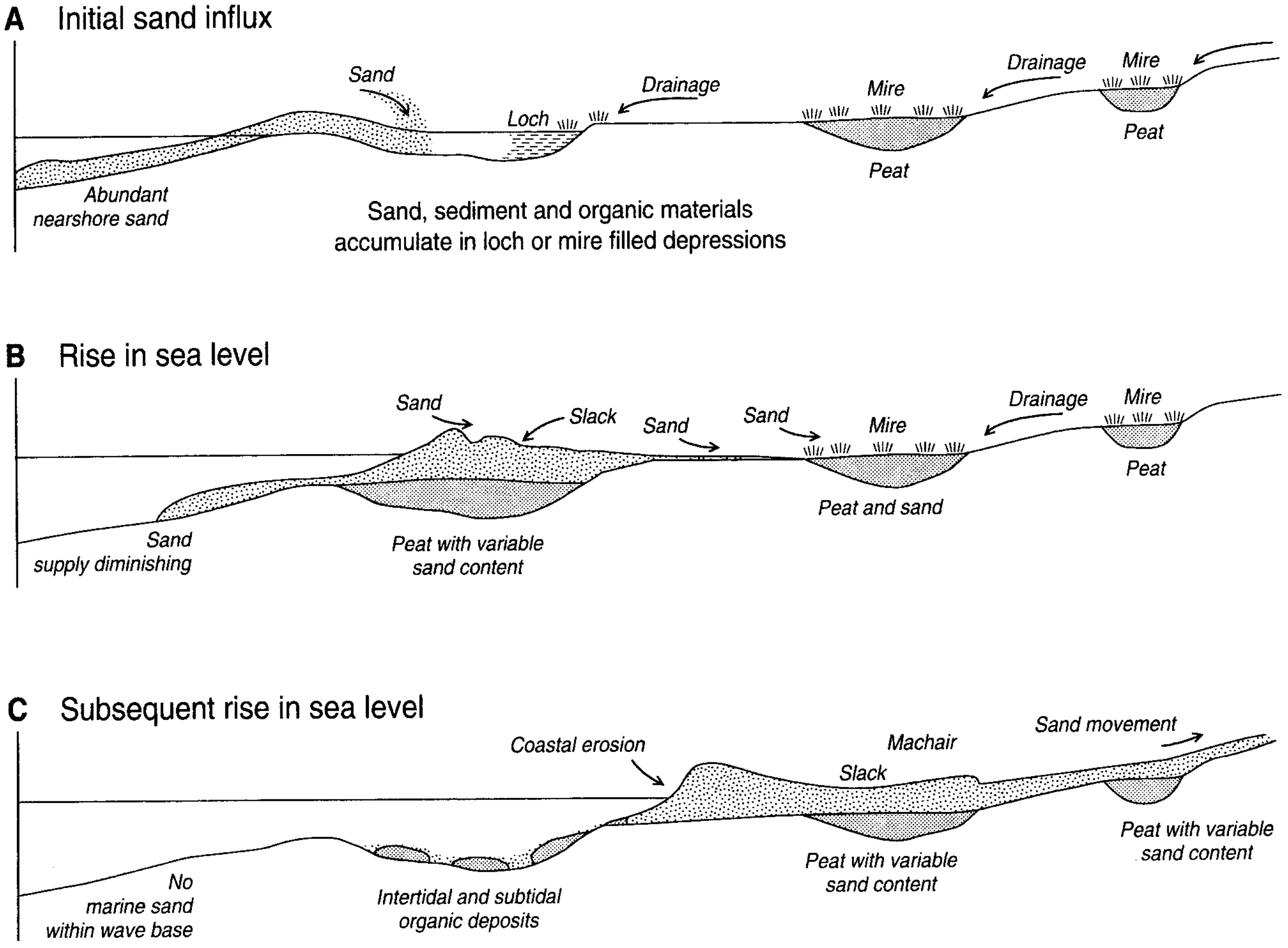

Figure 11 A refinement of the model of machair plain development as depicted in Figure 10, stages 2B–4B; the origin of inter-tidal organic deposits and their relation to machair sand movement is also shown.

(Bennett 1989), for the E half of the Outer Hebrides to be shown as supporting woodland, but with the W half bare. From about that time and since, however, further palynological work (Bohncke 1988; Bennett *et al.* 1997; Brayshay & Edwards 1996) has been undertaken and reappraisals of the vegetational history of the Outer Hebrides have been made (Fossitt 1990, 1996; Edwards *et al.* 2000). The cumulative result of this work was still to leave the status of the littoral zone in relation to a woodland cover as unknown.

The studies from the inter-tidal organic deposits reported here have shown that prior to the machair development significant quantities of the pollen of *Betula* and *Corylus* had been deposited. A recent statistical study (Brayshay *et al.* 2000) of the relationship between the present vegetation and contemporary pollen in a transect of South Uist, which included a woodland area, has shown that outside the wooded area arboreal pollen recruitment was very low, a finding which supported earlier considerations of this nature (Ashmore *et al.* 2000; Geary & Gilbertson 1988).This has two effects. First, it allays fears that evidence for former tree growth in the Outer Hebrides might have come from arboreal pollen recovered from deposits in those islands but originating from aerial transport from the mainland. Secondly, it confirms that the littoral zone, until the major machair sand incursions, had also supported a woodland cover. Furthermore, at An Ceòthan and Camas Mór there are, respectively, *Betula* and *Salix* roots and trunks *in situ* in the organic deposits.

In spite of the absence of known material remains for Mesolithic peoples in the Outer Hebrides, there are possible pollen and related records which could be interpreted as reflecting the impact of hunter-gatherers (Bohncke 1988; Edwards *et al.* 1995; Edwards 1996). Sites such as Borve and Peninerine reveal, variously, reductions in woodland taxa and expansions in *Calluna*, Poaceae and microscopic charcoal during the early and mid Holocene. The implications of this will be explored elsewhere and while it is not maintained that such impacts greatly impaired machair formation, it may have been the case that prehistoric human populations influenced the pace of machair sand spread in some areas.

4.2. The timing of the sand incursions

Gilbertson *et al.* (1999) identified several periods during which there was carbonate and/or quartzose sand drift in the Uists. In calendar years BP, the earliest drift dates from the period 9000–8300, with others occurring during 7500–7000, 6900–6400 and 5800–4200. Later sand drifts are also identified, but they are either local or fall outside the timespan covered by the inter-tidal sediments reported here. These extend from 8855 ± 60 BP (10170–9710 cal BP) to 5195 ± 45 BP (6000–5890 cal BP), supplemented by the site of Fiarigeo which has sandy sediments dated to 2630 ± 40 BP (2790–2710 cal BP). Dating sand inputs at these sites should provide supporting evidence for the periods defined by Gilbertson *et al.* (1999), especially as to whether each site was affected in each period of drift. Cladach Mór reveals the first major sand incursion (Fig. 2) and it falls within the 8300–9000 cal years BP episode identified by Gilbertson *et al.* (1999) which is the earliest on the Uists to involve carbonate sands. Although deposits were already present at Fiarigeo, An Ceòthan, Borve and Peninerine, none of these sites shows an abrupt sand deposition during this period. Camas Mór has such an incursion during the episode identified as occurring between 7500 and 7000 calibrated years BP. Cladach Mór, Borve and Peninerine, although possessing deposits which continue up to and beyond the final date of this episode, experienced no abrupt sand deposition but only a continuous input of sand into organic deposits. The fact that none of the pollen sites has any great depth of sand without incorporated organic material suggests that the major onshore incursion of sand across the position of the modern shoreline occurred after 5195 ± 45 BP (6000–5890 cal BP); that is the latest date which the truncated inter-tidal deposits can provide.

Close examination of the stratigraphy of all the inter-tidal sand and organic deposits, including those described in this paper, emphasises the need to consider the probable nature and location of the sites throughout the time of deposition. This interpretation is helped by a consideration of both the contemporary vegetation in the pollen sequence and recent changes in machair evolution. Relatively thick sand horizons without organic material occur close to zones of active erosion, either blow-outs or, more generally, at or near the coastal edge. Thin sand layers with organic material occur in landwards marginal machair zones, as either marshes or shallow lochs. Similar mixtures of organic materials and sand also occur in low machair hollows, analogous to dune slacks. Massive sand influxes would also occur, however, if there was a time when the dunes and machair were relatively unvegetated which could be a consequence of weather conditions, very rapid geomorphological change, or, possibly, anthropogenic disruption or disturbance.

It was noted earlier, however, that there is an occurrence of machair on the E coast of the Uist chain on the islands of Grimsay and Benbecula. The sand there owes its existence to transfer through the flooded North Ford between North Uist and Benbecula (Whittington & Ritchie 1988). The base of the major sand deposit at Kallin on Grimsay is dated to 4550 ± 70 BP (SRR-2988) and so it lies within the period 5840–4200 cal BP of extreme sand drift in the Outer Hebrides and NW Europe (Gilbertson *et al.* 1999). This date of *c.* 4500 BP may identify the time when the sea reached a critical level and breached the dune and machair barrier of the Atlantic seaboard to open up the North Ford, but it might also represent a coincidence with a time of increased storminess which would have mobilised extensive sand drifting throughout the Uists.

5. Conclusions

Results from five new sites on the Uist littoral have allowed several aspects of its evolution to be clarified or more firmly established. It has been shown that Holocene woodland, predominantly of birch and hazel, interspersed with open areas occurred in the western littoral zone until incursions of sand led to changes typified by the spread of calcareous grassland. The existence of this woodland also makes it probable that it was developed in coastal situations elsewhere in the Outer Hebrides and also inland on a greater scale than has hitherto been recognised.

The nature of the sand incursions which led to the development of the machair landforms is confirmed as having been very complex, both in time and space. Given the stratigraphy of the inter-tidal deposits, however, it would seem that most of the present onshore deposition of machair sand took place in the period calibrated to 5800–4200 BP, known to be one of strong sand drift on the coasts of NW Europe. The initiation of the pre-machair accumulation of sand at the coastline occurred earlier, probably at the time of the Holocene sea-level rise influxion. Within the major periods of sand drift defined by Gilbertson *et al.* (1999), there is every likelihood that alteration to the machair landscape was a continuing process. Whether such changes were continuous, punctuated by extreme events, cyclic or pulsed, or closely linked to the rate and amount of sea-level rise cannot yet be determined. Historical evidence also indicates the local significance of storm events, and land-use changes, perhaps including human activities since Mesolithic times.

The evolution of the coastal area of the Uists has been explored by the integration of evidence from two sub-regional sources. From South Uist has come the elucidation of machair landforms with their wide, flat deflation plains and marginal lochs and marshes. The part played in their creation by the Holocene Marine Transgression has been derived from an interpretation of dated and undated inter-tidal (and occasional sub-tidal) relict stratigraphy; this information has come mostly from Benbecula and North Uist. Thus two spatially distinct sources of evidence have been combined to indicate the nature of coastal evolution of the Uists. An examination of all machair areas in these islands, however, reveals that they contain similar major landform elements, but there are local differences due to a number of factors, among which are pre-sand topography, variations in water-table and drainage, nearshore bathymetry and the orientation of the coasts to the dominant source and direction of wave energy. Site-specific changes in agricultural practices since the Iron Age, with increasing impact in the historical period, have also produced local differences. Further research into the interactions of these factors would enable the evolutionary system to be increasingly refined and thus help in the understanding of contemporary changes which are presently of considerable importance in relation to the conservation and management of machair areas.

6. Acknowledgements

The authors wish to thank Mrs L. A. Wood for pollen preparations, Mr G. Sandeman for cartographic work and three referees for helpful comments. Grateful acknowledgement is made to the Carnegie Trust for the Universities of Scotland and the Royal Scottish Geographical Society for meeting the costs of the fieldwork, and NERC for the funding of the radiocarbon dates carried out at East Kilbride under the supervision of Dr D. D. Harkness and Mr B.F. Miller.

7. References

Angus, S. 1997. *The Outer Hebrides: the shaping of the islands.* Cambridge: The White Horse Press.

Armit, I. 1996. *The Archaeology of Skye and the Western Isles.* Edinburgh: Edinburgh University Press.

Ashmore, P., Brayshay, B. A., Edwards, K. J., Gilbertson, D. D., Grattan, J. P., Kent, M., Pratt, K. E. & Weaver, R. E. 2000. Allochthonous and autochthonous mire deposits, slope instability and palaeoenvironmental investigations in the Borve Valley, Barra, Outer Hebrides, Scotland. *The Holocene* **10**, 97–108.

Bennett, K. D. 1989. A provisional map of forest types for the British Isles 5000 years ago. *Journal of Quaternary Science* **4**, 141–4.

Bennett, K. D. 1994. *Annotated catalogue of pollen and pteridophyte spore types of the British Isles.* http://www.kv.geo.uu.se/pc-intro.html

Bennett, K. D., Fossitt, J. A., Sharp, M. J. & Switsur, V. R. 1990. Holocene vegetational and environmental history at Loch Lang, South Uist, Scotland. *New Phytologist* **114**, 281–98.

Bennett, K. D., Bunting, M. J. & Fossitt, J. A. 1997. Long-term vegetation change in the Western and Northern Isles, Scotland. *Botanical Journal of Scotland* **49**, 127–40.

Beveridge, E. 1911. *North Uist, its Archaeology and Topography, with notes upon the Early History of the Outer Hebrides*. Edinburgh: William Brown.

Beveridge, E. 1926. The submerged forest and peat of Vallay, North Lewis. *Scottish Naturalist*, 24–5.

Birks, H. J. B. & Madsen, B. J. 1979. Flandrian vegetation history of Little Loch Roag, Isle of Lewis, Scotland. *Journal of Ecology* **67**, 825–42.

Blackburn, K. B. 1946. On a peat from the island of Barra, Outer Hebrides. Data for the study of post-glacial history. X. *New Phytologist* **45**, 44–9.

Bohncke, S. J. P. 1988. Vegetation and habitation history of the Callinish area, Isle of Lewis. *In* Birks, H. H., Birks, H. J. B., Kaland, P. E. & Moe, D. (eds) *The Cultural Landscape, Past, Present and Future*, 445–61. Cambridge: Cambridge University Press.

Boyd, J. M. (ed.) 1979. The natural environment of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* **77B**.

Brayshay, B. A., Gilbertson, D. D., Kent, M., Edwards, K. J., Wathern, P. & Weaver, R. E. 2000. Surface pollen-vegetation relationships on the Atlantic seaboard: South Uist, Scotland. *Journal of Biogeography* **27**, 359–76.

Brayshay, B. A. & Edwards, K. J. 1996. Late-glacial and Holocene vegetational history of South Uist and Barra. *In* Gilbertson, D., Kent, M. & Grattan, J. (eds) *The Outer Hebrides; the Last 14,000 Years*, 13–26. Sheffield: Sheffield Academic Press.

British Geological Survey. 1988. *Sea bed sediments and Quaternary Geology*. 1:250 000: Sheet 57N 08W (Little Minch); Sheet 56N 08W (Tiree).

Clark, J. A. 1980. A numerical model of worldwide sea level changes on a visco-elastic earth. *In* Mörner, N. A. (ed.) *Earth Rheology, Isostasy and Eustasy*, 525–34. New York: Wiley.

Dawson, A. G. 1992. *Ice Age Earth*. London: Routledge.

Edwards, K. J. 1996. A Mesolithic of the Western and Northern Isles of Scotland? Evidence from pollen and charcoal. *In* Pollard, T. & Morrison, A. (eds) *The early prehistory of Scotland*, 23–38. Edinburgh: Edinburgh University Press.

Edwards, K. J., Whittington, G. & Hirons, K. R. 1995. The relationship between fire and long-term wet heath development in South Uist, Outer Hebrides, Scotland. *In* Thompson, D. B. A., Hester, A. J. & Usher, M. B. (eds) *Heaths and moorland: cultural landscapes*, 240–8. Edinburgh: HMSO.

Edwards, K. J., Mulder, Y., Lomax, T. A., Whittington, G. & Hirons, K. R. (2000). Human-environment interactions in prehistoric landscapes: the example of the Outer Hebrides. *In* Hooke, D. (ed.) *Landscape: the richest historical record, Society for Landscape Studies, Supplement Series 1*, 13–32.

Faegri, K. & Iversen, J. 1989. *Textbook of pollen analysis*, 4th edn by K. Faegri, P. E. Kaland & K. Krzywinski. Chichester: John Wiley & Sons.

Fairbridge, R.W. 1961. Eustatic changes in Sea Level. *Physics and Chemistry of the Earth* **4**, 100–85.

Farrow, G. E., Cucci, C. & Scoffin, T. P. 1978. Calcareous sediments on the nearshore continental shelf of western Scotland. *Proceedings of the Royal Society of Edinburgh* **76B**, 55–76.

Flinn, D. 1978. The glaciation of the Outer Hebrides. *Geological Journal* **13**, 195–9.

Fossitt, J. A. 1990. Holocene Vegetation History of the Western Isles, Scotland (Unpublished Ph.D. thesis, University of Cambridge).

Fossitt, J. A. 1996. Late Quaternary vegetation history of the Western Isles of Scotland. *New Phytologist* **132**, 171–96.

Geary, B. & Gilbertson, D. D. 1988. Pollen taphonomy of trees in a windy climate: Northbay Plantation, Barra, Outer Hebrides. *Scottish Geographical Magazine* **113**, 113–20.

Geikie, J. 1873. On the glacial phenomena of the Long Island or Outer Hebrides (First Paper). *Quarterly Journal of the Geological Society* **29**, 532–45.

Geikie, J. 1878. On the glacial phenomena of the Long Island or Outer Hebrides (Second Paper). *Quarterly Journal of the Geological Society* **34**, 819–70.

Gilbertson, D., Kent, M. & Grattan, J. (eds) 1996. *The Outer Hebrides: the last 14,000 years*. Sheffield: Sheffield Academic Press.

Gilbertson, D. D., Schwenninger, J.-L., Kemp, R. A. & Rhodes, E. J. 1999. Sand-drift and Soil Formation Along an Exposed North Atlantic Coastline: 14,000 Years of Diverse Geomorphological, Climatic and Human Impacts. *Journal of Archaeological Science* **26**, 439–69.

Grimm, E.C. 1991. *TILIA and TILIA.GRAPH*. Springfield: Illinois State Museum.

Hall, A. M. 1996. Quaternary geomorphology of the Outer Hebrides. *In* Gilbertson, D. D., Kent, M. & Grattan, J. P. (eds) *The Outer Hebrides; the last 14,000 Years*, 5–12. Sheffield: Sheffield Academic Press.

Halstead, C. A. 1979. A statistical approach to the geomorphology of the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* **77B**, 85–96.

Hansom, J. D. 1999. The coastal geomorphology of Scotland: understanding sediment budgets for effective management. *In* Baxter, J. M. (ed.) *Scotland's Living Coastline*, 34–44. London: The Stationery Office.

Jelgersma, S. 1966. Sea level changes during the last 10 000 years. *In World Climate from 8000 to 0 B.C. Proceedings of an International Symposium*, 54–71. London: Royal Meteorological Society.

Jelgersma, S. 1980. Late Cenozoic sea level changes in the Netherlands and the adjacent North Sea basin. *In* Mörner, N. A. (ed.) *Earth Rheology, Isostasy and Eustasy*, 435–48. New York: Wiley.

Lambeck, K. 1995. Glacial isostasy and water depth in the Late Devensian and Holocene on the Scottish Shelf west of the Outer Hebrides. *Journal of Quaternary Science* **10**, 83–6.

Lewis, F. J. 1906. The plant remains of the Scottish peat mosses. II. The Scottish Highlands. *Transactions of the Royal Society of Edinburgh* **45**, 335–59.

Lewis, F. J. 1907. The plant remains of the Scottish peat mosses. III. The Scottish Highlands and the Shetland Islands. *Transactions of the Royal Society of Edinburgh* **46**, 33–70.

MacGillivray, W. 1830. Account of the series of islands usually denominated the Outer Hebrides. *Edinburgh Journal of Natural and Geographical Sciences* **1**, 245–50; **2**, 87–95.

McVean, D. N. & Ratcliffe, D. A. 1962. *Plant Communities of the Scottish Highlands*. London: HMSO.

Martin, M. 1703. *A description of the Western Isles of Scotland*. London: Bell.

Mate, I. D. 1991. The theoretical development of machair. *Scottish Geographical Magazine* **108**, 35–8.

Mörner, N. A. 1976. Eustasy and glacial changes. *Journal of Geology* **84**, 123–51.

Mörner, N. A. (ed.) 1980. *Earth Rheology, Isostasy and Eustasy*. New York: Wiley.

Mulder, Y. 1999. Aspects of vegetation and settlement history in the Outer Hebrides, Scotland (Unpublished Ph.D. thesis, University of Sheffield).

Pantin, H. M. 1991. The sea-bed sediments around the United Kingdom: their bathymetric and physical environment, grain size, mineral composition and associated bedforms. *British Geological Survey Research Report*. SB/90/1.

Peacock, J. D. 1984. *Quaternary geology of the Outer Hebrides*. Report of the British Geological Survey **16**, No. 2.

Pirazzoli, P. A. 1996. *Sea-level Changes: The last 20 000 Years*. Chichester: Wiley.

Ritchie, W. 1966. The post-glacial rise in sea-level and coastal changes in the Uists. *Transactions of the Institute of British Geographers* **39**, 79–86.

Ritchie, W. 1976. The meaning and definition of machair. *Transactions of the Botanical Society of Edinburgh* **42**, 431–40.

Ritchie, W. 1979. Machair development and chronology in the Uists and adjacent islands. *Proceedings of the Royal Society of Edinburgh* **77B**, 107–22.

Ritchie, W. & Whittington, G. 1994. Non-synchronous aeolian sand movements in the Uists: the evidence of inter-tidal organic and sand deposits at Cladach Mór. *Scottish Geographical Magazine* **110**, 40–6.

Samuelsson, G. 1910. Scottish peat mosses. *Bulletin of the Geological Institute of Uppsala* **10**, 197–260.

Smith, D. E. & Dawson, A. G. (eds) 1983. *Shorelines and Isostasy*. London: Academic Press.

Stace, C. 1997. *New flora of the British Isles*, 2nd edn. Cambridge: Cambridge University Press.

Stoker, M. S., Hitchen, K. & Graham, C. C. 1993. *The geology of the Hebrides and West Shetland shelves, and adjacent deep-water areas*. London: HMSO for the British Geological Survey.

Stuiver, M., Reimer, P. J., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, F. G., van der Plicht, J. & Spurk, M. 1998. INTCAL98 Radiocarbon Age Calibration, 24,000–0 cal B.P. *Radiocarbon* **40**, 1041–83.

Stuiver, M. & Reimer, P. J. 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* **35**, 215–30.

von Weymarn, J. A. 1974. Coastline development in Lewis and Harris, with particular reference to the effects of glaciation (Unpublished Ph.D. thesis, University of Aberdeen).

von Weymarn, J. A. 1979. A new concept of glaciation in Lewis and Harris. *Proceedings of the Royal Society of Edinburgh* **77B**, 97–105.

Whittington, G. & Edwards, K. J. 1997. Evolution of a machair landscape: pollen and related studies from Benbecula, Outer Hebrides, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **87** (for 1996), 515–31.

Whittington, G. & Ritchie, W. 1988. *Flandrian Environmental Evolution on North-East Benbecula and Southern Grimsay, Outer Hebrides, Scotland.* O'Dell Memorial Monograph, Department of Geography, University of Aberdeen **21**.

Wilkins, D. A. 1984. The Flandrian woods of Lewis (Scotland). *Journal of Ecology* **72**, 251–8.

WILLIAM RITCHIE, Office of the Vice-Chancellor, University of Lancaster, Lancaster LA1 4YW, UK

GRAEME WHITTINGTON, School of Geography and Geosciences, Irvine Building, University of St Andrews, St Andrews, Fife KY16 9AL, UK

KEVIN J. EDWARDS, Department of Geography & Environment and Centre for Northern Studies, University of Aberdeen, Elphinstone Road, Aberdeen AB24 3UF, UK

MS received 5 June 2000. Accepted for publication 14 December 2000.