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Evaluation of Rapid Relative Sea-Level Changes in North-West Scotland During the Last Glacial-Interglacial Transition: Evidence from Ardtoe and Other Isolation Basins

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ABSTRACT

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Detailed biostratigraphic and lithostratigraphic analyses from a new isolation basin at Ardtoe, northwest Scotland, provide interpretations of tendencies of sea-level movement and environmental changes during the time period from the early Lateglacial Interstadial to the early Holocene. Microfossil analyses record the gradual transition of the isolation basin from a marine basin to a freshwater lake within an area of isostatic uplift (the basin isolation contact is dated 12,040 ± 110BP). The new data, correlated with previously published data from isolation basins at Rumach and Loch nan Eala, provide evidence for a continuous fall in relative sea level in northwest Scotland from the early–Lateglacial Interstadial to the early Holocene. This conflicts with previously published reconstructions of relative sea-level changes from a number of areas in Scotland which show rapid falls and rises during the last glacial-interglacial transition. Trends similar to those predicted by geophysical (numerical) models are inferred from these new data.

Palynological, foraminiferal and dinoflagellate cyst stratigraphy link the oceanic record of major climate and oceanic circulation changes to the terrestrial biostratigraphic record. Movement of the oceanic Polar Front, west and north, during a period of relative climatic amelioration within the early–mid Lateglacial Interstadial and a corresponding change in the position of the North Atlantic Current may be inferred from the dinoflagellate cyst record.

ADDITIONAL INDEX WORDS: *biostratigraphy, Lateglacial Interstadial, foraminifera, diatoms, pollen, dinoflagellate cysts.*

INTRODUCTION

The last glacial-interglacial transition (14–9ka BP) is well documented as characterised by a series of major changes in climate (*e.g.,* WALKER, *et al.,* 1994 and Table 1). In Scotland, the climate changes were sufficient to cause ice cap growth, the Loch Lomond Advance (or Readvance) and decay. Relative sea levels during this period, as reconstructed from geomorphologic and stratigraphic evidence, changed rapidly at various sites. The altitudinal changes varied spatially because of differential isostatic movements, but a similar general pattern of relative sea-level change is reported in a number of studies (*e.g.,* SISSONS, 1983; DAWSON, 1984; SUTHERLAND, 1988; FIRTH and HAGGART, 1989). In contrast, recent investigations at a series of sites in northwest Scotland provide evidence for relative sea-level changes quite different from those reconstructed with empirical models, based upon field evidence, for other parts of Scotland (SHENNAN, 1994; SHENNAN *et al.,* 1993, 1994, 1995a, b). These recent investigations show relative sea-level changes following a similar pattern, though significantly different in detail, to those predicted by mathematical models (*e.g.,* LAMBECK 1993a, b).

The aims of this paper are (a) to correlate a range of proxy indicators of environmental change for the last glacial-interglacial transition at a new site, Ardtoe, in northwest Scotland; (b) to illustrate how sediment successions from isolation basins can improve our understanding of both the nature of land/sea level variations and environmental changes in the coastal zone; and (c) evaluate the evidence, from Ardtoe and other sites in the area, for rapid changes of sea level during the last glacial-interglacial transition.

Context

Several reconstructions of relative sea levels suggest (a) a rapid fall of sea level following deglaciation to a minimum level during the Loch Lomond Stadial; (b) a subsequent rise to a maximum towards the end of the Stadial; (c) a fall during the early Holocene to a second minimum, before (d) a mid-Holocene rise and (e) a late Holocene fall (Figure 1). The curve for the Ardyne area is derived from radiocarbon dated sub-tidal mollusc assemblages (PEACOCK *et al.,* 1977, 1978). These produce a large error band of around 7m for the estimates of past sea levels. Nevertheless, the authors interpret a rise in the order of 2m at the end of the Loch Lomond Stadial. SUTHERLAND (1988) shows a rise of similar magni-

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Table 1. *Chronology (terms used in this paper and their equivalents, after* Walker et al., *1994) and major climate/ice sheet events.*

Approximate ^{14}C Age (uncalibrated)			
10 ka BP to present	Holocene	Flandrian	
11 to 10 ka BP	Loch Lomond Stadial	Younger Dryas	Loch Lomond Advance or Readvance—ice cap and local glaciers. Thermal minimum 10.7–10.2 ka BP
13 to 11 ka BP	Lateglacial Interstadial		Rapid climatic amelioration, thermal maximum c. 13–12.5 ka BP, then gradual cooling. Most, perhaps all, of Scotland becomes ice free. Ardtoe area ice free by c. 13 ka BP.
pre 13 ka BP	Late Devensian*	Late Weichselian	Last ice sheet maximum circa 18–20 ka BP

*Note the Stage name Late Devensian is also applied to the whole period through to the opening of the Flandrian/Holocene (see Bowen *et al.,* 1986)

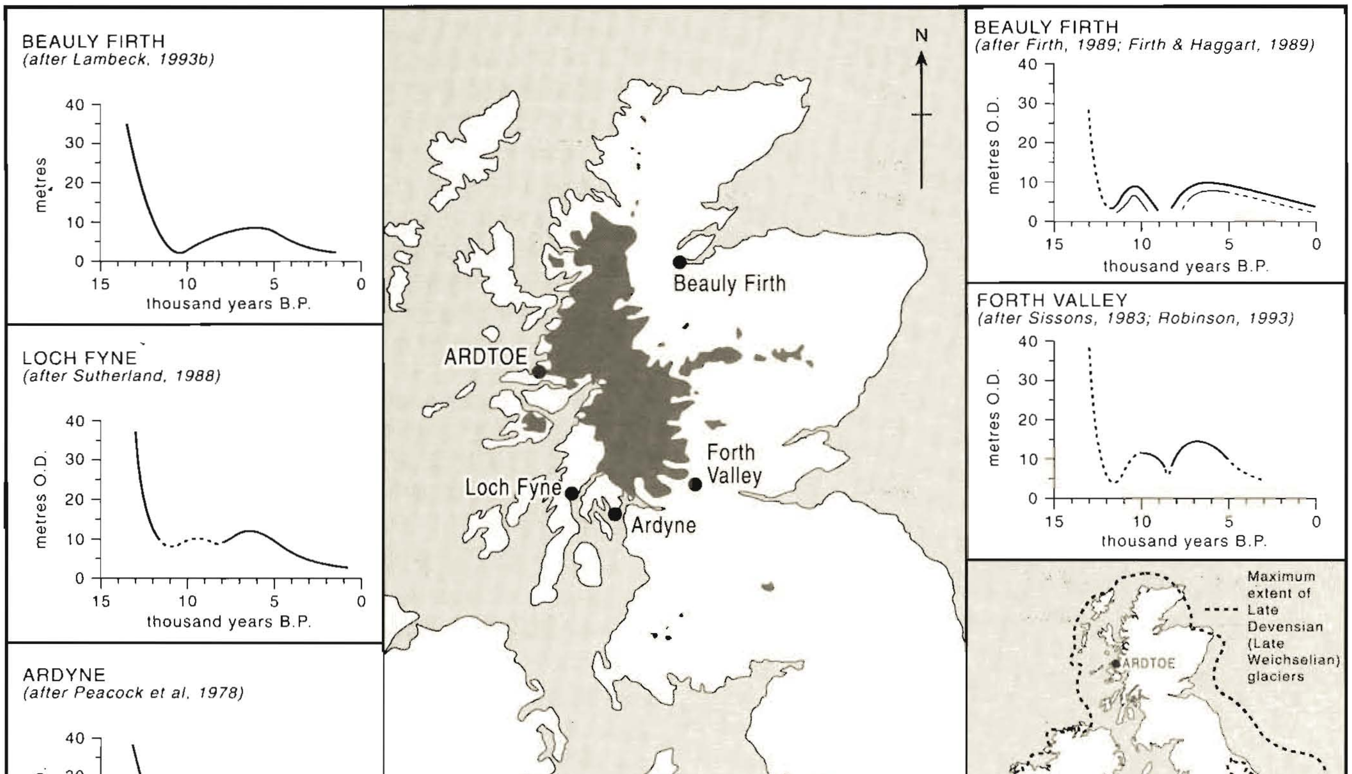

Figure 1. Location of Ardtoe and generalised relative sea-level curves, 0–15 ka BP, from the Firth of Forth (interpreted from data presented by Sissons, 1983 and Robinson, 1993), the Beauly Firth (after Firth, 1989; Firth and Haggart, 1989 including error band), the Ardyne area (after Peacock, *et al.,* 1978, including error boxes) and Loch Fyne (after Sutherland, 1988). Radiocarbon control is absent for significant parts of some of these curves. Dashed lines represent less certainty in the reconstruction of relative sea level. The predicted relative sea-level curve for the Beauly Firth area (after Lambeck, 1993b) shows altitudes standardised to present mean sea level.

tude for the Loch Fyne area, but this part of the curve is poorly fixed. SISSONS (1983) and FIRTH & HAGGART (1989) indicate much greater rises, around 7–8m, towards the end of the Loch Lomond Stadial in the Forth Valley and the Beauly area, respectively. Numerous other studies of relative sea-level change in Scotland are mainly limited to the period after the sea-level maximum towards the end of the Loch Lomond Stadial. Such investigations are not considered further since the preceding oscillations in relative sea level are the focus of the discussion in this paper. In contrast to those studies based upon detailed geomorphologic mapping and stratigraphic investigations, LAMBECK (*e.g.,* 1991, 1993a, b) has constructed mathematical models of isostatic rebound in Scotland. The predicted relative sea-level changes do not include an oscillation at the end of the Loch Lomond Stadial, but simply a relative sea level fall through the Lateglacial Interstadial and the Loch Lomond Stadial to a minimum around 10 ka BP. The age and altitude of the minimum vary spatially, depending on the magnitude of isostatic uplift.

The data from Ardtoe and the other isolation basins were collected independently from both the empirical and mathematical models and so provide a test of the applicability of the models to the region of northwest Scotland.

ARDTOE

The site (Grid Reference NM63257055) is a small sedimentary basin situated at 20–25 m OD on the rocky headland to the north of Kentra Bay (General location: Figure 1; site details: Figure 2). It is bounded by steep rocky slopes which rise to over 70 m. The current catchment draining into the basin is less than 0.25 km^2, and outflow is south to the sea some 150 m distant at Kentra Bay. There are cols at just below 30 m OD to the north and west (Figure 2). The site lies outside the Loch Lomond ice limit, represented by an ice-contact slope 5 km southeast at Acharacle (MCCANN, 1966). Fluvioglacial outwash descends westwards from Acharacle (location shown in Figure 6) and underlies peat at Kentra Moss. MCCANN (1966) suggests that the outwash was reworked to approximately +7 m OD during the mid-Holocene rise in relative sea level. Subsequent detailed lithostratigraphic, pollen, diatom and radiocarbon analyses record a relative fall in sea level (using indicators of approximately mean high water of spring tides) from +7.7 m OD at 4.0 ka BP through to the present tidal marshes at Kentra Bay (SHENNAN *et al.,* 1995a, b).

Lithostratigraphy

A preliminary borehole survey revealed over 900 cm of unconsolidated sediments in the deepest part of the basin (borehole 91/1, Figure 2). In 1994, the site was resampled with a piston corer to obtain an undisturbed core for detailed analysis and to investigate the morphology of the basin beneath the unconsolidated sediments. The results are summarised in Figure 2 and show five main units. At the southern end of the section, peat (Unit 5) overlies a rock sill. The morphology of the sill was established using a grid of boreholes, and the threshold of the sill is at 20.6 m OD at borehole 94/48. The thickest sequences are restricted to the area around the original borehole, 91/1, and the 50 mm diameter piston core, 94/1, used for further study (Table 2). Gravel prevented sampling below 825 cm with the piston corer.

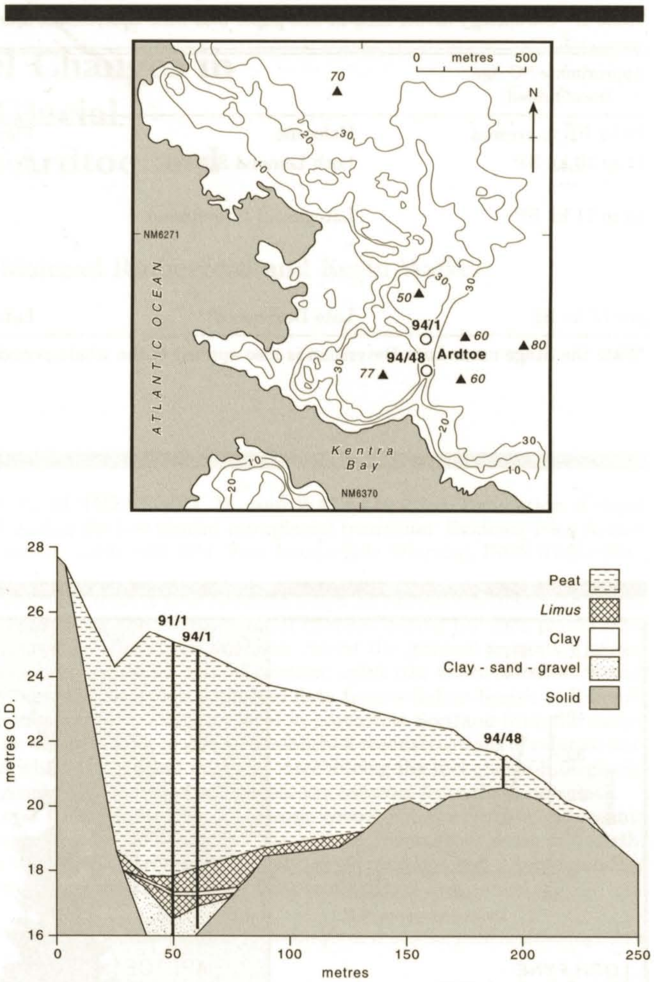

Figure 2. Location and generalised lithostratigraphy of the Ardtoe isolation basin. The map shows the 10, 20 and 30 m OD contours, and the high points of individual hills (black triangles). The major lithostratigraphic units contain sub-units, as detailed in Table 2 for the lower part of core 94/1, but unit 5 (peat) is not sub-divided further for the purposes of this paper.

The sequence in this core represents the infilling of a shallow body of water and the colonisation of the sediment surface by semi-terrestrial peat-forming communities similar to the Cyperaceae—Gramineae—*Sphagnum* communities typical of the surface of the site at the present day.

Biostratigraphy—Methods

Samples for microfossil analyses were prepared using standard procedures (*e.g.,* MOORE *et al.,* 1991; PALMER and ABBOTT, 1986; SCOTT and MEDIOLI, 1980). Microfossil nomenclature follows MOORE *et al.,* (1991), MURRAY (1979), HARTLEY (1986) and HARLAND (1983). Diatom frequencies (Figure 3) are expressed as a percentage of total diatom valves (%TDV) using a minimum sum of 300, except in 4 samples

Table 2. *Lithostratigraphy of core Ardtoe 94/1 (terminology follows* Troels-Smith, *1955). Loss on ignition (%LOI, obtained after 4 hours at 550°C) every 2 cm 742–824 cm except for unit 2a (sample 787–790 used for radiocarbon date).*

Unit	Sub-unit	Depth (cm)	Description	% LOI
5		0–677	*Turfa* peat with *Sphagnum* near to base Sh2, Th^{2}2, Tb(*Sphag*)^2++	
4		677–749	Dark brown *limus* with very fine plant remains (wood at 735 cm) Ld^{2}4, Dl++, Ag+	18–40
3		749–757	Green grey clay As4, Ag++, Ld^3++	8–11
2	b	757–786	Dark brown *limus* with very fine plant remains Ld^{2}4, Ag+	33–52
	a	786–791	Green brown clay *limus* Ld^{3}3, As1, Ag++	
1	d	791–796	Green grey organic clay As3, Ld^{3}1, Ag++	4–8
	c	796–807	Grey silt clay with sand As2, Ag2, Ga++	2–4
	b	807–813	Grey sand clay with silt As2, Ga1, Ag1	2–3
	a	813–825	Very coarse sand within a matrix of grey silt clay with shells and gravel Ga3, As1, Ptm1, Ag++	1–2

where preservation is poor and 150 or 200 were counted. Diatom species are summarised according to the halobian classification (Vos and de Wolf, 1993). Pollen and spore frequencies are shown (Figure 4) as a percentage of total land pollen (%TLP, excluding aquatics and spores, minimum TLP sum of 200, except at 794 and 796 cm where the pollen concentration is very low and TLP sum <100) to facilitate comparison with previously published diagrams. In addition, Figure 4 shows TLP concentration and the concentrations of dinoflagellate cysts and freshwater algae (*Pediastrum* and *Botryococcus*) preserved in the samples prepared for pollen analysis. Addition of exotic *Lycopodium* spores during sample preparation provides the concentration information (Stockmarr, 1971). Stratigraphically unconstrained incremental sum of squares cluster analyses, based upon those taxa which attain a minimum of 2%TLP or TDV, define the pollen and diatom assemblage zones. For foraminiferal analysis, 5 cm^3 of sediment was disaggregated, left for 24 hours, then sieved between 63 μm and 500 μm, the coarse fraction scanned before being discarded. All foraminifera in the sample were counted and are represented on the diagram (Figure 5) as the number of individuals per 5 cm^3 of sediment. Oogonia of charophytes, green algae which live submerged in fresh and brackish water (Moore, 1986), occur in some of the foraminiferal preparations (Figure 5).

Correlation of the assemblage zones defined separately for the foraminifera, diatom, dinoflagellate, freshwater algae, charophyte and pollen data led to the identification of 13 composite biozones (Table 3). No single microfossil group illustrates all 13 biozones.

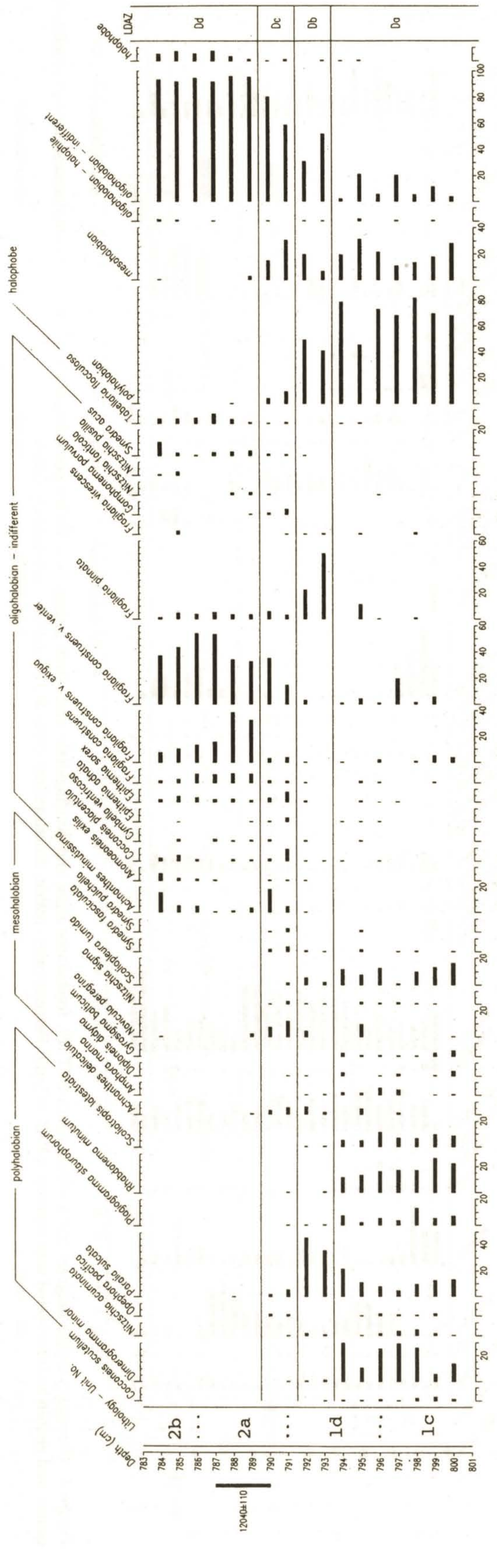

Figure 3. Diatom diagram from Ardtoe 94/1, showing species which attain 2%TDV. LDAZ = Local Diatom Assemblage Zones.

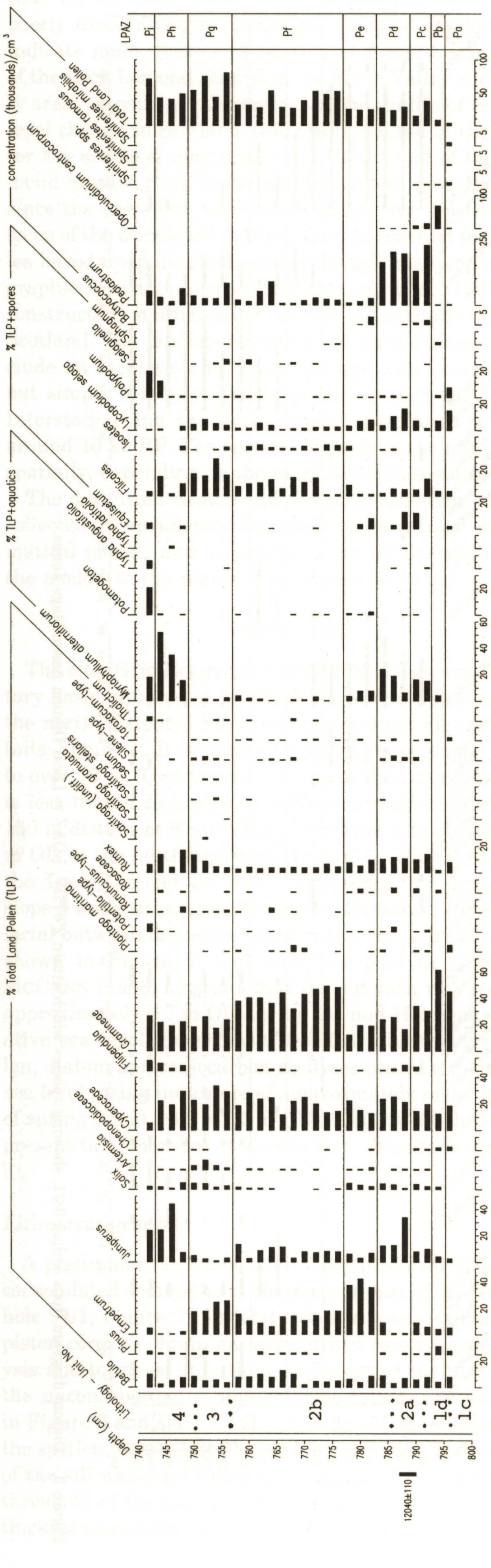

Figure 4. Summary pollen diagram (taxa which attain 2%TLP), freshwater algae and dinoflagellate cysts from Ardtoe 94/1. Pollen percentages for the lowest 2 samples are based on small pollen counts and should be interpreted with caution. LPAZ = Local Palynomorph (pollen, dinoflagellate cysts & *Pediastrum*) Assemblage Zones.

Biozone A (Samples 819–824 cm)

Foraminifera are the only microfossils identified in this zone, although there are frequent shell fragments. This is the most diverse foraminiferal assemblage, with 10 species present. The dominant species are *Elphidium excavatum, Cibicides lobatulus* and *Brizalina variabilis.* The absolute abundance of specimens varies from 20–100 specimens/5 cm^3 sediment. All the species found in this sample are common nearshore subtidal species indicative of normal marine conditions (MURRAY, 1979, 1991; HAYNES, 1973). The palaeoenvironment represented by this assemblage is most likely one of a standing body of water with normal marine salinity.

Biozone B (Samples 815–816 cm)

Diatoms are absent and the foraminiferal assemblage has a low species diversity. Four species were found, *Elphidium williamsoni* being the dominant species along with *E. incertum, E. excavatum* and *Elphidium* spp. Foraminiferal test linings are also found. Total foraminiferal abundances are low, 35 specimens/ 5 cm^3. *E. williamsoni* is indicative of marginal marine environments, lagoonal or estuarine, having a very high tolerance for salinity variation (MURRAY, 1979). The other species in this zone are more indicative of shallow marine conditions and may have been transported into the basin. This assemblage represents a tidal pond with fluctuating salinity, caused by inundation of tides over the sill of the basin. It is likely that all high tides penetrated the basin.

Biozone C (Samples 803–812 cm)

This zone is dominated by organic foraminiferal test linings (100–200 specimens/5 cm^3), with rising frequencies of agglutinated species, *Trochammina macrescens* and *T. haynesi,* and *Ammonia beccari var. limnetis,* a calcareous species. The dominance of test linings in this zone is probably caused by dissolution of the foraminiferal test in contact with acidic waters from the organic sediments above 790 cm. There are low frequencies of two diatom species, *Paralia sulcata* and *Scoliopleura tumida.*

The rare occurrence of *A. beccari var. limnetis* in this zone suggests a brackish lagoonal/estuarine environment. This form can tolerate diurnal salinity variations of 0–35‰ (MURRAY, 1979). *T. macrescens* and *T. haynesi* are diagnostic of tidal marsh environments and can resist extreme environmental variation (HAYNES, 1973; MURRAY, 1979). This assemblage reflects a brackish lagoon with fringing tidal marsh and regular tidal influx over the basin sill, though perhaps not during all high tides.

Biozone D (Samples 796–800 cm)

This zone contains foraminifera, diatoms and dinoflagellate cysts and is differentiated from Biozone E by a significant change in the dinoflagellate assemblage and the first occurrence of charophyte oogonia. The diatom and foraminiferal assemblages are not clearly subdivided into Biozones D and E and are discussed together in the next section.

The single dinoflagellate sample, 796 cm, has a low concentration (note the scale change on Figure 4), and the as-

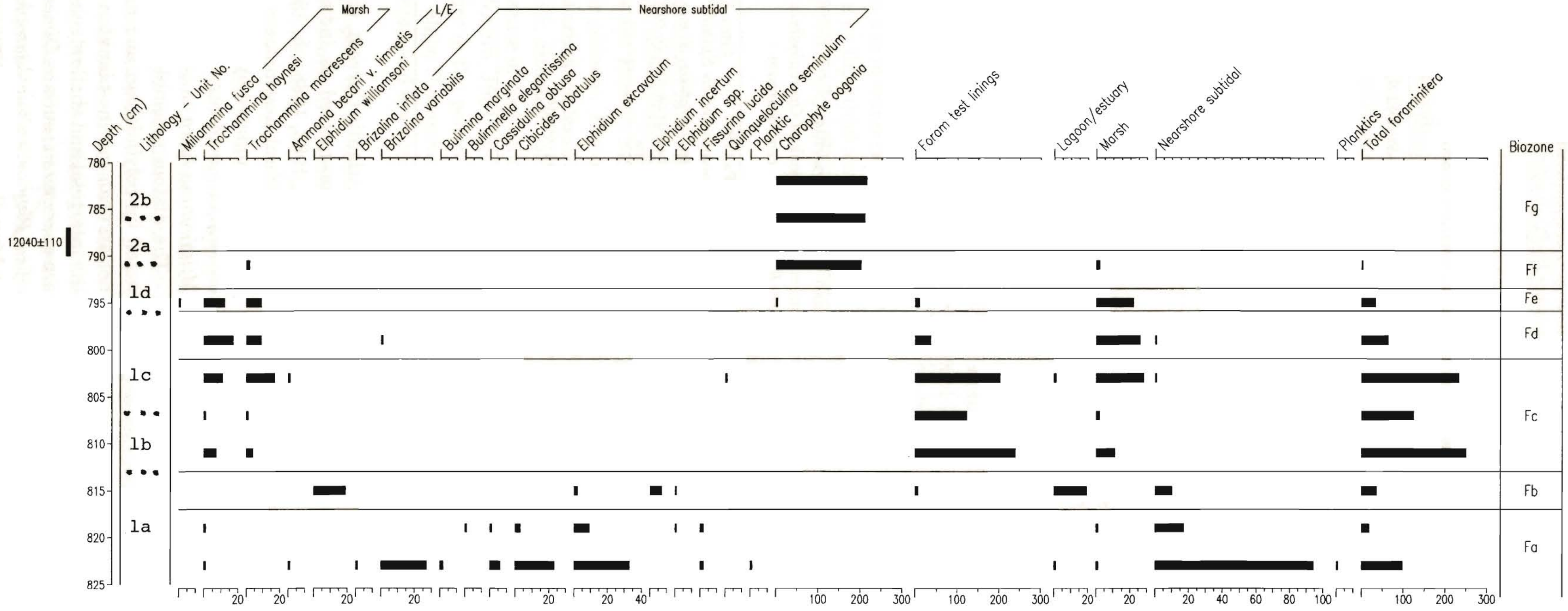

Figure 5. Foraminifera and charophyte oogonia from Ardtoe 94/1, showing the number of individuals/5 cm³. LFAZ = Local Foramineral and Charophyte Assemblage Zones.

Table 3. *Ardtoe 94/1 composite biozones. The composite biozones A–M (column 1) are produced from the correlation of the assemblage zones defined separately for the foraminifera (zone Fa–Fg), charophyte (zones Fd–Fg), pollen (zones Pc–Pi), dinoflagellate cysts and freshwater algae (zones Pa–Pi). Numbers refer to depths (cm) of samples (see Figures 3–5).*

Biozone	Depth Range of Samples (cm)	Foraminifera	Charophyte Oogonia	Diatoms	Dinoflagellate Cysts and Freshwater Algae (*Pediastrum*)	Pollen
M	742	not counted	not counted	not counted	**Pe–Pi** (742–782) *Pediastrum*, no dinoflagellates	**Pi** (742) *Juniperus*, Gramineae, *Myriophyllum alterniflorum*, *Potamogeton*
L	744–748					**Ph** (744–748) *Juniperus*, Gramineae, Cyperaceae, *M. alterniflorum*
K	750–756					**Pg** (750–756) Gramineae, Cyperaceae, *Empetrum*, *Artemisia*
J	758–776					**Pf** (758–776) Gramineae, Cyperaceae, *Empetrum*
I	778–782	**Fg** (782–786) absent	**Fg** (782–786) common			**Pe** (778–782) *Empetrum*, *Rumex*
H	784–789			**Dd** (784–789) *Fragilaria construens* vars.	**Pd** (784–788) *Pediastrum* & few *Operculodinium centrocarpum*	**Pd** (784–788) *Juniperus*, Gramineae, Cyperaceae, *Rumex*, *M. alterniflorum*
G	790–791	**Ff** (791) very rare *Trochammina macrescens*	**Ff** (791) common	**Dc** (790–791) *F. construens v. venter*, *Navicula peregrina*	**Pc** (790–792) *Operculodinium centrocarpum*, *Pediastrum*	**Pc** (790–792) Gramineae, Cyperaceae, *Rumex*, *M. alterniflorum*, *Juniperus*
F	792–793			**Db** (792–793) *F. pinnata*, *Paralia sulcata*		
E	794–795	**Fd–e** (795–799) *Trochammina macrescens*, *T. haynesi*	**Fe** (795) rare	**Da** (794–800) *Dimerogramma minor*, *P. sulcata*, *Rhabdonema minutum*, *Scoliotropis latestriata*, *Scoliopleura tumida*	**Pb** (794) peak of *Operculodinium centrocarpum*	794–796 low pollen concentration
D	796–800		**Fd** (799–823) absent		**Pa** (796) dominated by *Spiniferites mirabilis*, *S. membranecus* and *S. ramosus*	
C	803–811	**Fc** (803–811) test linings		804–812 rare *P. sulcata*, *S. tumida*		
B	815–816	**Fb** (815) *Elphidium williamsoni*, *E. incertum*		816–824 absent	not counted	not counted
A	819–823	**Fa** (819–823) *E. excavatum*, *Cibicides lobatulus*				

semblage is dominated by the *Spiniferites* group, especially *S. mirabilis* and *S. ramosus*. *Operculodinium centrocarpum* is also present but in relatively low numbers. *Spiniferites* spp. are associated with neritic environments and the recorded taxa are indicative of temperate conditions (HARLAND 1988a).

Biozone E (Samples 794–795 cm)

The dinoflagellate assemblage at 794 cm is near monospecific with abundant *Operculodinium centrocarpum* and rare *Spiniferites* spp. recorded. *O. centrocarpum* is extremely common in British offshore Quaternary sediments, and WALL, *et al.*, (1977) refer to its common distribution within outer neritic settings. The present day distribution is associated with the North Atlantic Current, and in fossil sequences, its abundance is interpreted as indicative of climatic amelioration (HARLAND, 1983, 1988a, b, 1992, 1994; WILLIAMS, 1971).

Foraminiferal assemblages at 795 and 799 cm show low diversity, dominated by species typical of a tidal marsh: *Trochammina macrescens* and *Trochammina haynesi*, with rare *Miliammina fusca* in the upper sample.

The diatom assemblages in Biozones D and E are dominated by polyhalobian and mesohalobian species. They are not an open marine plankton assemblage but are related to the intertidal and shallow sub-tidal zone. Many of the species are episarmmic, such as *Dimerogramma minor, Opephora pacifica, Plagiogramma staurophorum* (ROUND *et al.*, 1990, VOS and DE WOLF, 1988, 1993), and indicate the proximity of sandy environments, either marginal to or within the basin. Other episarmmic species, for example *Scoliotropis latestriata, Scoliopleura tumida, Diploneis didyma, Nitzschia sigma,* and *Navicula peregrina* (ROUND *et al.,* 1990, VOS and DE WOLF, 1988, 1993) reflect finer sediments. *Paralia sulcata* is described both as a member of the marine plankton (VOS and DE WOLF, 1988) and as a species often associated with sandy sediments (WHITING and MCINTIRE, 1985) being brought inshore whenever the sediments are disturbed. However, the abundance of long chains of *Paralia sulcata* during periods of connection of the basins at Loch nan Eala to the sea strongly suggests that the species can live in the shallow water of such basins (SHENNAN, *et al.,* 1994). Overall, these diatom assemblages are consistent with the foraminiferal evidence for a tidal marsh fringing the open water of the basin landward of the sill. *Rhabdonema minutum,* which reaches over 20%TDV, is generally found attached to both seaweed and rock surfaces (ROUND *et al.,* 1990). Intermittent flushes of freshwater into the basin are indicated by isolated peaks of *Fragilaria pinnata* and *Fragilaria construens* var *venter.* Near the top of Biozone E, the first occurrence of charophyte oogonia, the pollen of *Myriophyllum alterniflorum* and a low concentration of *Pediastrum,* are indicative of freshwater influence.

Biozones D and E reflect a decreasing marine influence into the basin, as fewer tides cross the sill. The sediments accumulated in approximately 3.5 m of water behind the rock sill. The open water was fringed by intertidal sand and mudflat and marsh, although the steep, rocky sides of the basin would limit their extent.

Biozone F (Samples 792–793 cm)

This zone differs from Biozone G only in the diatom assemblages. In Biozone F, the diatom assemblage is mixed, dominated by the polyhalobian species *Paralia sulcata* and the freshwater epiphyte, *Fragilaria pinnata.* The other polyhalobian and mesohalobian species are much less abundant than in Biozone E. *Fragilaria pinnata,* although tolerant of some salt water, may reflect the presence of cool running streams, with abundant macrophytes (ROUND, 1981; DE WOLF, 1993).

At 792 cm, a major rise occurs in the pollen of *Myriophyllum alterniflorum.* Freshwater algae *Pediastrum* reach their highest concentration at this depth and low concentrations of dinoflagellates are recorded.

This zone represents the first part of the transition from an intertidal basin to an increasingly freshwater environment. LOWE and WALKER (1986), following previous workers, explain the abundance of *M. alterniflorum* in freshwater lakes in terms of temperature response, the taxon benefiting from the warmer conditions of the earlier Lateglacial Interstadial, and later at the opening of the Holocene. WALKER (1970) notes that the species is a major member of the submerged macrophyte phase which, following an initial phase of microbiological activity, occurs in the hydroseral succession in the early stages of colonisation in newly formed lakes. Increased biological productivity is also indicated by the gradual increase in organic content in the sediment revealed by % loss on ignition (Table 2). The *M. alterniflorum* peak in Biozone F could indicate either, or both, a change from brackish to freshwater or a rise in water temperature.

Biozone G (Samples 790–791 cm)

This zone reflects the continued transition to a freshwater lake behind the rock sill. The foraminiferal assemblage comprises only 2 specimens of *Trochammina macrescens,* while charophyte oogonia are common. *Pediastrum* and pollen of *Myriophyllum alterniflorum* are abundant and the concentration of dinoflagellate cysts is further reduced. Almost all the polyhalobian diatoms have disappeared. Mesohalobian species account for 10–20%TDV and the most common, *Achnanthes delicatula* and *Navicula peregrina,* are typical of the present high tidal marsh at Kentra Bay (INNES *et al.* 1993) but are also indicative of shallow sub-tidal environments (VOS and DE WOLF, 1988). However, the diatom assemblages are dominated by a wide range of oligohalobous species, in particular the freshwater planktonic *Fragilaria construens* var *venter,* although it can tolerate low salinities (DE WOLF, 1993). Several of the species indicate a shallow slightly brackish lake in which macrophytes are abundant. The diatom, dinoflagellate and foraminiferal assemblages indicate that tidal input into the lake was still present but becoming increasingly limited to perhaps occurring only during highest spring tides.

Sediment from 787–790 cm, across the transition to Biozone H, gave a radiocarbon age of 12,040 ± 110 BP (SRR-5167) for this stage of the isolation of the basin from the sea.

Biozone H (Samples 784–789 cm)

The diatom assemblages show a diverse freshwater flora, although most of the species can tolerate low salinities. The presence of *Tabellaria flocculosa,* a halophobic, fully freshwater epiphytic species, confirms the trend to complete isolation from the sea. There are no foraminifera, only rare polyhalobian and mesohalobian diatoms, while dinoflagellate concentrations are very low and are absent above 784 cm.

The zone represents the end of the transition to a freshwater lake, with only extreme tides or intermittent storm surges crossing the sill. By the end of the zone the basin is totally isolated from the sea.

Biozones I to M (Samples 742–782 cm)

These zones are differentiated only upon their pollen assemblages (Table 3 and Figure 4). The primary application of the pollen data from Ardtoe is to elucidate the vegetation changes which took place within and around the basin at the time of its isolation from the sea and during the ensuing period. The ecological effects of the retraction of direct marine influence from the site should be reflected clearly in vegetation communities. Although the small size, steep slopes and rocky nature of the basin would have provided limited opportunity for intertidal saltmarsh vegetation to develop, the presence of the halophyte taxa Chenopodiaceae and *Plantago maritima* in biozones D to G coincides with the diatom, foraminifera and dinoflagellate evidence of the presence and then removal of marine conditions. However, pollen from the vegetation communities surrounding the basin, above the tidal marsh, dominate the assemblages. These vegetation communities reflect the broader scale responses to climate and environmental changes. Once the basin was isolated from the sea, the pollen assemblages continue to reflect these regional-scale changes. Therefore, the pollen stratigraphy, Biozones D to M, is also used as a relative dating technique alongside the radiocarbon evidence for a period in which "radiocarbon plateaux" and other potential difficulties may constrain interpretations (*e.g.*, AMMANN and LOTTER, 1989; LOWE, 1991). The pollen assemblage zones from Ardtoe can be compared with other radiocarbon dated profiles from the region, many of which exhibit very similar pollen assemblage successions.

Regional Correlation of Biozones

Recent research in Skye, Mull and adjacent areas of the Scottish mainland has established a consistent pattern of pollen assemblage change which is considered a direct response to the climate history of the area during the last glacial-interglacial transition (TIPPING 1988, 1991; BENN *et al.*, 1992; WALKER *et al.*, 1994). Some diachroneity in this pattern exists and is attributed to local site factors such as degree of exposure or soil variability (LOWE and WALKER 1986). Rapidly changing, dynamic successional vegetation communities characterise this period of environmental transition.

WALKER *et al.* (1994) describe the establishment of open ground communities, usually dominated by Gramineae, Cyperaceae and *Rumex,* after deglaciation. The age of this event is poorly known and will have varied spatially, but the date of 13140 ± 100BP from Loch an t-Suidhe on Mull (LOWE and WALKER 1986) is probably a good estimate for the Ardtoe area. Rapid establishment of heath and low shrub communities, dominated by *Juniperus* mainly, occurred around 13 ka BP and persisted for several centuries (WALKER *et al.,* 1994). *Juniperus* is relatively high in Biozones F–H, with a single peak at the base of H. The radiocarbon date, 12040 ± 110 BP, from the Biozone G/H boundary, is consistent with the regional data. WALKER *et al.,* (1994) suggest that a temperature decline at around 12.5 ka BP marks the start of a step-like deterioration in climate after the thermal maximum, with a further abrupt fall around 12.0 ka BP when *Juniperus* is replaced by a low heath and herb association (WALKER *et al.* 1988, TIPPING 1991) with *Empetrum* characteristic. Although not well represented at all sites, this change is the main biostratigraphic event in the middle of the Lateglacial Interstadial. Dates of 12400 ± 200BP at Loch Ashik on Skye (WALKER and LOWE 1990) and 11860 ± 80 BP at Loch an t-Suidhe on Mull (LOWE and WALKER 1986) bracket this event. At Rumach Meadhonach, the *Juniperus–Empetrum* transition is dated to 11820 ± 145 BP (SHENNAN, *et al.,* 1993). The *Empetrum* peak defines Biozone I at Ardtoe.

A continued decline in climate and vegetation cover occurs regionally with assemblages in the latter half of the Lateglacial Interstadial characterised by a more open ground flora dominated by Gramineae, Cyperaceae and *Empetrum* (WALKER *et al.,* 1994) as reflected in Biozone J.

The trend of climate deterioration culminates in the Loch Lomond Stadial phase of extremely severe cold climate which is characterised in all cases by tundra type herb vegetation and unstable soil conditions. This frequently resulted in the erosion of inorganic material into lakes and the deposition of clastic layers in the sediment column. *Artemisia* is diagnostic of this phase, particularly the latter half (TIPPING 1991, BENN *et al.,* 1992), and *Rumex,* Gramineae, Cyperaceae and *Selaginella* are also characteristic, along with a range of ruderal herbs. The Loch Lomond Stadial is represented by Biozone K, and coincides with the clastic unit 3 (Table 2). The timing of the Loch Lomond Stadial is now well dated. WALKER and LOWE (1990) suggest limits of c.10.7 ka BP and c.10.2 ka BP, which are in agreement with dates from Rumach Iochdar, 10785 ± 75 BP and 10145±70 BP, where the basin was isolated c.10.8 ka BP (SHENNAN, *et al.* 1993).

The start of the Holocene after the close of the Stadial sees the early Interglacial succession of *Rumex* and then *Juniperus,* with abundant *Myriophyllum alterniflorum* (Biozone L) and then *Potamogeton* (Biozone M).

DISCUSSION

Coastal Evolution

The range of biostratigraphical data obtained reveals a consistent trend in the transition from fully marine water to a freshwater lake. This is interpreted as a relative fall in sea level. The earliest signal of a negative tendency of sea-level movement is in the foraminiferal assemblage change from Biozone A to B. Regular tidal inundation of the basin continues through to the G/H boundary and evidence of occasional extreme high water levels, probable storm surges, is found until the end of Biozone H. This interpretation of the biostratigraphic data appears to be supported by the lithostratigraphic evidence (Table 2), with the transition from predominantly clastic to organic sediments at 791 cm, the lowest sample in Biozone G. This is summarised in Figure 6. This model cannot be quantified exactly and clearly a precise chronology is required. The major parameters affecting the sediments and ecology of the basin are rate of sea-level change, tidal range, freshwater input into the basin, basin dimensions, and sedimentation rate. The radiocarbon and pollen correlations discussed in the preceding section indicate a period of at least 500 and perhaps more than 1000 years for the complete isolation process as recorded between the base of Biozone B to the top of Biozone H. Relative sea-level fall in the Arisaig area, farther north, is in the order of 8–9 m/1000 years (8–9 mm.a $^{-1}$) between 11.8 and 10.5 ka BP (SHENNAN *et al.* 1993). Current spring tide range is 4.2 m and extreme tide range is over 5m. Storm surges can easily add another meter. Using these as guideline figures, the tidal range during the period of isolation would have been of a similar magnitude to the present day.

The major changes in coastal palaeogeography can be estimated from the present 20 m and 30 m OD contours (Figure 6). In Biozone A the full marine conditions would require a Highest Astronomical Tide level of at least 26 m OD, assuming a tidal range similar to the present. Therefore, for a shoreline forming at approximately Mean High Water of Spring Tides, the 30m contour represents a period slightly

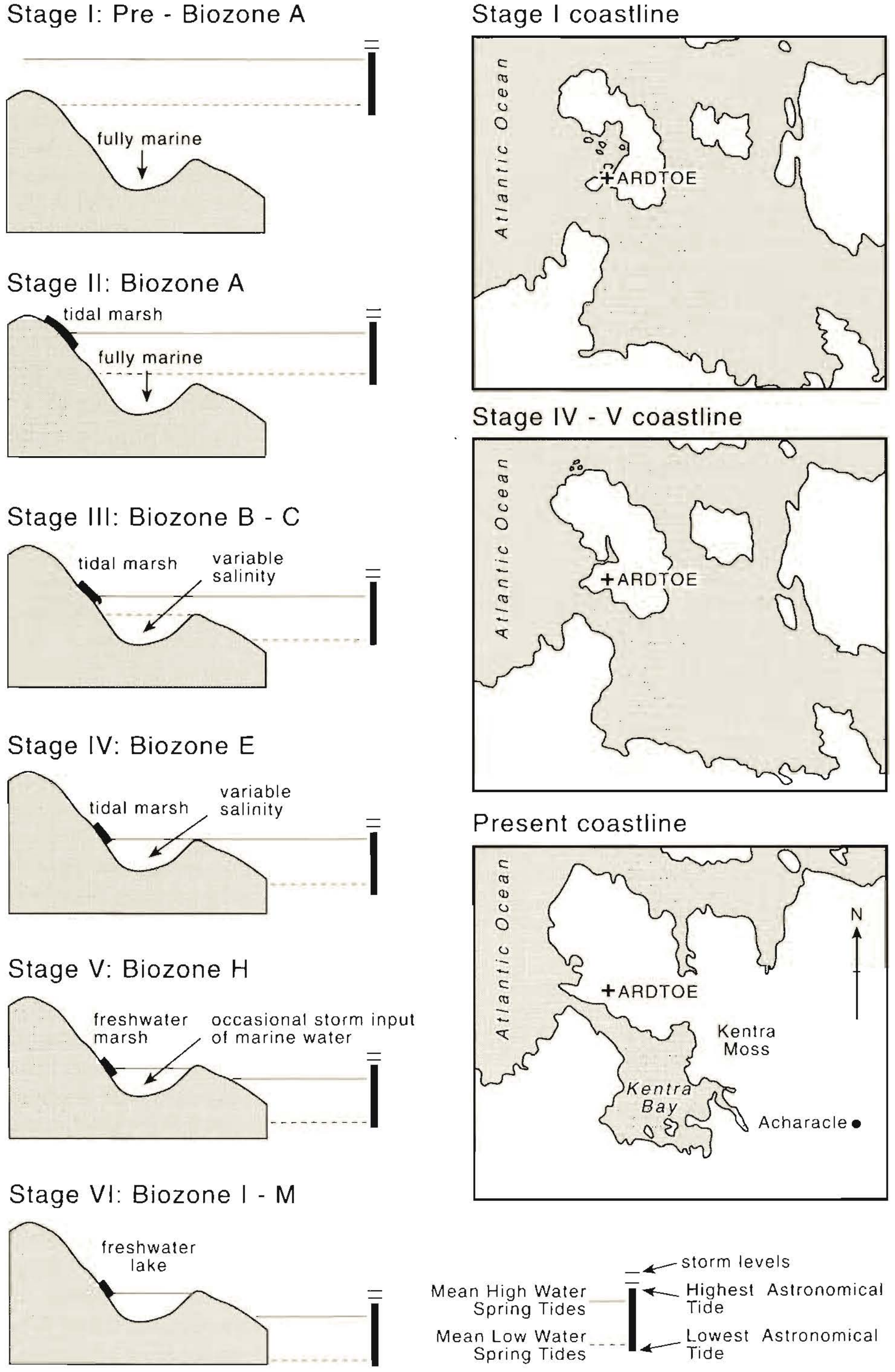

Figure 6. A model of the isolation of the basin at Ardtoe and the major changes in palaeogeography of the area, relating the six stages of the isolation process to the Biozones described in the text.

Table 4. *Altitude of the sill and age of the isolation of each basin. The sill altitude and radiocarbon date define the relative fall in sea level recorded at each site.*

Site	Altitude of Basin Sill (m OD)	Conventional ^{14}C Age BP ($\pm 1\sigma$) of Isolation Contact	Laboratory Code	Correlation with Ardtoe Biozone
Ardtoe	20.6	12,040 ± 110	SRR-5167	G/H boundary
Rumach Meadhonach	17.8	11,820 ± 145	UB-3643	top of H
Rumach Iochdar	9.3	10,755 ± 90	SRR-4862	top of J
Loch nan Eala—upper basin	6.3	10,500 ± 90	SRR-4865	K
Loch nan Eala—main basin	5.2	10,060 ± 86	UB-3633	L

earlier, Stage I in the model (Figure 6). There are no well developed high-level raised beach deposits reflecting such a sea level in the immediate vicinity; but from 15 km further north, DAWSON (1994) reports a series of raised beach terraces rising to 37.5 m OD. The 20 m contour represents the period around the final isolation of the basin, Stage V. During Stage I in the model (Figure 6) connection between the open sea and the basin was across cols at approximately 29 m OD to the north and west in addition to the sill, at 20.6 m OD, at the southern edge of the basin. From Stage II, correlated with Biozone A, onward, the only connection would have been over the southern sill.

The Ardtoe Peninsula was an island probably until the Loch Lomond Stadial, when the outwash discharging from the ice front at Acharacle, 5 km to the southeast (Figure 6), was deposited and made a connection to the mainland. Since the borehole surveys on Kentra Moss do not penetrate the outwash sands and gravels to bedrock, this cannot be stated with full certainty.

Relative Sea-Level Change

Ardtoe is the fifth basin in the area to provide radiocarbon dated isolation contacts within the last glacial-interglacial transition, the others being two at Loch nan Eala (SHENNAN *et al.*, 1994) and those at Rumach Iochdar and Rumach Meadhonach (SHENNAN *et al.*, 1993). It must be remembered that Ardtoe is 15 km south of the Rumach/Loch nan Eala area and some differential uplift between the two areas is probable. Nevertheless, the five dates form a series in which decreasing altitude of the isolation contact is matched by decreasing age (Table 4).

The pollen assemblages at the time of isolation at Loch nan Eala, Rumach Iochdar and Rumach Meadhonach correlate biostratigraphically with the pollen record from Ardtoe.

The isolation at Rumach Meadhonach, dated at 11820 ± 145 BP, has a *Juniperus* and *Rumex* assemblage immediately before a rise of *Empetrum*. This correlates well with the same pollen change, the top of Biozone H, at Ardtoe. The date of 10755 ± 90 BP from Rumach Iochdar shows a Gramineae, Cyperaceae and *Empetrum* assemblage which fits well with the latter part of Biozone J, the end of the Lateglacial Interstadial. At Loch nan Eala, the isolation, dated at 10500 ± 90 BP, shows a Gramineae, Cyperaceae, *Artemisia* and *Rumex* assemblage which correlates with Biozone K and confirms its mid-Loch Lomond Stadial age. The youngest isolation contact in this sequence, 10060 ± 86 BP, from Loch nan Eala has a *Juniperus* dominated assemblage which agrees well with an early Holocene age and correlates with Biozone L. Although there can be problems with the reliability of radiocarbon dates from Late Devensian sediments (AMMANN and LOTTER, 1989; LOWE, 1991), the pollen data support the view that the dates discussed in this paper form a consistent series to constrain the Late Devensian fall of sea level in this area.

The series of dates indicates a relative fall in sea level throughout the Lateglacial Interstadial and the Loch Lomond Stadial, into the Holocene. This trend is similar to those predicted from geophysical models (Figure 1 and LAMBECK, 1993a, b; see discussion in SHENNAN *et al.*, 1995b). There is no evidence, either in the correlations between the basins or within the lithostratigraphy and biostratigraphy of any individual basin, for a relative rise in sea level during the Loch Lomond Stadial as proposed for other areas (Figure 1). The two basins at Loch nan Eala have sills only 1.1 m different in altitude and would be expected to have recorded any relative sea level rise of the magnitudes shown in Figure 1 between 10.5 and 10 ka BP. Prior to 10.5 ka BP the rate of relative sea-level fall is around 8–9 mm. a^{-1}, reducing to about 5 mm.a^{-1} by 10 ka BP (Table 4 and SHENNAN *et al.*, 1994). Ongoing research at another basin at Rumach (SHENNAN, 1994) shows that this fall continued to a low stand between about 9.5 and 9.0 ka BP.

These new results clearly require verification from other locations. Likewise, the evidence for the major oscillations in sea level during the last-glacial interglacial transition, described in the introduction, also deserves renewed evaluation. This must involve a re-assessment of the age and indicative meanings of every sea-level index point used, including quantifying the error terms involved with each one. If these oscillations in relative sea level are verified then the cause of the difference between the northwest sites (Ardtoe-Rumach-Loch nan Eala area) and those shown in Figure 1 must be established. It is essential that the re-assessment and verification processes are undertaken before the data are used further because the implications arising from the noted differences are great. For example, the shoreline and relative sea-level data have been interpreted previously as providing evidence for block faulting, shifts in the position of the centre of isostatic uplift, and redepression of the lithosphere, all resulting from loading by Loch Lomond Stadial ice (*e.g.*, FIRTH *et al.*, 1993). Even fundamental correlation of late glacial shorelines and the inferred combination of climate and geomorphological conditions under which they formed (*e.g.*, GRAY, 1978) deserve re-assessing. Furthermore, in order to achieve a better fit between the field data and the numerical predictions of relative sea-level change LAMBECK (1993b) suggests that a 17% increase in ice load over northern Scotland is required. Whether there are field data to support this ice model should now be investigated.

Climate and Palaeoceanography

Co-occurrence of pollen and dinoflagellate cysts affords the possibility of correlation between marine and terrestrial sequences and palaeoenvironments.

HARLAND (1988a, 1992, 1994) observes that dinoflagellate cyst assemblages in North Sea sediments illustrate a clear change from assemblages dominated by *Bitectatodinium tepikiense* to those dominated by *Operculodinium centrocarpum* during the Lateglacial Interstadial. A comparable, though less distinct change, is seen in sediments from the north east Atlantic (*e.g.*, STOKER *et al.*, 1989; GRAHAM *et al.*, 1990; PEACOCK *et al.*, 1992), although the sampling interval is coarse and the chonostratigraphic control poor in some cores. At Ardtoe, *O. centrocarpum* is present in Biozones E-H, reaching a maximum concentration in Biozone E (Figure 4). *B. tepikiense* and the transition to *O. centrocarpum* are not recorded in the Ardtoe sequence. Dinoflagellate cysts are best preserved in fine-grained marine sediments and their absence below 796 cm may result from the increasing sand content of the sediment. The rich *O. centrocarpum* assemblage at Ardtoe is recorded before the isolation of the basin at 12040 ± 110 BP and may be correlated with assemblages of the Lateglacial Interstadial such as those described above.

The conspicuous change to assemblages dominated by *O. centrocarpum* within the Lateglacial Interstadial and the Holocene Interglacial has been linked to both the influence of the North Atlantic Current and the position of the oceanic Polar Front (HARLAND, 1992). Distribution maps of dinoflagellate cysts in bottom sediments from the North Atlantic (HARLAND 1983) illustrate a clear association of this cyst with the North Atlantic Current. The cysts are extremely common in British offshore Quaternary sediments and although cosmopolitan in distribution, may be considered opportunistic or pioneering species in north-temperate to arctic environments where assemblages are almost monospecific (HARLAND 1983). RUDDIMAN & MCINTYRE (1981) map Polar Front movements during deglaciation, based on $CaCO_3$ and polar faunal assemblages. Their phase IIIa (13.0–11.0 ka BP) illustrates that the east-central subpolar Atlantic became markedly warmer within this time period, with the oceanic Polar Front retreating far to the west and north. The peak of *O. centrocarpum* occurs before 12040 ± 110 BP; and if the correlation with the influence of the North Atlantic Current and the position of the oceanic Polar Front is correct, then the retreat of the oceanic Polar Front to the north of Ardtoe must have occurred before this time.

This date is supported by the pollen chronology described earlier and illustrates the benefit of correlating the marine and terrestrial record. Within the Ardtoe core, the climatic amelioration, as interpreted from the assemblages of *O. centrocarpum*, is succeeded upsection by the pollen evidence from the thermal maximum, Biozones F–H, and then the marked temperature decline at the Biozone H/I boundary.

Further assessment of the movement of the oceanic Polar Front and the North Atlantic Current, using dinoflagellate cyst assemblages from the Rumach and Loch nan Eala sediments (SHENNAN, *et al.*, 1993, 1994), is underway.

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