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Mid-Holocene environmental changes in the Bay of Skaill, Mainland Orkney, Scotland: an integrated geomorphological, sedimentological and stratigraphical study

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ABSTRACT: A detailed multidisciplinary investigation of intertidal freshwater sediments exposed in the north of the Bay of Skaill, Mainland Orkney, Scotland, have revealed a complex sedimentary sequence. This provided evidence for dynamic coastal environmental changes in the area since the mid-Holocene. Freshwater ponds developed on glacial sediments ca. 6550 ± 80 yr BP (cal. BC 5590–5305). From ca. 6120 ± 70 yr BP (cal. BC 5040–4855), these were infilled by blown sand from the distal edge of a dune ridge located to the west. Thereafter, a series of sand-blow events alternating with periods of quiescence occurred until ca. 4410 ± 60 yr BP (cal. BC 3325–2900). Between ca. 5240 ± 160 and 4660 ± 80 yr BP (cal. BC 4370–3115), pollen and charcoal records show evidence of anthropogenic activities, associated with the nearby Neolithic settlement of Skara Brae. Agriculture was probably affected by recurrent sand movement and widespread deposition of calcium carbonate in the hinterland of the bay. Machair development between ca. 6100 and 5000 yr BP (cal. BC 5235–3540) corresponds to a mid-Holocene phase of dune formation recorded elsewhere in northwest Europe. The more recent and progressive formation of the bay has probably been related to increasing external forcing via storminess, long-term relative sea-level change and sediment starvation within this exposed environment. Copyright © 2000 John Wiley & Sons, Ltd.

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KEYWORDS: intertidal freshwater deposits; machair; Neolithic impact; Skara Brae; Orkney.

Introduction

In the British Isles, machair—low-altitude coastal landforms primarily composed of blown, often calcareous sand—is characteristically found in the southwestern Outer Hebrides, along the Atlantic seaboard of mainland Scotland and Ireland and in limited areas of coastal southwest England (Ritchie, 1967, 1979; Evans, 1979; Bassett and Curtis, 1985; Robertson-Rintoul and Ritchie, 1990). Gilbertson *et al.* (1999) presented a machair chronostratigraphy for the Outer Hebrides and reviewed models of its formation. Two of the latter are considered during the analysis of the sedimentary sequences investigated here. Firstly, Ritchie (1966, 1979) proposed that rising Holocene relative sea levels resulted in the remobilisation inland of a finite volume of off-shore glacigenic and biogenic sand into dune ridges, the erosion of which resulted in the formation of machair. Significant differences in machair morphology encountered in the Uists, Outer Hebrides, were related to whether ground elevation rose or fell inland from the coastline (Ritchie, 1979). Sediment starvation of the coastal system eventually led to dune migration inland over back-dune freshwater marsh and pond habitats, with their associated sediments (marl and peat) ultimately reappearing on the seaward face of the dune in an intertidal position (Ritchie, 1985). Secondly, Mate (1992) believed that continuous production of off-shore biogenic carbonate sand would result in the consistent formation of machair through time. A chronology of machair formation was proposed for the Outer Hebrides by Ritchie (1979) based on morphology, stratigraphy and related horizons of anthropogenic occupation. However, locally variable stratigraphical sequences resulting from non-synchronous sand-blow events were later encountered in the archipelago,

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thereby restricting their use for the establishment of a regional history of machair formation (Ritchie and Whittington, 1994). Local variations also have been encountered in attempts to establish regional patterns of dune development in other parts of the British Isles (e.g. Delany and Devoy, 1995; Wilson and Bradley, 1997). Detailed chronologies of sand instability are therefore restricted to small geographical units (e.g. Whittington and Edwards, 1997; Gilbertson *et al.*, 1999).

Despite such local variations, early to mid-Holocene periods of increasing sand instability associated with episodes of dune building activity have been identified in northwest Europe. Early Holocene (ca. 8.5 to 7.7 ka) evidence of sand movement in the British Isles is restricted to sites on the Cumbrian coast and in the Outer Hebrides (Huddart *et al.,* 1977; Ritchie and Whittington, 1994). Mid-Holocene dune building episodes, however, occurred widely in northwest Europe between 6.7 and 4 ka (Jelgersma and van Regteren Altena, 1969; Cruickshank, 1980; Hamilton and Carter, 1983; Pye and Neal, 1983; de Ceunynck, 1985; Tooley, 1990; Wilson, 1991; Carter and Wilson, 1993; Whittington and Edwards, 1997; Gilbertson *et al.*, 1999).

Hitherto, most studies of machair have been either of a geomorphological or stratigraphical nature, with biostratigraphical data rarely coming from more than one fossil group. For example, machair morphological types have been described (e.g. Ritchie, 1979; Bassett and Curtis, 1985) and mollusc analysis of machair and dune-sand sections has enabled local environmental conditions to be reconstructed (e.g. Spencer, 1975; Evans and Spencer, 1977; Evans, 1979). A combined stratigraphical and sedimentological approach has often been used in the study of intertidal and subtidal freshwater deposits located seaward of machair. Detailed vegetational changes and local aeolian processes have been deduced from pollen analyses (e.g. Whittington and Edwards, 1993, 1997). Multidisciplinary work of the type described in this paper has been restricted mainly to areas where direct evidence of relative sea-level change has been encountered (e.g. Jennings *et al.*, 1998).

In Orkney, dune and machair landforms are locally extensive, for example in the northern isles where they cover one-third of Sanday (Davidson and Jones, 1993). Despite a study of its sand beaches by Mather *et al.* (1974), little research into machair mode of formation and evolution has been carried out in the archipelago. Numerous exposures of intertidal freshwater deposits have been recorded (Fig. 1) since the nineteenth century (Watt, 1820; Traill, 1868; Traill Dennison, 1893), but their potential for reconstructing past coastal environments has been largely ignored. This paper combines morphological, lithostratigraphical, sedimentological, biostratigraphical (pollen and charcoal, mollusc and ostracod) and chronostratigraphical data from two intertidal exposures of freshwater sediments in the northern part of the Bay of Skaill, Mainland Orkney, with the aim of reconstructing in detail the local coastal environment.

Site location and previous palaeoenvironmental work in the area

The Bay of Skaill (National Grid: HY2319), located on the western coast of Mainland Orkney, is wide, semi-circular and strongly exposed to westerly winds (Figs 1 and 2). It is characterised by a high-energy coastal environment that has resulted in a diverse morphology. Between the two headlands at the mouth of the bay, a shallow submerged ridge of unknown composition appears to be present, sometimes acting as a breakwater in swell conditions. The irregularity of the latter phenomenon suggests a mobile landform (Mr. P. Rice, personal communication). A low-angle sandy foreshore is backed by a steep, swash-aligned (*sensu* Carter and Orford, 1993) gravel beach, the height of which ranges between ca. +5.1 and +9.3 m OD (Fig. 2). This feature has mostly overridden a truncated dune ridge, the remaining parts of which attain ca. +10 m OD. Immediately inland is extensive machair, mainly of hillocky and hilly types (*sensu* Ritchie, 1979). The machair vegetation is characteristically short pasture including *Festuca rubra*, *Agrostis tenuis*, *Carex flacca* and *Plantago maritima* (Keatinge and Dickson, 1979).

The Neolithic settlement of Skara Brae, occupied between ca. 4.7 and 3.8 ka (cal. BC 3640–1942) (Clarke, 1976; Ashmore, 1998), lies at the southern end of the bay (Fig. 2). Despite a lack of evidence, Childe (1931) considered that this settlement had originally been located near a freshwater loch. Early palaeoenvironmental work in the bay involved a brief description of plant macrofossils from an intertidal peat bed by Watt (1820), who believed some of them to be from coniferous trees. The analysis of land molluscs from dune-sand sections south of Skara Brae (Number 4 in Fig. 1) indicated that prior to the deposition of sand, open woodland extended inland of the sites investigated, with grassland to the west, probably in the coastal depression now occupied by the bay (Spencer, 1975). As sand accumulated, open vegetation replaced the woodland. The observed lithostratigraphical and biostratigraphical changes were attributed to increasing storminess and salt-spray deposition, and possibly restricted Neolithic woodland clearance.

Keatinge and Dickson (1979) analysed pollen profiles from sedimentary sequences at Loch of Skaill and Pow, located at the inland margins of the machair (Fig. 1). Their findings supported Spencer's conclusions. An open *Betula-Corylus* woodland existed until ca. 5 ka. The associated understorey community was characterised by tall herbs and ferns, probably including *Juncus effusus*, *Luzula sylvatica*, *Deschampsia caespitosa*, *Filipendula ulmaria*, *Athyrium felix-femina* and *Dryopteris dilitata*, which today constitute the 'treeless woodland' found in Orcadian dales and sheltered gullies (Bullard, 1973). Rapid sand accumulation was initiated thereafter, and together with increasing anthropogenic impact on the surrounding landscape, resulted in the decline of woodland. The understorey community remained for some time, before declining as machair grassland was gradually established. Additionally, Keatinge and Dickson (1979) investigated an intertidal *Phragmites* peat located seaward of Skara Brae, and suggested that the bay itself was once the site of a freshwater loch, isolated from the sea by a barrier. Increasing wind speed and storminess, coupled with a rising sea-level, were considered the likely cause of the breaching of this barrier, and thus the creation of the bay between ca. 5.7 and 5 ka. These authors believed that machair landforms developed subsequent to the formation of the Bay of Skaill and its sandy beach, as blown sand was redistributed inland from ca. 5 ka.

Methods

The most significant morphological features below +10 m OD were mapped in the field at a scale of 1:10000 (Fig.

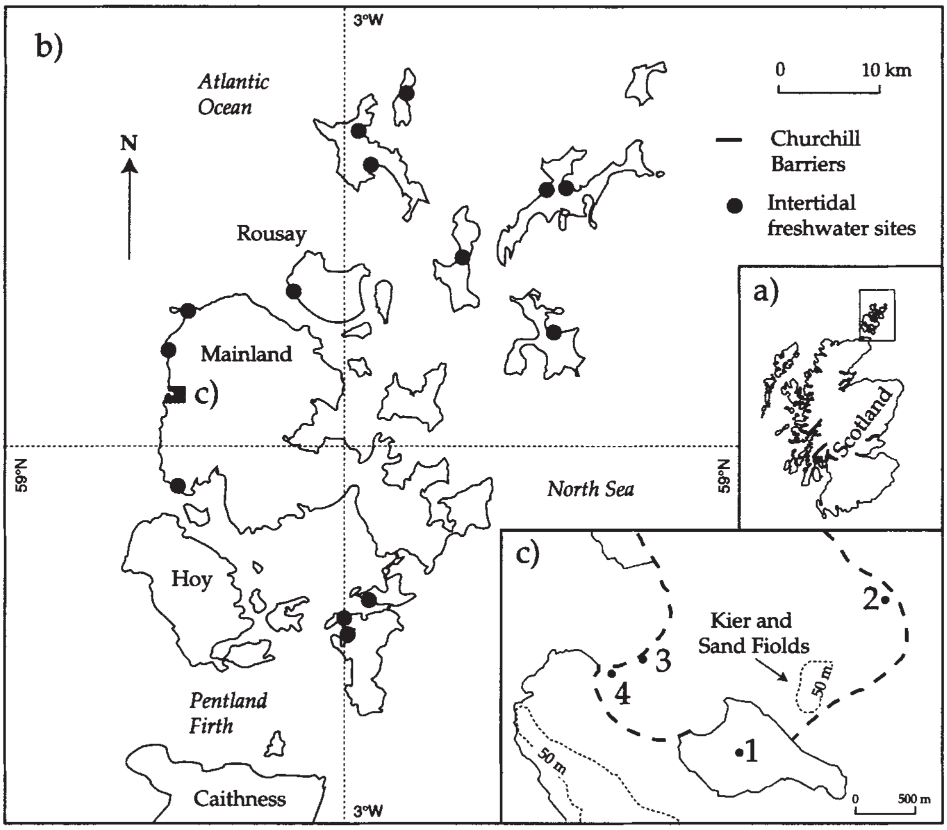


Figure 1 Location map (a) Orkney; (b) intertidal freshwater deposits reported in the literature (see text for references); (c) Bay of Skaill and location of the palaeoenvironmental sites mentioned in the text; 1, Loch of Skaill; 2, Pow; 3, *Phragmites* peat (Keatinge and Dickson, 1979); 4, dune sand sites south of Skara Brae (Spencer, 1975). Thick dashed line: limit of blown sand (Keatinge and Dickson, 1979; de la Vega Leinert, 1998).

2). A short lithostratigraphical transect (A) of boreholes was made using an Eijelkamp gouge. The thickest sedimentary sequence (Core SK94) was subsequently sampled with a Stitz percussion corer. A stepped profile was prepared ca. 30 m north of transect A, from which monoliths were taken (Core SK134). Lithostratigraphical descriptions are based on a modified version of the Troels-Smith scheme (1955). All boreholes, and heights along the gravel beach crest, were levelled instrumentally to Ordnance Datum (OD Newlyn). High and low temperature loss-on-ignition (LOI—to estimate the organic, minerogenic and carbonate content of the sediments) and particle size analyses (using a Malvern 2600 longbed laser granulometer) were carried out on the sediments from core SK134.

The preparation of pollen followed Stockmarr (1971) and Barber (1976). Pollen identification was based on the keys of Andrew (1984) and Moore *et al.* (1991), and the Department of Geography, Coventry University, modern type-slide collection. Plant nomenclature is that of Stace (1991), as recommended by Bennett *et al.* (1994). Pollen concentrations were low in all samples. A minimum of 300 land pollen was counted at each sampled level, except a few sand-dominated levels where the minimum was 100. Arboreal pollen includes both tree and tall shrub taxa. Coryloid pollen is assumed to be from *Corylus* rather than *Myrica*, as proposed by previous workers in the area on the basis of both fossil and modern records of these genera (Moar, 1969; Keatinge and Dickson, 1979; Bunting, 1994). The pollen data are presented as percentages of total land pollen (TLP). For non-land pollen, the related sum was obtained by adding TLP to the respective sum of the group required (e.g. TLP + spores). Pollen and spore concentrations were calculated for both cores, with the addition of influx rates for core SK134. The percentage data were used to designate local pollen assemblage zones (LPAZs) and subzones with the CONISS statistical program (Grimm, 1987). Concentration and influx data were processed similarly, but this did not produce significantly different sets of LPAZs. The percentage LPAZs were therefore transferred to both concentration and influx diagrams. Microscopic charcoal areas were counted following Clark (1982) and are expressed in cm^{-2} cm^{-3}. Additionally, Charcoal:Pollen (C:P) ratios were calculated to obtain statistically representative charcoal input estimates (Patterson *et al.*, 1987; Whittington and Edwards, 1997). The diagrams were drawn using *Tilia 2.0.b.5* and *Tilia.Graph* (Grimm, 1991–1993).

Mollusc taxonomy and ecological information were based on Sparks (1961), Kerney (1976) and Kerney and Cameron (1976). Ostracod identification and taxonomy followed Athersuch *et al.* (1989), Henderson (1990) and Griffiths (1995). Mollusc and ostracod samples were washed through 250 and 125 μm sieves and dried overnight in an oven at 40°C. All mollusc specimens were identified and frequencies are expressed in total numbers. Ostracod frequencies represent either total numbers (SK134) or percentages (SK94—with a total ostracod sum of 300 specimens per counted sample). It is assumed that the thickness of the bulk samples analysed (between 3 and 5 cm) minimised any differential mollusc and ostracod distribution which could have been due to seasonality. Local mollusc and ostracod assemblage zones (LMAZs and LOAZs) were designated by eye, as both the number of levels investigated and taxa recorded were low.

Nine sediment samples (3 from SK95 and 6 from SK134)

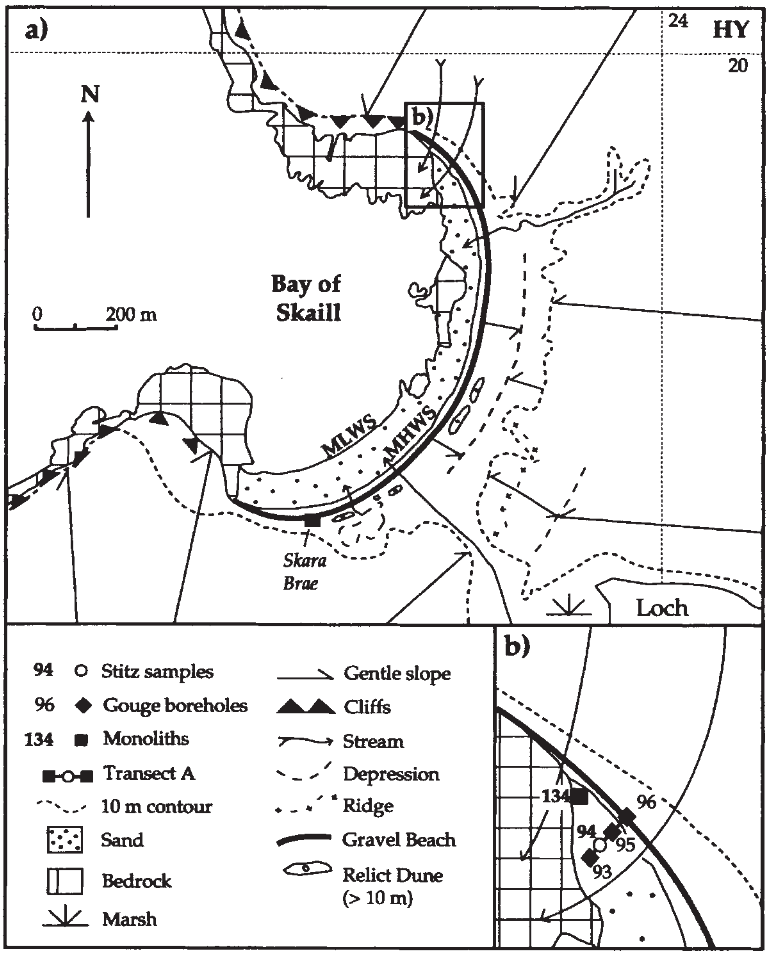


Figure 2 Morphological map and location of transect A and core SK134 (source: OS Map 1:10000 and fieldwork).

were sent to Beta Analytic for radiocarbon analysis. None exceeded 2 cm in thickness and each was pre-treated following the method of Pilcher (1991). According to their organic content, the samples were processed using either the AMS or standard radiometric technique. Both radiocarbon years before present (BP) and calibrated years BC are quoted in the text. The calibration of the radiocarbon results was performed by Beta Analytic using the Pretoria curve (Vogel *et al.*, 1993).

Results and interpretation of the data

Lithostratigraphy and sedimentology

Despite altitudinal differences, the lithostratigraphical units recorded in both cores are similar (Fig. 3 and Table 1). Core SK134 is the thickest sequence. The basal glacially derived sediments, composed of blue-grey, gritty clay, are overlain by a thin veneer of humified, minerogenic peat (in SK94), and by an olive, organic marl with fragments of *Phragmites*. *Chara* oospores were observed in the marl during detailed laboratory description. The marl indicates a carbonate-rich substrate, low-energy environment and high aquatic productivity. Overlying this is a series of light-coloured minerogenic units (coarse sand primarily composed of marine shell debris) alternating with dark organic-rich layers (humified minerogenic peat and organic sandy silt).

In SK134, the organic content is generally low (except in unit 9, where it reaches ca. 50%), and increases discretely in silty clay horizons (Fig. 4). The latter indicates that vegetation colonisation was sparse in the vicinity of the site throughout the deposition of the sand units, and suggests that the sandy landforms nearby were mostly bare. Carbonates (assumed to be primarily $CaCO_3$) attain 22%, with values highest in the sand units. There is a clear coarsening upward trend in particle size distribution. Initially, coarse to medium silt dominates the sequence, although medium sand becomes prominent towards the top. Mean grain sizes in the sand units of either core range between 250 and 500 μm, a range compatible with an aeolian origin (Briggs, 1977). To test the latter, a sample of modern blown sand from Traigh Morgabost, Isle of Harris, Outer Hebrides (National Grid: NG04659693), was analysed in order to compare its particle size distribution with that of the Bay of Skaill sand units. The modern sample had a fairly well sorted, unimodal distribution with particles ranging from 19 to 1400 μm, and a mean grain-size of 630 μm. The coarser particles were tabular shell fragments, the low density of which would have favoured their entrainment by wind. The fossil sand samples were similar in texture to the modern one although their particle-size was less well sorted. The presence of fine silt and clay and the absence of any visible stratification within the sand units precludes the possibility of winnowing action. Moreover, the coarse sand fraction only rarely reached 30%, and although the sand units are composed of marine shell debris there is no evidence in the palaeoecological data to suggest that these units relate to either storm or beach material. It is therefore concluded that all sand units in the Bay of Skaill sites relate to a combination of

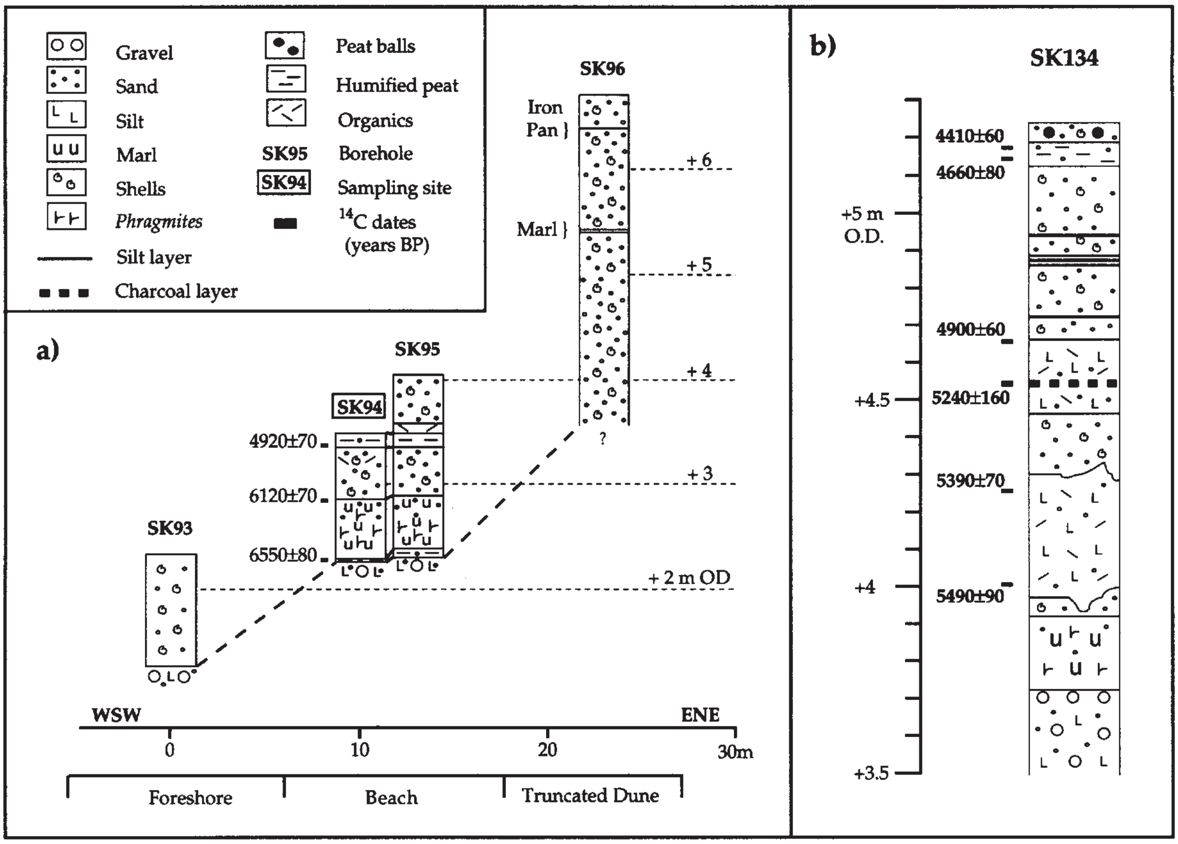


Figure 3 Lithostratigraphy: (a) transect A; (b) core SK134 (see Fig. 2 for the location of transect A and core SK134).

Table 1 Lithostratigraphy of cores SK94 and SK134

SK94 (HY23431963) Surface altitude (m OD)	Lithostratigraphy	Unit	SK134 (HY23431967) Surface altitude (m OD)
—	Inorganic, shelly sand	10	+5.25
—	Minerogenic, humified peat	9	+5.19
—	Inorganic, shelly sand	8	+5.13
—	Organic, sandy silt (charcoal layer at +4.54 m)	7	+4.66
—	Inorganic, shelly sand	6	+4.48
+3.48	Minerogenic, humified peat/organic, sandy silt	5	+4.26
+3.35	Inorganic, shelly sand	4	+3.97
+2.86	Olive, sandy, *Phragmites* marl	3	+3.92
+2.29	Minerogenic, humified peat	2	—
+2.26	Blue-grey, gritty clay	1	+3.72

aeolian action and freshwater deposition. The coarsening trend in particle size is interpreted as indicating an increase in environmental energy and sand mobility. Gradual strengthening of aeolian processes and/or a more proximal source of sediment supply may have been involved. Frequent marked oscillations in particle size are observed in horizons where silt and clay predominate (Fig. 4). These fine-grained horizons may mark phases of either reduced sand blow, or declining sand supply, although flooding by freshwater was probably an important factor.

Chronostratigraphical framework

The radiocarbon dates obtained provide a secure mid-Holocene context for the environmental changes identified. However, there are problems which militate against the use of the dates for finer resolution interpretation. Firstly, the calculation of sediment accumulation rates is impaired by the age overlaps the dates display at two standard deviations (Fig. 5 and Table 2). This is especially the case for several dates obtained on SK134, which are statistically inseparable at the 95% confidence level. Although a fast sediment accumulation rate could account for these overlaps, a combination of other factors, including a hard-water effect, may have played a significant role. The underlying carbonate-rich Stromness Flags bedrock (Mykura, 1976), combined with recycling of old carbon by aquatic plants (Pilcher, 1991) are likely causes for this. It is also possible that contamination by carbon in macroscopic charcoal of a younger age than that of its sedimentary matrix has taken place. Harkness (in Keatinge and Dickson, 1979) attempted to quantify errors from hard-water contamination in this

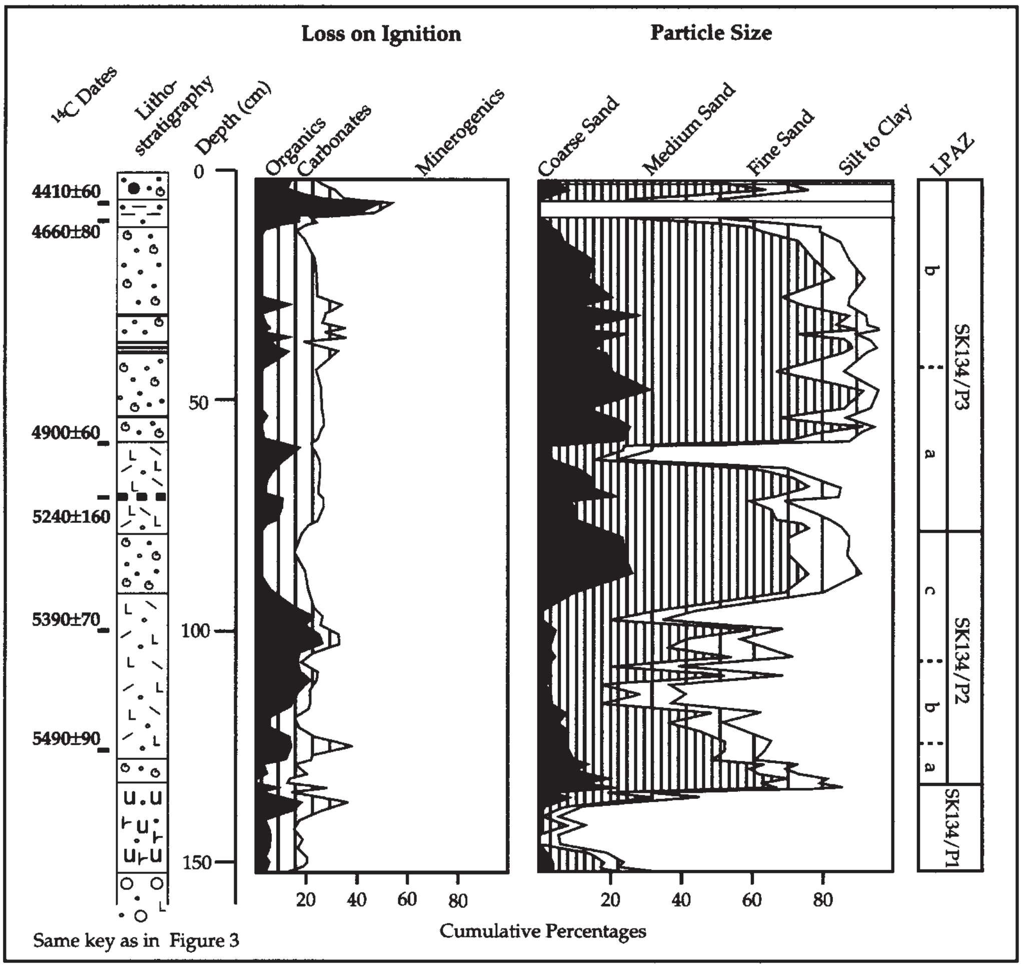


Figure 4 Loss-on-ignition and particle size data for core SK134 (same key as in Fig. 3).

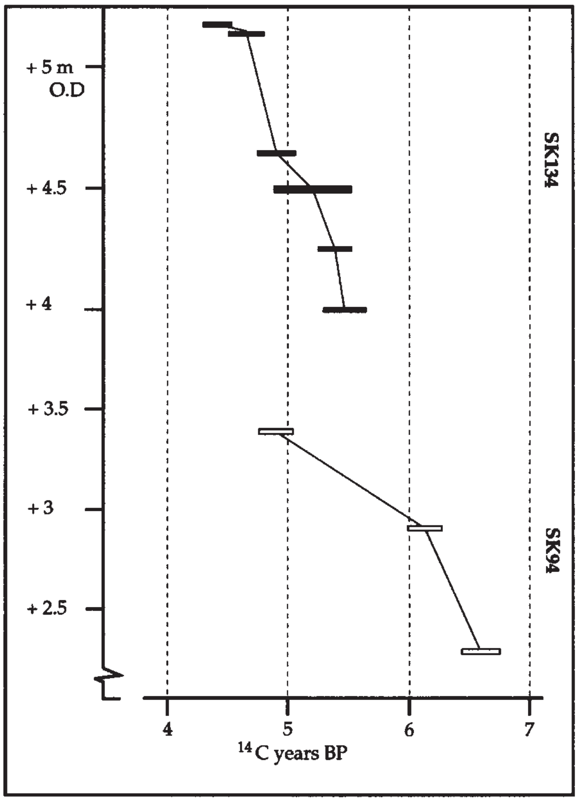


Figure 5 Radiocarbon age–depth curve from the Bay of Skaill (2 standard deviations used).

area by dating separately the inorganic and organic carbon components of the Loch of Skaill sediments, and applying a correcting factor to the ages. This exercise could not be repeated in the present work. Sediment accumulation rates appear, however, to have been much slower in the basal marl (SK94) than in the upper, sand-dominated part (SK134—Fig. 5).

Secondly, there is a significant discrepancy in the dates obtained for the upper contact of the first sand layer (lithostratigraphical unit 4), which range from 4920 ± 70 yr BP (cal. BC 3925–3540) in SK94 to 5490 ± 90 yr BP (cal. BC 4490–4140) in SK134. This may be explained by a hiatus in sedimentation in SK94, combined with a much slower sediment accumulation rate at this locality. However, as the two sampling sites are only ca. 30 m apart and the thickness of this first sand unit is far greater in SK94 (49 cm) than in SK134 (5 cm), differential lateral sedimentation is more likely to have occurred. Local geomorphological variations related to different long-term primary and secondary sand supply also could have played a significant role.

Pollen analysis

Figures 6 and 7 present the pollen sequences for SK94 and SK134. Possible correlation between the two pollen profiles is inferred below.

SK94/P1a-b and SK134/P1

Arboreal pollen reaches maximum frequencies (over 65%) and indicates the proximity of open *Betula–Corylus* dominated woodland, also probably including *Alnus, Quercus* and *Salix*. Local growth of *Pinus* was unlikely because of the low frequencies of grains of this taxon (ca. 5%) and their susceptibility to long-distance transport. Poaceae and Cyperaceae species and *Filipendula* are well represented and may have formed a tall-herb understorey associated with ferns, including *Dryopteris*. However, they also could have occupied waterside habitats together with Ranunculaceae species. Abundant aquatic plant pollen (especially *Nymphaea*), colonies of *Pediastrum* and *Chara* oospores suggest alkaline, eutrophic ponded water. Pollen concentrations are high (14×10^4 grains cm^{-3}), but influx values moderate (3.5×10^3 grains cm^{-2} yr^{-1}), which suggests low sediment accumulation rates and also low environmental energy. Charcoal:Pollen ratios are relatively high at the base of SK94/P1, but negligible in SK134/P1.

SK94/P2 and SK134/P2a

Pollen concentration and influx values fall sharply and the pollen spectra are dominated by very few taxa, a combination that suggests landscape instability. This could have been the result of an increased sedimentation rate related to greater environmental energy. Only Cyperaceae species are well represented and their concentration values increase significantly. Aquatic plant pollen has virtually disappeared. Increasing aeolian sand input may have caused decreased water depths and the decline of pond and adjacent wetland vegetation. The rapid decline in arboreal pollen and fern spores could reflect woodland reduction nearby, as sand was redistributed landward.

SK134/P2b

Stabilisation and colonisation of the site and its surrounding area by a greater variety of plant communities is suggested by a better representation of herbaceous taxa in the subzone. There is also a significant increase in overall pollen concentration and influx values. Arboreal pollen concentration and influx values rise irregularly, and suggest that woodland taxa were still present within the catchment. Machair, probably including *Plantago coronopus, P. maritima, P. lanceolata, Rumex acetosa*, *Anthemis* and Lactuceae species, developed. Meadow and/or waterside habitats were better represented, and may have included *Filipendula*, Ranunculaceae and *Mentha* species. Aquatic plants and *Pediastrum* continued to be present, although decreasing pollen frequencies suggest the decline of open water habitats in the vicinity of the site.

SK134/P2c

Pollen concentrations are high (52×10^3 grains cm^{-3}), and influx values increase to a maximum (12×10^3 grains cm^{-2} yr^{-1}). A period of stability during which plant colonisation and development was undisturbed is indicated. This is followed by a rapid decline in overall pollen concentration and influx values towards the conclusion of this zone, which indicates the recurrence of environmental instability and a reduced vegetation cover within the pollen catchment. From this point, arboreal pollen concentration and influx values do not recover and indicate the probable disappearance of woodland and scrub in the vicinity of the site. *Succisa, P. media/major* and Brassicaceae species nevertheless became significant, and probably occurred in machair grassland. A shallow, muddy substrate of low base status is suggested by the increase of *Menyanthes trifoliata*. As frequencies of *Pediastrum* remain high, however, there also could have been nutrient-rich open water. Ranunculaceae species are well represented throughout and probably imply the persistence of local damp habitats marginal to the water.

Table 2 Radiocarbon dates for SK94 and SK134: (✧) AMS, (●) radiometric standard, (⊗) extended counting time. The calibrated dates were obtained using the Pretoria calibration curve (Vogel *et al.*, 1993)

Laboratory number	Altitude (m OD)	Material	$^{13}C/^{12}C$ (%)	Radiocarbon age (yr BP) 1 σ	Calibrated age range (cal yr BC) 2 σ
SK94					
Beta-90822 (✧)	+3.39/+3.40	Humified, minerogenic peat	–30.0	4920 ± 70	3925–3875 3810–3625 3565–3540
Beta-90823 (✧)	+2.86/+2.87	Organic marl	–22.8	6120 ± 70	5235–4855
Beta-90824 (✧)	+2.27/2.29	Humified, minerogenic peat	–27.1	6550 ± 80	5590–5305
SK134					
Beta-104795 (●)	+5.17/+5.18	Humified, minoergenic peat	–28.8	4410 ± 60	3325–2900
Beta-104796 (●)	+5.12/+5.13	Humified, minerogenic peat	–29.6	4660 ± 80	3640–3300 3235–3115
Beta-104797 (●)	+4.65/+4.66	Organic silt	–29.9	4900 ± 60	3790 ± 3625 3565–3540
Beta-104798 (⊗)	+4.535/+4.55	Organic silt	–29.8	5240 ± 160	4370–3695
Beta-104799 (●)	+4.25/+4.26	Organic silt	–29.0	5390 ± 70	4355–4035
Beta-104800 (⊗)	+3.99/+4.00	Organic marl	–29.1	5490 ± 90	4490–4140

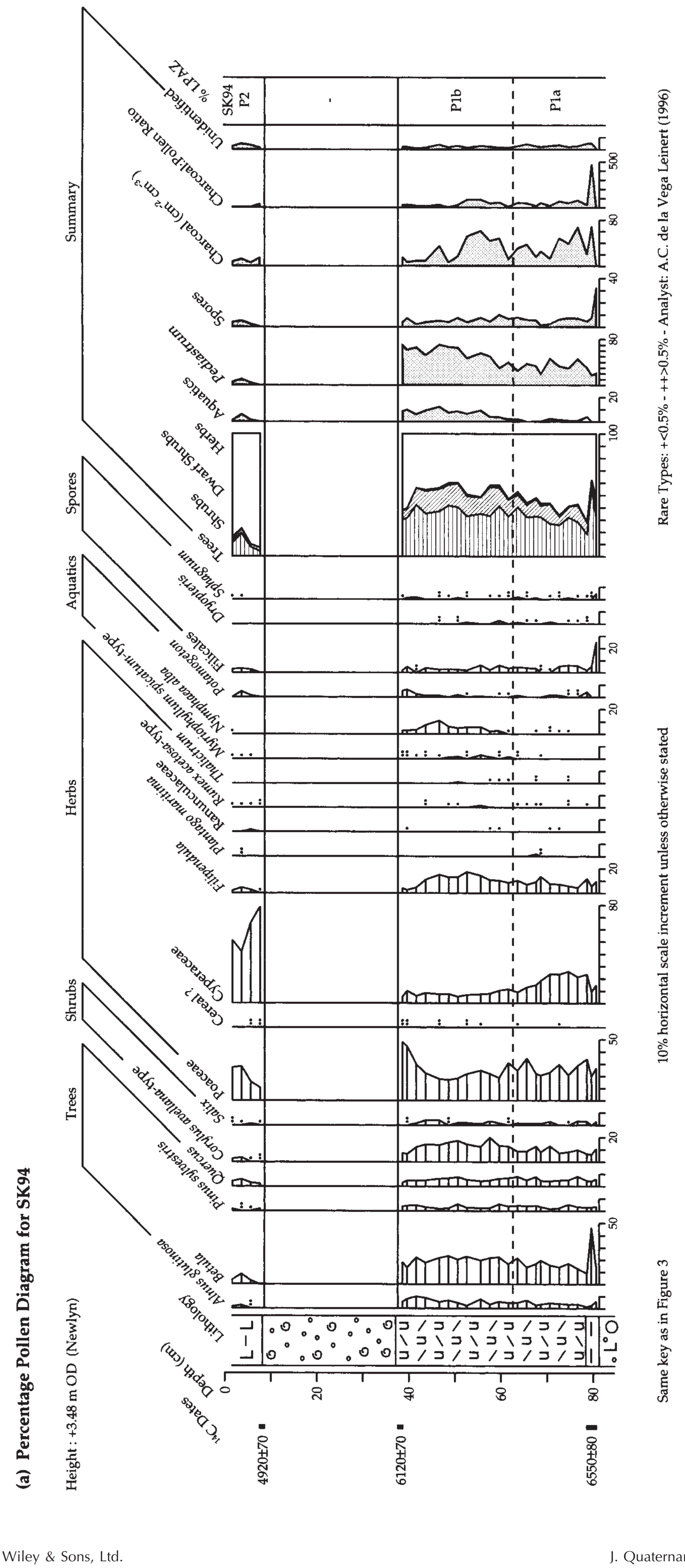


Figure 6 Pollen assemblage in core SK94: (a) percentage data for selected taxa; (b) concentration data for selected taxa.

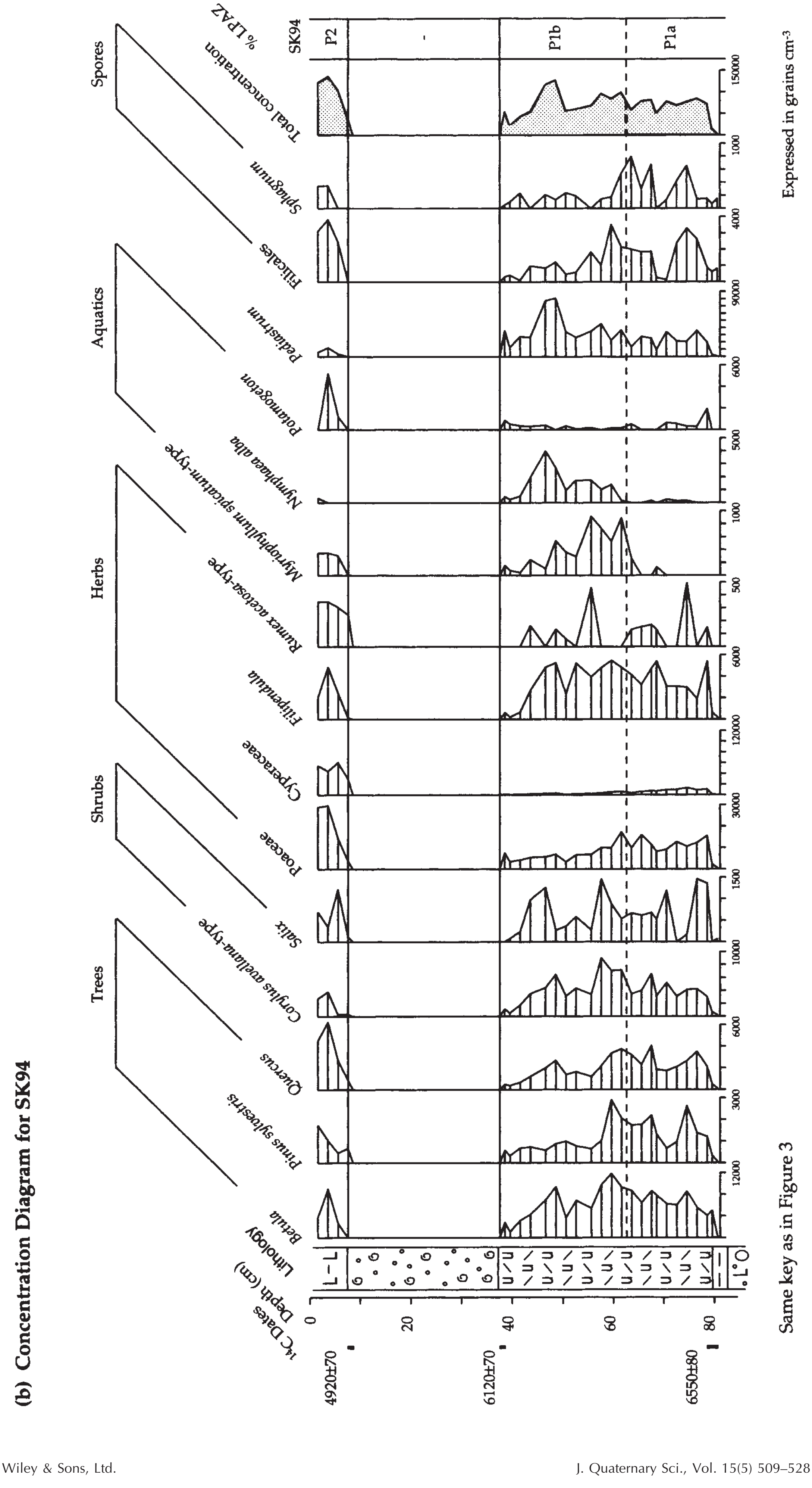


Figure 6 Continued.

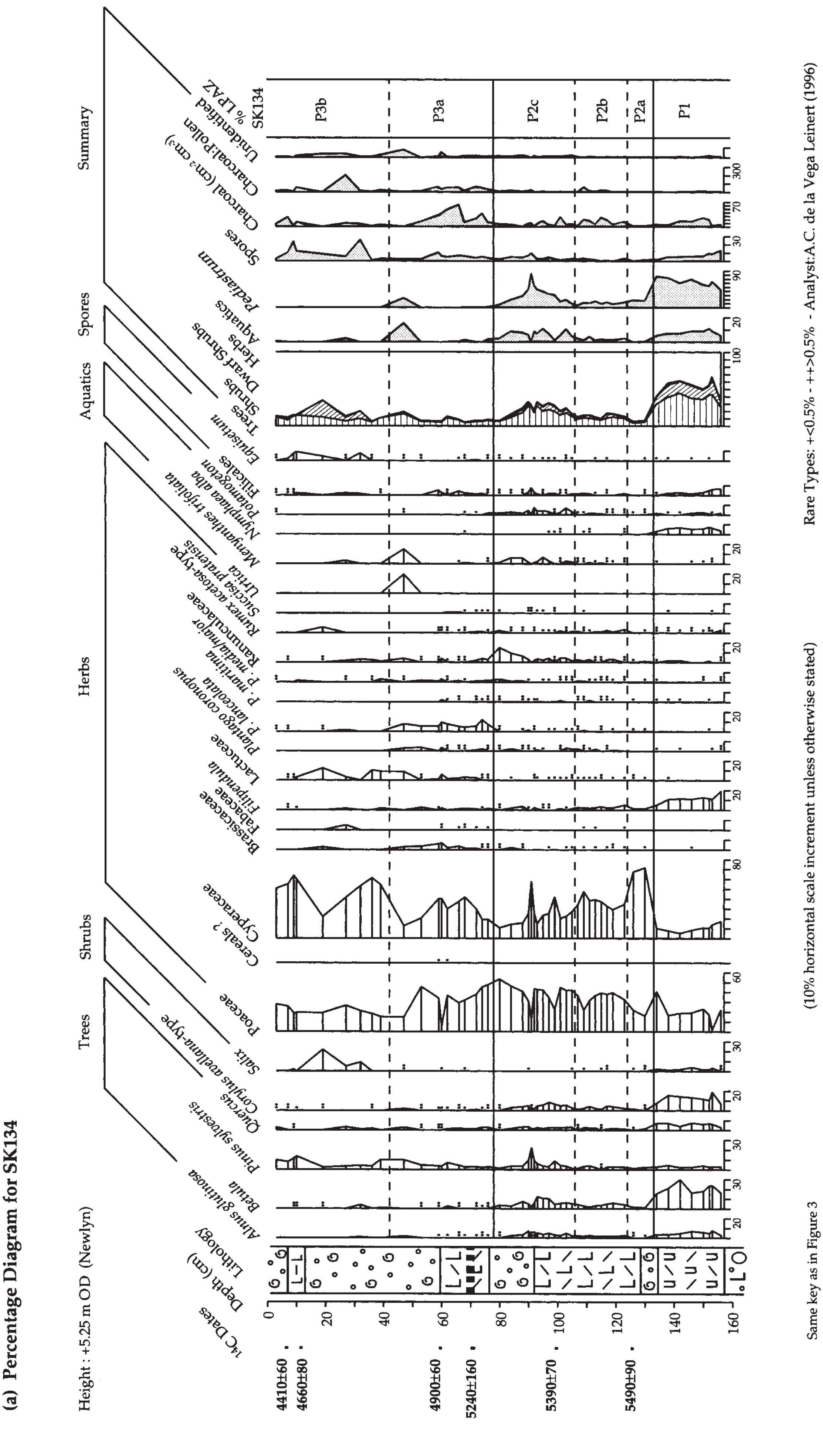


Figure 7 Pollen assemblage for core SK134: (a) percentage data for selected taxa; (b) concentration data for selected taxa; (c) influx values for selected taxa.

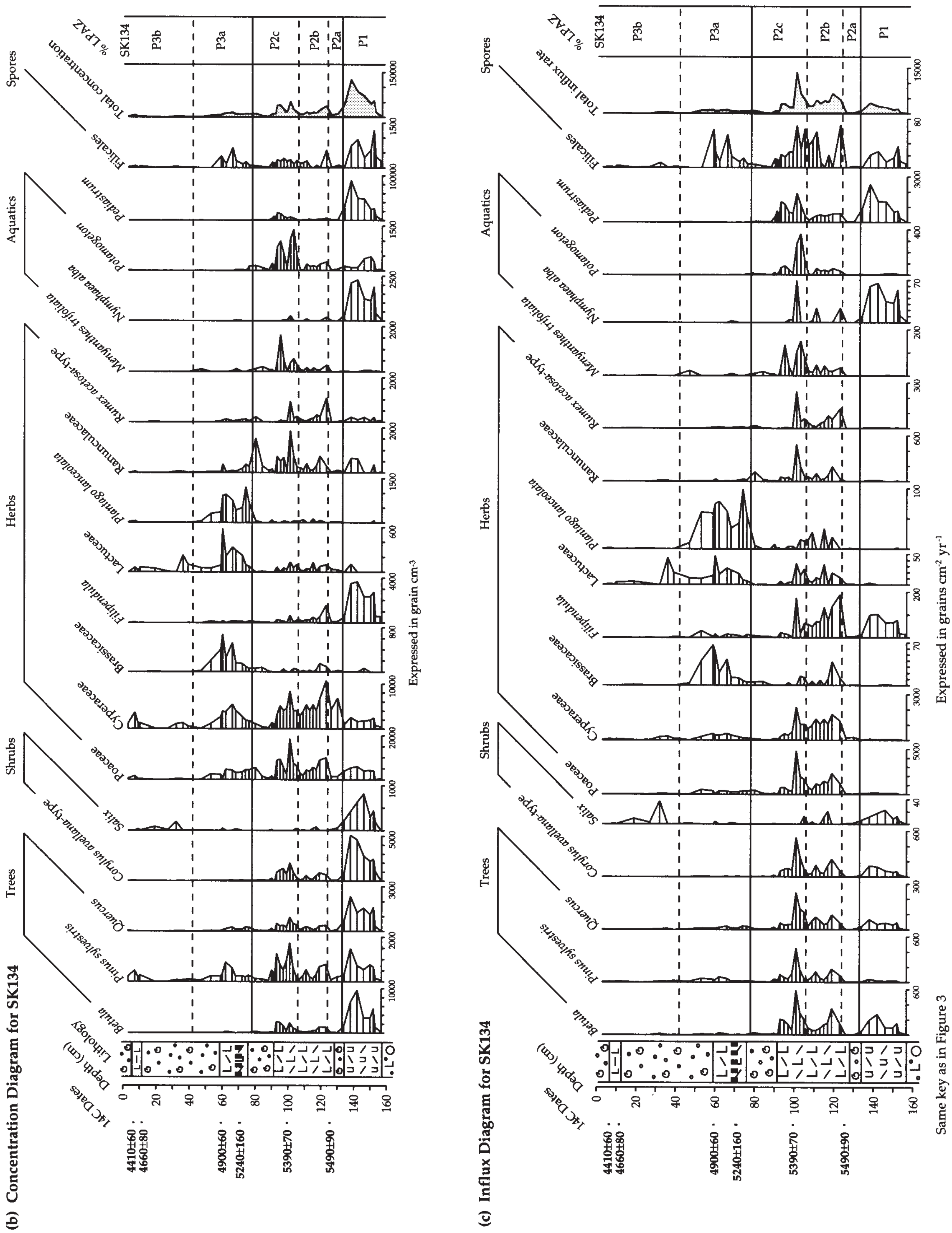


Figure 7 Continued.

SK134/P3a

Despite an overall decline in pollen concentration and influx values, some taxa (e.g. Lactuceae and Brassicaceae species) remained well represented, probably still as components of machair. *Plantago lanceolata* has a continuous curve, and other possible indicators of anthropogenic activity are Fabaceae and cereal-type. Arboreal pollen frequencies are reduced to very low levels; C:P values increase, and a thin layer of macroscopic charcoal, primarily of herbaceous taxa, and probably mainly Poaceae (Dr. J.-C. Carcaillet, pers. comm.), occurs in the corresponding lithostratigraphy. These phenomena also point towards anthropogenic impact on the surrounding landscape. Aquatic and wetland plant pollen is also less represented, suggesting open water habitats had progressively disappeared.

SK134/P3b

A further decline in concentration and influx values may be associated with a renewed episode of environmental instability and increased sand accumulation rates. Cyperaceae and Poaceae species are well represented and this probably reflects their dominance of wetland and machair vegetation. A number of herbaceous taxa disappear from the pollen spectra, a likely consequence of heightened sand mobility. The absence of aquatic plant pollen indicates that infilling of the existing water bodies occurred once more. Increased percentages of *Salix* may reflect its localised growth in dune-slack wetland along with *Equisetum*.

Mollusc analysis

Mollusc data are presented in Figs 8 and 9.

SK94/M1 to 3 and SK134/M1

An aquatic assemblage composed of catholic (*sensu* Sparks, 1961) taxa such as *Lymnaea peregra* (Müller), *Armiger crista* (Linné), *Gyraulus laevis* (Alder) and *Pisidium nitidum* Jenyns is present in the basal marl. This fauna is characteristic of newly developed coastal ponds occupying dune-slack locations in many parts of the British Isles (Keen, 1981). The dominance of *G. laevis* associated with *P. nitidum* in SK94/M1 also indicates that macrophytic vegetation was sparse. This early ponding phase may have been slightly brackish, as *G. laevis* can withstand salinity up to 5‰ (Ökland, 1990). The subsequent decline of these taxa and their replacement by *A. crista* in SK94/M2–3 and SK134/M1 suggests the gradual development of aquatic vegetation and possibly an increase of sediment input. The occurrence of *Pisidium subtruncatum* Malm may indicate some water movement (Ellis, 1962), and probably reflects the discharge of freshwater from several streams and springs entering the northern part of the Bay of Skaill (Fig. 1).

SK134/M2

Lymnaea truncatula (Müller) and *Carychium minimum* Müller replace the aquatic assemblage of the previous biozones and indicate the development of a calcareous marsh. The presence of *Vertigo antivertigo* Draparnaud suggests a *Phragmites* swamp. Both *C. minimum* and *V. antivertigo* are thermophiles and today are extinct in Orkney. Their occurrence hints at temperatures a little higher than those of the present in the area (Kerney and Cameron, 1979).

SK134/M3

This is an aquatic assemblage composed of the same species as in SK94/M1–3 and SK134/M1, although the numbers of *L. peregra* and *G. laevis* are greatly reduced. *Armiger crista* dominates at the base, but the rapid decline of its numbers towards the top may indicate that macrophytic vegetation in the pond progressively decreased.

SK134/M4

This is a marsh assemblage with *C. minimum* and *Vallonia pulchella* Müller most abundant. The fauna suggests local wet grassland rather than the fen or swamp recorded in SK134/M2. Such conditions are also indicated by the presence of *Cochlicopa lubrica* (Müller) and *Cochlicopa lubricella* Porro, which are both inhabitants of grassland. Single fragments of *Clausilia* spp. (probably *Clausilia bidentata* (Ström), which was recorded by Spencer (1975)) and *Euconulus fulvus* Müller were likely to have been blown as clasts from shaded habitats—e.g. scrub or tall herbs outside the marsh.

Ostracod analysis

Ostracod data are presented in Figs 10 and 11.

SK94/O1–3 and SK134/Oa

Cyprideis torosa (Jones) is the most significant taxon in SK94/O1 and SK134/O1a. This suggests restricted salinity levels of up to 5‰ (Athersuch *et al.,* 1989), which may be related to carbonate precipitation from marine shelly sand within the pond. *Cyprideis torosa* was progressively replaced in SK94/O2 by freshwater species that prefer permanent, shallow (up to 1 m deep) water, but which can withstand occasional drying out. *Candona candida* (O.F. Müller) then becomes dominant. This is a widely distributed species that tolerates a broad range of aquatic conditions. *Cypria ophtalmica* (Jurine), *Limnocythere inopinata* (Baird) and *Pseudocandona* Kaufman *marchica* (Hartwig), however, suggest that either macrophytic vegetation or organic detritus was abundant in the water body (Benzie, 1989). The presence of *Potamocypris zschokkei* (Kaufmann) could signal the occurrence of spring-fed ponds (Meisch, 1984). In SK94/O3, a less diverse assemblage occurs, dominated by *C. candida* with low numbers of *Cyclocypris laevis* (O.F. Müller) and *C. ophtalmica*, a species association that has been related to the presence of *Phragmites*-dominated vegetation (Sharf, 1983; Benzie, 1989). The disappearance of *P. marchica* suggests either a shallowing or a non-permanent water body. *Limnocythere inopinata*, a species that prefers a sandy substrate, decreased rapidly and may indicate the presence of mud (Benzie, 1989).

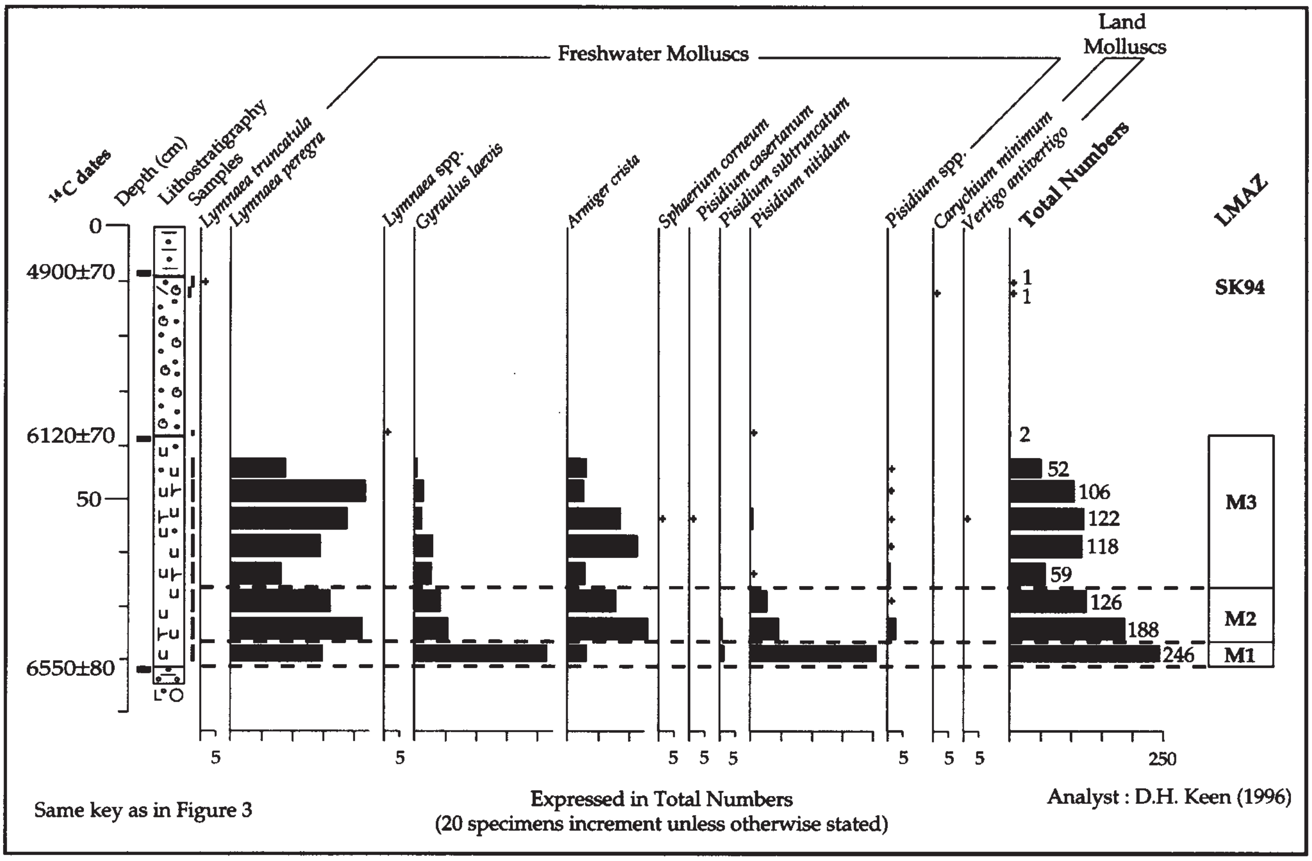


Figure 8 Mollusc assemblage in core SK94 (total numbers).

SK94/O4 and SK134/O1b-c

Marked changes are recorded, with the decline of most species identified in the previous assemblage and the dominance of *Ilyocypris gibba* (Ramdohr). The first appearance of *Potamocypris pallida* Alm indicates a nutrient-poor water body and could reflect either the infilling or drying out of the basin. Values for *L. inopinata* recover slightly at this level, which could signal increasing sand input. The latter also may be indicated by the appearance of Foraminifera in SK134/O1c, which could have been wind-transported from the high-water mark.

SK134/02a

This assemblage is similar to that of SK94/O1–3 and SK134/O1b. A shallow, probably non-permanent water body is indicated, and the absence of *C. torosa* suggests that salinity levels were close to zero.

SK134/O2b

Candona candida, C. laevis and *C. ophtalmica* decline gradually and *P. zschokkei* dominates. This probably reflects the occurrence of spring discharge into the basin and could explain the continued existence of a water body, and of conditions favourable for marsh formation, despite regular infilling by aeolian sand. *Pseudocandona marchica* is well represented and implies the presence of a deeper, permanent water body. *Darwinula stevensoni* (Brady and Norman), a taxon that cannot swim and prefers permanent water that contains some organic detritus, also is present.

SK134/O3

All species previously identified disappear, except *C. candida* and *Potamocypris villosa* (Jurine). *Potamocypris variegata* (Brady and Norman) is recorded for the first time. The small numbers of ostracods may indicate that only residual pools and/or damp patches persisted.

Discussion

Initial ponding phase

The formation of freshwater intertidal deposits and machair in and around the Bay of Skaill appears to fit models developed for these in the Outer Hebrides (Ritchie, 1979, 1985; Ritchie and Whittington, 1994). Trends of Holocene relative sea-levels (RSL) in Orkney are poorly known (de la Vega Leinert, 1998). However, the evidence that exists is not inconsistent with data obtained from the Wick River valley, northeast Scotland (Dawson and Smith, 1997), some 45 km south of Mainland Orkney. There, apart from minor stillstands, RSL has been continuously rising from approximately –4 m OD at ca. 7 ka to the present. The Bay of Skaill now occupies a structural depression that was probably deepened by Devensian glacial action. Although exten-

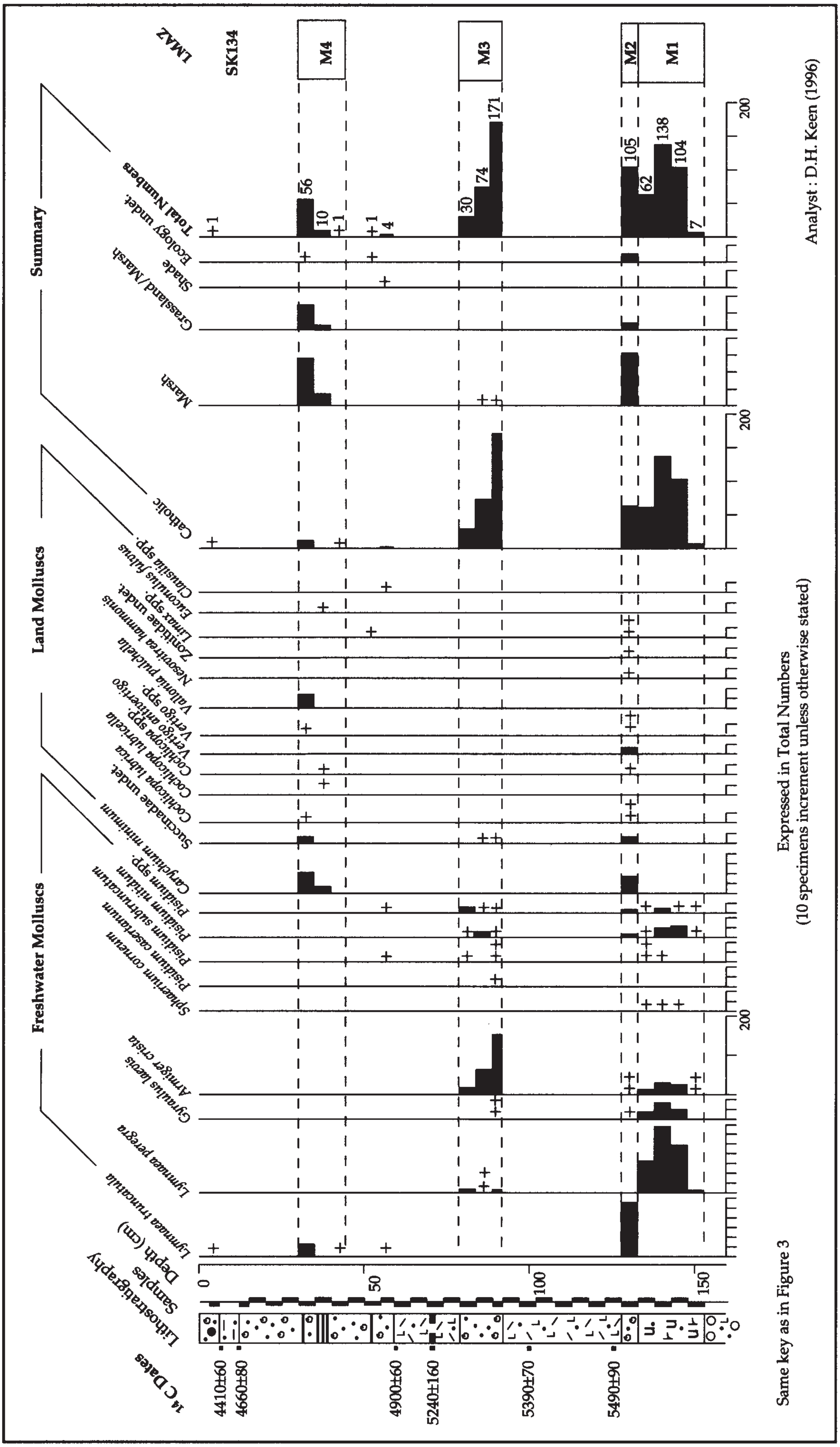


Figure 9 Mollusc assemblage in core SK134 (total numbers).

Table 3 Summary of palaeoenvironmental data for SK134

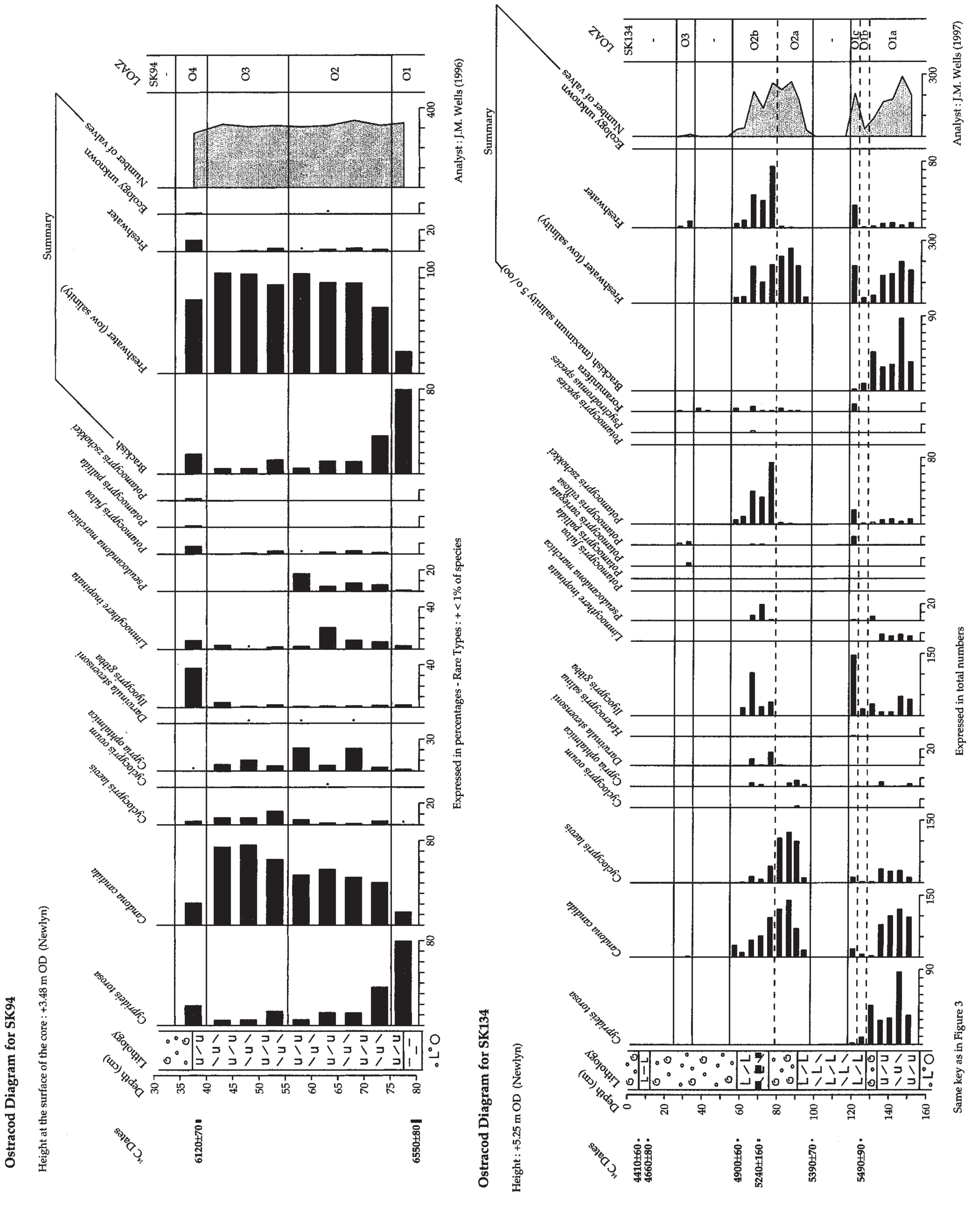
Altitude (m O.D)	^{14}C Dates	Litho-strat.	Sedimentation	Energy Regime	Pollen	Molluscs	Ostracods
	4410±60		Aeolian	High	Open vegetation (less diverse) Restricted anthropogenic impact Final decline in woodland	None	None
			Dune slack	Low			
+5	4660±80		Aeolian	High			
			Decreasing sand? Distal deposition?	Fluctuating		Marsh wet grassland	Ephemeral pool-Damp patch
			Aeolian	High			None
	4900±60 5240±160		Ponding High water table	Low	Machair vegetation Anthropogenic impact (pastoralism, arable cultivation)	None	Deeper, permanent pond
+4.5			Decreasing sand	Decreasing	Charcoal layer (Possibly Poaceae)		Shallow, non permanent pond
			Aeolian	High	Open grassland (machair development)	Shallow reedy pond	
	5390±70		Ponding High water table	Low	Persisting woodland (regeneration ?)	None	None
+4	5490±90		Decreasing sand	Decreasing	Freshwater pond (aquatic vegetation)		Infilling of pond
			Aeolian	High	Decline in woodland/ open vegetation	Marsh-reedy pond	Shallow non permanent pond
	6120±70		Increasing sand	Increasing	Woodland and rich understorey	Increasing aquatic vegetation and sediment influx Freshwater aquatic environmnent (Maximum Salinity 5 ‰)	
			Ponding High water table	Low	Freshwater pond (aquatic vegetation)		
	6550±80		Glacial -Fluvioglacial	High	Rare	None	

▭ ^{14}C dates from the base of SK94 - Same key as in Figure 3

sive studies of offshore sedimentary facies have been carried out around the Outer Hebrides (Binns *et al.*, 1974; Stoker *et al.*, 1993), little is known about them off Orkney, in particular the availability of glacigenic and biogenic sand. From ca. 6.6 ka (cal. BC 5590–5305), a freshwater marsh developed in the coastal depression, probably in response to a rising water table associated with stream and spring discharge on to a glacigenic surface of low permeability (Table 3 and Fig. 12a). Seaward, on-shore winds combined with a rapidly rising relative sea-level, remobilised off-shore sand of uncertain origin, which probably accumulated across the mouth of the present bay to form a beach. The latter process could have been aided by the presence of a ridge of unknown composition linking the two headlands and acting as a sediment anchor-point. As more and more sand became available, a dune ridge would have been produced. The absence of any palaeoecological indicators of saltmarsh and/or estuarine habitats throughout the profiles investigated precludes the possibility of a marine embayment occupying the coastal depression at any time during the mid-Holocene.

The basal pollen assemblages presented here (especially their arboreal sums) are comparable to those from the *Phragmites* peat in the bay investigated by Keatinge and Dickson (1979). These deposits therefore could be of similar age and indicate that the freshwater marsh was extensive. Subtidal peat of mid-Holocene age is apparently still being eroded within the bay. This is attested to by evidence of numerous wave-polished peat pebbles on the foreshore after storms, the pollen assemblages of which have been related to LPAZs SK134/P2b–c (de la Vega Leinert, 1998). *Betula*, *Corylus* and *Salix* dominated open woodland with a rich understorey of tall herbs and ferns was present in the pollen catchment from at least ca. 6.6 ka (cal. BC 5590–5305). Close to the coastline, exposure to wind and marine influence, especially salt spray, probably restricted tree and tall shrub growth to sheltered locations, whereas in the hinterland of the bay, a more closed woodland developed (cf. Keatinge and Dickson, 1979; Bunting, 1994). Around Skaill, *Alnus* and *Quercus* also may have been woodland components, the former on damp ground and the latter on better drained soils. *Ulmus* and *Pinus* were seemingly absent. Such a tree and tall shrub flora is in agreement with that proposed for other parts of Orkney (Bunting, 1994) and for Shetland (Bennett *et al.*, 1992). However, Bunting (1994) believed that *Pinus* grew on Mainland Orkney.

Sustained elevation of the freshwater table was probably linked to either a continued RSL rise, to spring inflow into the depression, or to a combination of both factors. This resulted in the formation of shallow, carbonate-rich, eutrophic ponds, which are indicated by the basal mollusc and ostracod assemblages. These ponds may have been interconnected. The presence of *Pisidium subtruncatum* suggests water movement compatible with spring flow and lake wave-action (Ellis, 1962). Several streams and springs currently drain into the Bay of Skaill and, in the past, these could have fed a more extensive water body, perhaps similar in size and depth to the present Loch of Skaill. The rise in *A. crista* frequencies suggests the development of aquatic vegetation within the water bodies. The presence of *Phrag-*



Ostracod Diagram for SK94
Height at the surface of the core : +3.48 m OD (Newlyn)
¹⁴C Dates
6120±70
6550±80
Depth (cm)
Lithology
Cyprideis torosa
Candona candida
Cyclocypris laevis
Cyclocypris ovum
Cypria ophtalmica
Darwinula stevensoni
Ilyocypris gibba
Limnocythere inopinata
Pseudocandona marchica
Potamocypris fulva
Potamocypris pallida
Potamocypris zschokkei
Brackish
Freshwater (low salinity)
Freshwater
Ecology unknown
Number of valves
Summary
LOAZ
SK94
O4
O3
O2
O1
Expressed in percentages - Rare Types : + < 1% of species
Analyst : J.M. Wells (1996)
Ostracod Diagram for SK134
Height : +5.25 m OD (Newlyn)
4410±60
4660±80
4900±60
5240±160
5390±70
5490±90
Heterocypris salina
Potamocypris variegata
Potamocypris villosa
Potamocypris species
Psychrodromus species
Foraminifera
Brackish (maximum salinity 5 o/oo)
SK134
O2b
O2a
O1c
O1b
O1a
Same key as in Figure 3
Expressed in total numbers
Analyst : J.M. Wells (1997)

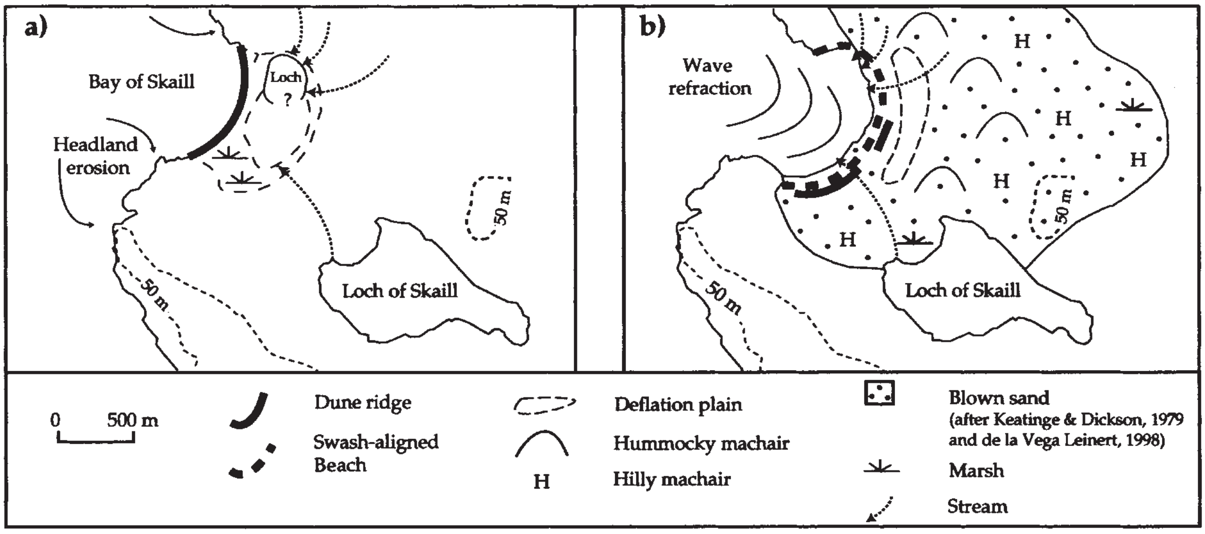


Figure 12 Mid-Holocene coastal evolution in the Bay of Skaill: (a) before ca. 6.1 ka; (b) after ca. 4.4 ka.

mites macrofossils within the marl indicates that a swamp had developed on the margin of the water bodies. *Phragmites*, *C. torosa* and *G. laevis* can tolerate slightly brackish conditions. The ponds therefore could have been of low salinity in their early phase, although as mentioned above, they were never directly exposed to marine influence. Salt spray and the possible precipitation of salt crystals from small amounts of dune sand blown into the ponds could provide an explanation for the low salinity recorded.

Machair formation and Neolithic impact

Shelly sand occurs in the upper part of the marl and implies that aeolian processes began to affect the site of deposition before ca. 6.1 ka (cal. BC 5235–4855). By that date, sand input had increased sufficiently to substantially infill the water bodies. The latter probably resulted in a shallowing and/or non-permanent water body, as suggested by the decline of *P. marchica* in the ostracod record. Increased representation of *L. truncatula*, *C. minimum* and *V. antivertigo*, which favour reedswamp habitats, and a corresponding decline in aquatic molluscs, support this. The presence of *P. pallida* and the progressive replacement of *Nymphaea* by *M. trifoliata* suggests that until ca. 5.5 ka (cal. BC 4490–4140), nutrient input into the remaining pools declined. Continuing spring inflow in the depression, indicated by increasing numbers of *P. zschokkei*, could have delayed the response of molluscs and ostracods to these increasingly hostile environmental conditions. A marked decline in pollen influx suggests that sand accretion led to the demise of much of the plant cover surrounding the site.

By ca. 5.5 ka (cal. BC 4490–4140), pollen influx had recovered, and peaked about 100 yr later. This biostratigraphical change correlates with the replacement of blown sand by organic sandy silt, and indicates lower environmental energy and weakened aeolian processes. This supports the contention that tree and shrub growth was restricted primarily by sand accumulation. However, the recurrent deposition of $CaCO_3$ in the shelly blown sand favoured the progressive development and diversification of the machair flora inland of the present bay at that time. Between ca. 5.4 and 5.2 ka (cal. BC 4355–3695), a rise in Charcoal:Pollen ratios and in *P. lanceolata* pollen suggests that Neolithic inhabitants were present in the vicinity of the site and were engaged in pastoral farming. Whether the increase in Charcoal:Pollen values is related mainly to domestic fires or included some amount of clearing of the vegetation by burning cannot be specified. Moreover, an increase in either the frequency of local non-anthropogenically initiated fires or the deposition of far-travelled atmospheric charcoal, and the natural presence of *P. lanceolata* in coastal pasture, could be equally valid interpretations of such phenomena (Jones, 1988; Whittington and Edwards, 1993).

Sand deposition at the Loch of Skaill began ca. 5 ka (Keatinge and Dickson, 1979), ca. 1.1 kyr later than in the localities investigated in this study. This delay was probably due to the more proximal location of the bay sites to the source of sand. Ritchie and Whittington (1994) noted a significant temporal discrepancy between the radiocarbon dates obtained for the initial sand deposition at various sites in the Uists, Outer Hebrides. They range between 7810 ± 140 yr BP at Cladach Mór, North Uist, and 4366 ± 40 yr BP at Quinish, Pabbay. Ritchie and Whittington (1994) suggested that the first occurrence of sand layers in intertidal freshwater deposits may neither be synchronous, nor relate directly to the original sand input responsible for widespread machair development. Local factors, including coastal configuration, sand reworking and anthropogenic impact could be responsible for the stratigraphical variability of the sequences investigated. Moreover, at the inland limits of the machair, the first deposition of sand could have occurred well after the main phase of machair formation seaward.

However, the temporal discrepancy between the first appearance of sand at the bay sites and in the Loch of Skaill, 2 km inland, is small (ca. 1.1 kyr). Thus, it is inferred that the initiation of machair formation is well constrained and occurred between ca. 6.1 and 5 ka (cal. BC 5235–3540). Aeolian blow-outs probably resulted in the erosion of the dune ridge and in the redistribution of sand inland into machair landforms. The development of a mature deflation plain, as in the Uists (Ritchie, 1979), was neverthe-

Figure 10 Ostracod assemblage in core SK94 (percentages) (See opposite page).

Figure 11 Ostracod assemblage in core SK134 (total numbers) (See opposite page).

less prevented by the constricted configuration of the area around the present bay (Fig. 12b). Instead, frequent structural and glacigenic-derived topographic irregularities, coupled with rapidly rising ground, favoured the development of hillocky and hilly machair (*sensu* Ritchie, 1979). The power of the aeolian processes must have been considerable, because sand blankets an area up to 2 km inland, covering the tops of the low hills of Kier (57 m OD) and Sand Fiolds (42 m OD). Around the present bay, differential lateral sedimentation occurred, as the discrepancy in the thickness of the first sand layer in the cores suggests. The rapid changes in particle size observed throughout SK134 indicate either frequent short-lived changes in sand supply, or irregular aeolian dynamics. Similar trends in particle-size distribution were recorded at Benbecula, South Uist. Whittington and Edwards (1997) believed these to be the result of irregular sediment supply and variations in intensity of aeolian processes.

Soon after ca. 5.4 ka (cal. BC 4490–4140), a second sand-blow occurred. However, spring and stream flow into the locality, and a freshwater table rise associated with increasing RSL, probably continued. Aquatic molluscs, particularly *A. crista*, denote the presence of shallow, transient ponds with macrophytes. Patchy *Phragmites* swamp probably persisted at the margins of these water bodies. Sand deposition declined substantially before ca. 5.2 ka (cal. BC 4370–3695), when a last phase of ponding began. The occurrence of *P. marchica* and *D. stevensoni* indicates that a deeper, permanent water body existed until ca. 4.9 ka (cal. BC 3790–3540), when most aquatic and waterside flora and fauna decreased as a further sand-blow took place.

A final woodland decline occurred between ca. 5.2 and 4.9 ka (cal. BC 4370–3540). This is in agreement with the dates obtained for a similar event at the Loch of Skaill (Keatinge and Dickson, 1979). Further evidence for anthropogenic impact on the surrounding landscape is recorded in the pollen profiles, which point towards both pastoral and arable farming. The C:P ratios are at their maximum, and if the burning was local, charcoal may have come from either fires in the surrounding vegetation or domestic sites. This evidence of human impact pre-dates the early phase of settlement (ca. 4.7 to 4.3 ka—cal. BC 3640–2610) at Skara Brae (Clarke, 1976; Ashmore, 1998). If the radiocarbon dates are free from hard-water contamination, they imply a Neolithic presence in the area ca. 500 yr earlier than has hitherto been established. Bunting (1994) proposed that woodland clearance and mixed husbandry took place ca. 5 km northeast of the Bay of Skaill at ca. 5.1 ka. This suggests that Neolithic people were present in west Mainland then, and would correlate closely with the biostratigraphical and chronostratigraphical evidence presented here. The deposition of blown shelly sand produced fertile arable and pasture land favourable to agricultural exploitation (Evans, 1979). Nevertheless, episodes of sand instability, probably associated with increased storminess and salt spray deposition, are likely to have affected Neolithic settlement and activity. Sand layers are recorded at Skara Brae immediately prior to the first phase of occupation and throughout the later phases, indicating that the settlement experienced recurrent sand storms (Clarke, 1976). It is, moreover, possible to envisage that extensive and intensive anthropogenic impact on the surrounding vegetation also contributed to sand instability. Grazing could have led to a substantial thinning of the vegetation cover, and arable cultivation would have exposed large areas of soil, which could have been remobilised by wind action. Significant anthropogenic impact has been linked with soil erosion and sand blow events in the Uists (Ritchie and Whittington, 1994; Whittington and Edwards, 1997).

The overall coarsening trend in particle size observed earlier suggests that either aeolian processes strengthened throughout the later part of the mid-Holocene or that the sampling site (SK134) was located closer to the sand source than previously. Between ca. 4.9 and 4.7 ka (cal. BC 3790–3115), the thickest sand layer of the sequence was deposited. The general lack of organic matter in the sand units suggests the presence of bare sand surfaces, which would have been prone to deflation, in the vicinity of the site. Interestingly, occasional silt layers occur within the sand and must reflect brief periods of subdued aeolian activity associated with dominant input of fine terrestrial sediment. The presence of *C. minimum*, *V. pulchella* and *L. truncatula* within these silt layers indicates the short-lived existence of damp grassland and freshwater pools nearby. A sparse ostracod fauna also denotes the persistence of either ephemeral freshwater pools or damp hollows, perhaps promoted by continued spring-flow. A reduction in *P. lanceolata* pollen frequencies and C:P ratios ca. 4.9 ka suggests that anthropogenic activities had declined in the vicinity of the site. The presence of Neolithic people in the area is, however, thought to have lasted until ca. 3.8 ka (cal. BC 2573–1942), when Skara Brae was abandoned (Clarke, 1976; Ashmore, 1998). By ca. 4.7 ka (cal. BC 3640–3115), aeolian processes had weakened and dune-slacks developed. These were engulfed by a further phase of sand deposition, which began ca. 4.4 ka (cal. BC 3325–2900). Any sediments deposited after this date have been eroded by a combination of marine and aeolian activity.

It is possible to infer later coastal evolution than that described above in this locality, albeit from indirect evidence, including current landforms and sediments. Increasing storminess, associated with a still rising RSL and a sand supply that must have been progressively declining, would have resulted in the landward migration of the dune ridge. As this occurred, the ridge could have become more arcuate. This would have led to unequal distribution of sand, thinning of the ridge, localised instability and increased rates of dune migration. At present, the northern part of the bay displays low and patchy remains of this dune, while its vestiges reach over +10 m OD in the south. The differential thickness and preservation of the dune remnants may also relate to the underlying glacial drift and bedrock topography, which rises steadily from north to south. The gradual displacement of the dune could have led to the formation of an incipient bay, which was enlarged progressively as the rising sea reached the current coastal basin (Fig. 12b). Sometime after 4.4 ka (cal. BC 3325–2900), the dune ridge overrode the freshwater deposits, and attained its current position. This would mean that the present bay formed later than postulated by Keatinge and Dickson (1979). If this was the case, their associated hypothesis of catastrophic barrier breaching and consequent flooding of an inland depression by the sea also cannot be sustained for the mid-Holocene period as recorded in the sedimentary sequences investigated in here.

Conclusion

The importance of multidisciplinary investigations of coastal freshwater deposits exposed on the shoreface of gravel beach for the provision of local palaeoenvironmental information has been stressed by Jennings *et al.* (1998) and Buckland *et al.* (1998). However, there have been few such studies in the British Isles and elsewhere in northwest Europe. The present work demonstrates the usefulness of such an approach in reconstructing mid-Holocene environmental changes, and understanding the processes leading to machair formation, gravel beach dynamics and changes in coastal configuration.

At Skaill, local floral and faunal variations have been related to sedimentological and geomorphological changes that have accompanied rapid and significant alterations in coastal configuration since the mid-Holocene. These are the probable response to a combination of factors, including relative sea-level rise, sediment starvation, active aeolian processes, exposure to storminess and anthropogenic impact. The initiation of machair formation at Skaill has been dated to between ca. 6.1 and 5 ka (cal. BC 5235–3540), whereas the overall episode of sand movement is believed to have lasted until after ca. 4.4 ka (cal. BC 3325–2900). These dates are not dissimilar to the period of sand instability recorded at Borve, Benbecula, South Uist, dated to between ca. 6.8 and 3.4 ka (Whittington and Edwards, 1997). The Orcadian evidence is comparable with a phase of dune-drift detected elsewhere in northwest Europe between ca. 6.7 and 4 ka (Gilbertson *et al.*, 1999). Surface stabilisation associated with colonisation by machair and dune-slack vegetation occurred in the bay on several occasions between ca. 5.4 and 4.4 ka (cal. BC 4355–2900). This may have been related to a combination of factors, including decreasing sand input, a continuous freshwater supply and enhanced organic matter production via vegetation growth and decay.

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