Pergamon

Quaternary International, Vol. 26, pp. 97–123, 1995.

1040–6182/95 $29.00

1040–6182(94)00050–6

LATE DEVENSIAN AND HOLOCENE RELATIVE SEA-LEVEL CHANGES IN NORTHWESTERN SCOTLAND: NEW DATA TO TEST EXISTING MODELS

Ian Shennan, James B. Innes, Antony J. Long* and Yongqiang Zong
Environmental Research Centre and Department of Geography, University of Durham, Durham DH1 3LE, U.K.

Pollen, diatom, lithostratigraphic and radiocarbon data from five sites in northwestern Scotland provide new data from an area previously devoid of reliable and precise information on Late Devensian and Holocene sea-level changes. The sites cover a range of palaeoenvironments, indicative of diversity in coastal evolution since deglaciation. For each site and palaeoenvironment the reference water (tide) level, indicative range, age and tendency of sea-level movement of all sea-level index points are quantified to enable correlation of the diverse coastal environments.

The data record patterns of relative sea-level change and tendencies of sea-level movement from 12 ka BP to 1 ka BP. This is the longest and most comprehensive published record of relative sea-level change from the area. The information is used to test the accuracy of existing models of relative sea-level change. The results are only broadly consistent with a quantitative rebound model, and there is significant disagreement with empirical models during the Late Devensian and the early Holocene.

INTRODUCTION

In 1966 the Institute of British Geographers published a Special Issue of the *Transactions* titled "The Vertical Displacement of Shorelines in Highland Britain" (Farmer, 1966). The collection of papers summarised the most recent advances of over 100 years of research interlinking climate, glaciation, sea-level change and crustal movements. The papers represented a benchmark in research and have had a major influence on much of the subsequent sea-level research in Scotland. The methodologies developed for such studies of relative sea-level changes and crustal movements were influenced initially by the nature of the field evidence. Emerged landforms and sediment sequences are abundant in Scotland, and at an early stage Jamieson (1865) suggested these landforms showed that the growth and decay of ice sheets was accompanied by depression and then elevation of the crust (Smith and Dawson, 1983). Detailed geomorphological mapping, the identification and precise altitudinal levelling of palaeoshoreline features were the key methods employed early in the research. Later, detailed stratigraphic and micropalaeontological data were used to infer palaeoenvironments and date the features, but dateable horizons were spatially restricted and studies were mostly confined to sites in eastern, northeastern and southern Scotland (e.g. see the reviews by Jardine, 1982; Sissons, 1983; Haggart, 1986). The coastline of western and northwestern Scotland is characterised by a series of sea-lochs, rocky headlands and predominantly sandy embayments. Sheltered intertidal depositional environments are very restricted, and this in part explains the lack of systematic stratigraphic studies in this area (Sutherland, 1984) in contrast to most of the estuaries in the rest of Great Britain where extensive estuarine deposits have accumulated. Donner (1970) considered the biostratigraphic and radiocarbon evidence from sites in the Western and Northern Isles, as well as from southern and east-central Scotland, and stressed the potential importance of such data for the reconstruction of sea-level changes. Although working with a restricted database, Donner presented provisional sea-level curves and showed that, at least in marginal areas of Scotland, this approach had great potential to yield high resolution data.

Shennan (1992) illustrates that despite early differences in emphasis, due to the nature of the most readily available data, a common methodology can be applied to Holocene sea-level studies in Great Britain and also to other areas. In England, though there are restricted emerged marine features on the northeastern coast (e.g. Gunn, 1900), most data are derived from studies of unconsolidated semi-terrestrial, estuarine and intertidal sediments as uplift is replaced by subsidence in the areas farther south (Shennan, 1989, 1992). Thus, early studies from the coastal lowlands of England focused on the delicate balance between water-level changes and deposition of biogenic and clastic sediments rather than on differential crustal warping illustrated by tilted shorelines.

AIMS

A primary aim of IGCP Project 274 "Quaternary Coastal Evolution; Case Studies, Models and Regional Patterns" is to produce models, ranging from descriptive to numerical, of coastal change and evolution that will aid analysis in, and correlation with, other areas (van de Plassche, 1986). Shennan (1992) shows how such models can be applied to the east coasts of Scotland and England.

In this paper we aim to apply the methodology of sea-level research developed by the research group at Durham over the past 15 years to an area of northwestern Scotland, specifically to test various models of relative sea-level change that have been proposed. Full data from the individual sites are published elsewhere (e.g. Shennan *et al.*,

*Present address: Department of Geography, University of Southampton, Highfield, Southampton SO9 5NH, U.K.

1993, 1994, 1995). Here we summarise the data from each of the five sites by describing the lithostratigraphy of the site and then the biostratigraphy and chronostratigraphy of a single core. These illustrate the type of sea-level index points available from each site.

STUDY AREA

Most research undertaken in northwestern Scotland has been based on the interpretation of raised morphological features which are seldom radiocarbon dated (e.g. McCann, 1966; Kirk *et al.*, 1966; Sissons, 1967, 1983; Gray, 1974, 1978; Dawson, 1980, 1984).

In this paper five sites from northwestern Scotland, between Kentra Bay and Loch Morar (Fig. 1), provide stratigraphic, morphological, pollen, diatom and radiocarbon data to describe Late Devensian and Holocene relative sea-level changes. Sites were selected specifically where there was potential for preservation of low energy intertidal clastic deposits and organic sequences that could be radiocarbon dated. Therefore a wide range of palaeoenvironments, including raised tidal marshes (Kentra Moss), isolation basins (Loch nan Eala; Rumach) and wetlands associated with dune/beach systems (Mointeach Mhor; Glenancross) provide sea-level index points. The consistent methodology adopted here allows correlation to be made between these different palaeoenvironments.

None of the sites have been investigated before in such detail and the data were not available when the models described below were formulated. Therefore, the new data from these sites provide an independent test for the models.

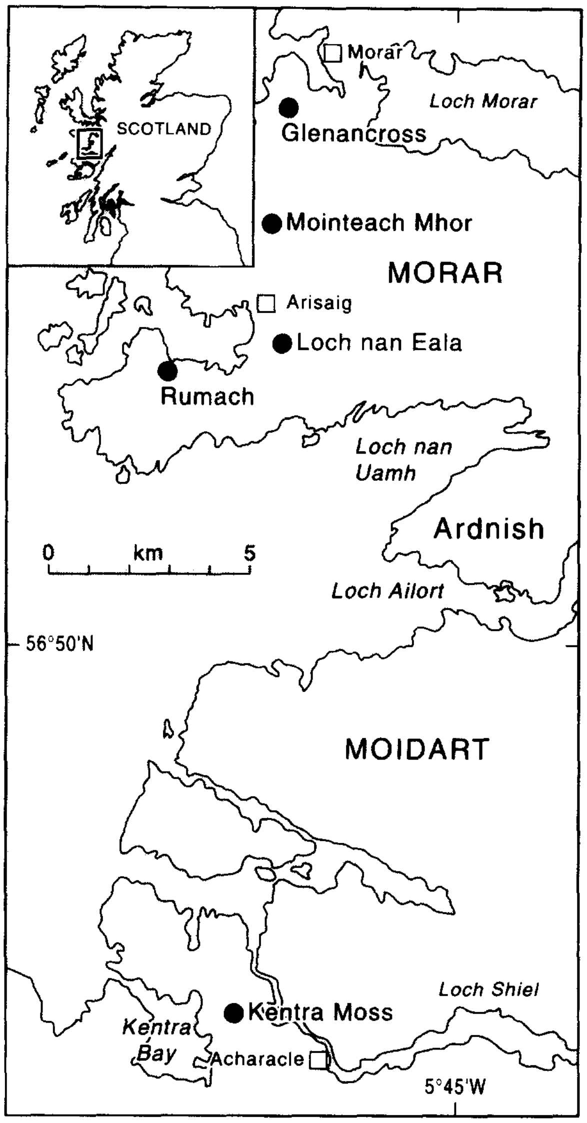

FIG. 1. Location of the study area and the five sites selected for detailed analysis.

MODELS

Sissons (1966, 1969, 1983; also Sissons and Brooks, 1971) proposed a chronology of relative sea-level changes for the western Forth Valley in southeastern Scotland and isobase maps for the major shorelines, in particular the "Main Lateglacial Shoreline" and the "Main Postglacial Shoreline". Much contemporary and subsequent research developed from the research methodology, ideas and results of Sissons (see Ballantyne and Gray, 1984; Dawson, 1984; Sutherland, 1984). Although the chronology and isobase maps were originally described as provisional, they have been quoted widely and used by many subsequent authors and are essentially empirical models for the age–altitude and spatial patterns of sea-level change applied to different areas in Scotland. The term model rarely appears in the literature on relative sea-level changes in Scotland although recently Haggart (1989) and Cullingford *et al.* (1991) applied the term to relative sea-level changes and isobase maps respectively. However, earlier uses of models are seen in the construction of shoreline height–distance diagrams using linear regression techniques and of isobase maps using trend surface analyses since both sets of methods are by definition mathematical models (e.g. Cullingford and Smith, 1966; Sissons, 1966; Smith *et al.*, 1969; Gray, 1974; Sutherland, 1984). In this paper we use the term 'model' as described by Haggett and Chorley (1967), i.e. a model can be a theory, or a law, or a hypothesis, or a structured idea, or a synthesis of data.

Isobase Models

The isobase models are quite well constrained between northeastern and southeastern Scotland (Cullingford *et al.*, 1991) but in western and northwestern Scotland the shoreline features are more fragmentary and none has been radiocarbon dated directly. Correlations are based on morphological criteria (e.g. Dawson, 1984). The Kentra Bay to Loch Morar area lies at the limit of existing analyses which predict the "Main Lateglacial Shoreline" to occur at +5 m to +8 m OD (OD is the national levelling datum for Great Britain) and the "Main Postglacial Shoreline" between +10 m and +12 m OD (e.g. Sissons, 1983; Sutherland, 1984; Firth and Haggart, 1989).

Age–Altitude Empirical Model

The age–altitude empirical model of relative sea-level change is shown in Fig. 2. The general form of the curve is derived from that originally proposed by Sissons for the Forth Valley, and subsequently described for other areas by later authors (e.g. Sissons and Brooks, 1971; Sissons, 1983; Firth and Haggart, 1989; Smith *et al.*, 1992; Sutherland, 1988). In contrast, Donner (1970) describes relative sea-level changes similar in general form to the predictions of the rebound model described below. The isobase data provide altitudinal constraints for the model shown in Fig. 2. The model predicts a fall in sea level from the time of deglaciation to a minimum ca. 11,200–10,800 BP. This minimum is represented by the "Main Lateglacial Shoreline" (Sissons, 1969, 1983; Sutherland, 1984, 1988; Firth and Haggart, 1989). There followed a relative rise in sea level to a maximum between ca. 10,300 BP (Sissons, 1983) and ca. 9500 BP (Sutherland, 1988), then a fall to a minimum ca. 8600–8000 BP (e.g. Haggart, 1989). Relative sea-level rise ensued, culminating at the "Main Postglacial Shoreline" at ca. 6800 BP in the western Forth Valley (Sissons and Brooks, 1971; Sissons, 1983) but probably slightly later in areas undergoing less glacio-isostatic uplift (e.g. Smith *et al.*, 1983). Second order fluctuations in relative sea level, not shown in Fig. 2, are proposed for some areas, particularly during the major relative falls in sea level 10,300 to 8600 BP and 6800 BP to the present (e.g. Sissons and Brooks, 1971).

Transposing a model developed for another area to the sites analysed in this paper is justified on two counts. First, it provides a working hypothesis which can be tested explicitly using a new and independent data set. Second, it reflects the approach that has been frequently followed in the past whereby features in one area are compared with the model originally proposed for southeastern Scotland. The procedure of testing a working hypothesis is simply the application of a formal scientific method to approaches commonly adopted over recent years. It is clear from different approaches to the analysis of the interaction of sea-level changes, crustal movements and ice loading and unloading that relative sea-level maxima and minima are variable in age and altitude, dependent upon geographical location (e.g. Shennan, 1987a, b; Lambeck, 1991a, b). There is limited radiocarbon evidence to illustrate diachroneity of the "Main Postglacial Shoreline" (Smith *et al.*, 1983; Cullingford *et al.*, 1991), but for older morphological features chronostratigraphic synchroneity seems implicit in many morphostratigraphic correlations. In contrast, the predictions of Lambeck (1991a) imply that diachroneity of relative sea-level maxima and minima should be identifiable, even after allowing for the error terms in radiocarbon assays.

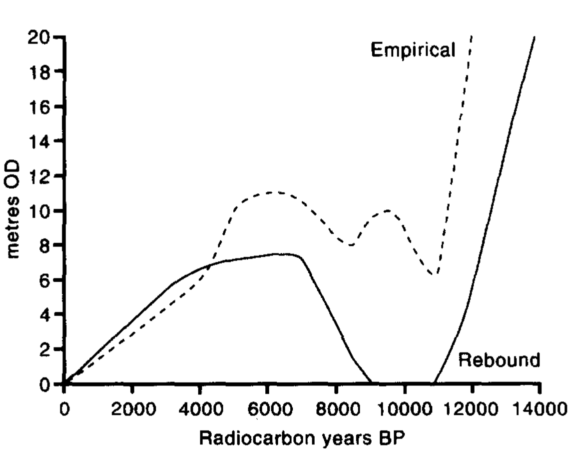

FIG. 2. Empirical and rebound models of relative sea-level change (m OD) for the study area. The curves illustrate the significant differences between the general trends but are not intended to define precise age and altitude limits (see text for details).

Rebound Models

Lambeck (e.g. 1991a, 1993) adopts an approach whereby high resolution quantitative glacial rebound models predict relative sea-level changes for specific areas. The ensuing relative sea-level curves for areas close to the present study area show a Late Devensian fall from the time of deglaciation to a minimum around 10,000 BP, a rise culminating 7000–6000 BP, then a fall to the present. The age and altitude of the early-Holocene minimum and the mid-Holocene maximum vary spatially. The curve shown as the 'rebound model' in Fig. 2 is derived from published predictions for relative sea level, in the form of maps and age–altitude graphs (Lambeck, 1993, Figs 23 and 24a).

The altitudes shown in Fig. 2 refer to Ordnance Datum (OD) to allow direct comparison with the isobase models. Because some sea-level index points form at different reference water levels, at a later stage of calculating relative sea-level changes each index point is standardised to present mean sea level by using the quantitative value for its indicative meaning (see van de Plassche, 1986; Shennan, 1982, 1986b).

The two curves shown in Fig. 2 represent the expected general trends of relative sea-level change for the Kentra Bay to Loch Morar area, based upon the empirical and rebound models. A relative fall in sea level from the mid-Holocene to the present is also expected from the model of current crustal movements proposed by Shennan (1989). For any age an altitudinal error in the order of ± 1 m should be applied but this is not indicated on Fig. 2 for the sake of clarity. The fluctuations shown on the empirical model are inferred from the morphostratigraphy in the original field locations and do not disappear when the ± 1 m error is applied. The methodological framework employing the identification of tendency of sea-level movement for each sea-level index point (see Shennan, 1982, 1983, 1986a, b, 1992; Long, 1992; Tooley, 1982) is followed throughout. By establishing the age, altitude, indicative meaning and direction of sea-level movement parameters for each index point, the empirical and rebound models shown in Fig. 2 are tested using the new data from the five sites in northwestern Scotland. The aim in this paper is to test the general trends rather than the exact correlation of altitude.

TECHNIQUES

Lithostratigraphic data were collected using a hand-gouge, and all cores levelled to OD using an automatic level and staff. The lithostratigraphy was recorded using the Troels-Smith scheme of stratigraphic notation (Troels-Smith, 1955). A 50 mm diameter piston corer was used to collect all samples for laboratory analyses. Samples for pollen, diatom and radiocarbon analyses were prepared using standard procedures (Moore and Webb, 1978; Palmer and Abbott, 1986). Frequencies of pollen and diatoms are expressed as a percentage of total land pollen (% TLP) and a percentage of total diatom valves (% TDV) respectively. A minimum of 200 is used for the pollen and diatom sums. Diatom species are summarised according to the halobian classification (Vos and de Wolf, 1993). Polyhalobian and mesohalobian classes represent marine conditions and oligohalobian forms reflect freshwater environments. Species present at < 5% TDV are aggregated within their halobian class and shown as 'others', followed by the number of species contributing to the 'others' total. All radiocarbon dates (Table 1) are reported as conventional ages ± 1 standard error, with no further correction or error term applied.

KENTRA MOSS

The site is a large outwash fan (ca. 2 × 3 km) covered in peat which lies adjacent to the large sheltered tidal embayment of Kentra Bay (Fig. 3). The surface of the fan slopes westwards from the ice-contact (Loch Lomond Stadial) slope near Acharacle (McCann, 1966; Peacock, 1970) to the coast (Figs 1 and 3). Wain-Hobson (1981) has described the feature and concluded that it was deposited subaerially when the Late Glacial sea level was at or below present. McCann (1966) suggested that the outwash deposits were reworked to approximately + 7 m OD during the mid-Holocene rise in relative sea level. In contrast published 'provisional' isobases for the "Main Postglacial Shoreline" (e.g. Sissons, 1983, see discussion above) are approximately +10 to +12 m OD at Kentra Moss. Full details of the present study of Kentra Moss will be published elsewhere (Shennan et al., 1995).

The stratigraphy is relatively simple (Fig. 3). All boreholes were finished in sand, sometimes containing gravel. Towards each end of the transect the sand is overlain by an organic silt, sandy at the base, and with a transition to an overlying herbaceous/*Eriophorum* peat. This fining-upward sedimentary transition is reflected in the contemporary environments at Kentra Bay; from silt sand of the intertidal flats, through the saltmarsh to the herbaceous/*Eriophorum/Sphagnum* raised bog communities. In the western part of the transect, the highest recorded altitude of the organic silt is at + 7.63 m OD at KM7. It is not recorded at KM8 in the northwestern part of the transect. Close interval coring (10 m) in the southwestern part of the transect allows the limit to be defined more precisely. At KM39 and KM38 the organic silt is clearly visible but at KM37 there is a transitional layer, an organic sand, between the herbaceous/*Eriophorum* peat and the basal sand. This is recorded at +7.67 m OD. At KM48 and KM36 there is no distinct transition layer, and the peat rests directly on coarse sand and gravel. From the lithostratigraphy the limit of marine sedimentation is between +7.63 and +7.67 m OD. In the development of raised bog over raised marine deposits Kentra Moss is comparable to the site of Moine Mhor, south of Oban (Haggart and Sutherland, 1992).

The sampling strategy was constructed to define relative sea-level changes and the limit of Holocene marine sedimentation. A series of sampling locations, from close to the present saltmarsh to above the limit of Holocene marine sedimentation, were chosen for biostratigraphic and chronostratigraphic analyses. At locations with marine sediments, defined from the lithostratigraphy and biostratigraphy, two boundaries are dated. First, the regressive overlap, defined as the onset of organic sediment accumulation, with sufficient organic carbon to obtain a

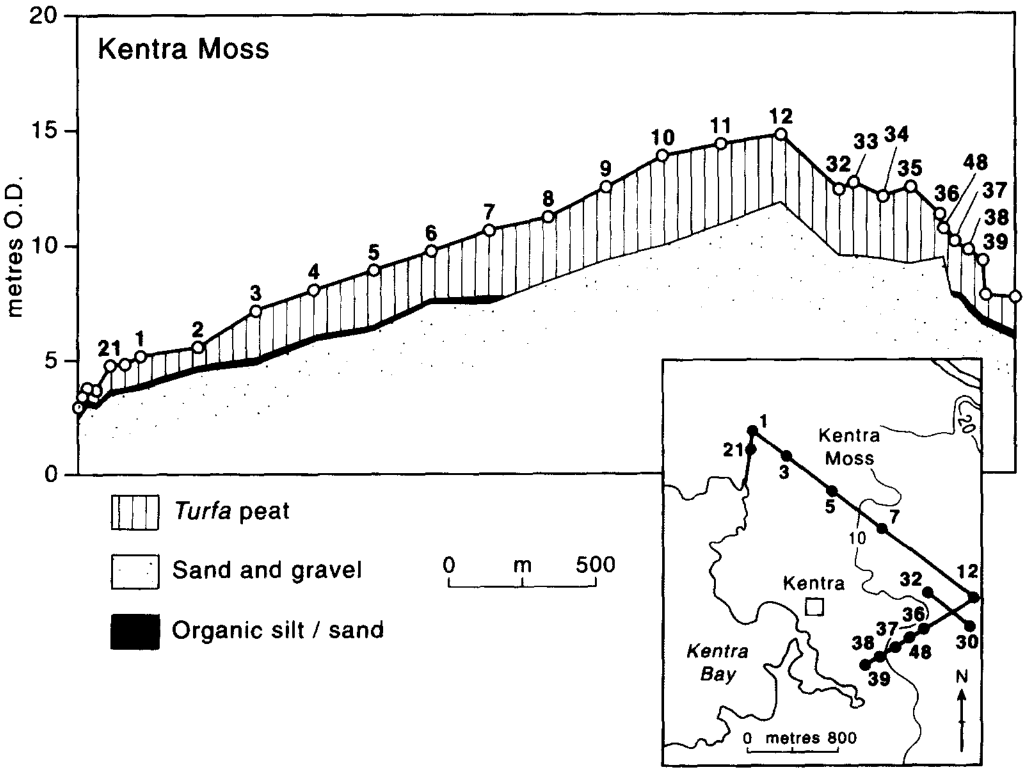

FIG. 3. Location of borehole transects and generalised stratigraphy at Kentra Moss. Stratigraphic symbols in this and all following diagrams are after Troels-Smith (1955) except where modified for clarity of presentation.

TABLE 1. Radiocarbon dates (conventional date ± 1σ) and relative sea-level change data

Site	Code	BP ± 1σ	ALT	RWL	rsl	IR	T	Comment
Glenancross 2-1	SRR4859	5805 ± 50	9.03	2.6	6.73	± 0.20	–	regressive contact at exposed site
Glenancross 2-2	SRR4858	5285 ± 45	9.19	2.9	6.59	± 0.20	–	transition to freshwater fen
Kentra Moss 21-1	SRR4722	1080 ± 40	3.87	2.9	1.27	± 0.20	–	transition to bog
Kentra Moss 21-2	SRR4723	1370 ± 45	3.75	2.75	1.30	± 0.20	–	upper saltmarsh
Kentra Moss 21-3	SRR4724	1480 ± 40	3.66	2.6	1.36	± 0.20	–	regressive contact
Kentra Moss 3-1	SRR4732	2255 ± 45	5.05	2.9	2.45	± 0.20	–	transition to bog
Kentra Moss 3-2	SRR4733	2410 ± 45	5.00	2.6	2.70	± 0.20	–	regressive contact
Kentra Moss 32-1	SRR4725	8320 ± 45	9.45	> 4.1	< 5.65		0	above influence of sea level
Kentra Moss 37-1	SRR4726	3880 ± 45	7.76	2.9	5.16	± 0.20	–	transition to bog
Kentra Moss 37-2	SRR4727	3860 ± 45	7.69	2.6	5.39	± 0.20	–	regressive contact
Kentra Moss 38-1	SRR4728	3515 ± 45	7.20	2.9	4.60	± 0.20	–	transition to bog
Kentra Moss 38-2	SRR4729	3730 ± 45	7.14	2.6	4.84	± 0.20	–	regressive contact
Kentra Moss 39-1	SRR4730	3435 ± 45	6.87	2.9	4.27	± 0.20	–	transition to bog
Kentra Moss 39-2	SRR4731	3940 ± 45	6.65	2.6?	4.35	± 0.20	–	regressive contact, but lower in contemporaneous marsh than other sites (Shennan *et al.*, 1995).
Kentra Moss 48-1	SRR4734	3225 ± 45	9.51	> 4.1	< 5.71		0	extreme storm level or above influence of sea level
Kentra Moss 5-1	SRR4735	3065 ± 45	6.39	2.9	3.79	± 0.20	–	transition to bog
Kentra Moss 5-2	SRR4736	3195 ± 40	6.35	2.6	4.05	± 0.20	–	regressive contact
Loch nan Eala 16	SRR4738	3745 ± 50	5.20	2.65	2.85	± 0.56	–	diatomological and hydrological isolation contact
Loch nan Eala 1-1	SRR4737	3440 ± 50	5.20	2.9	2.60	± 0.56	–	hydrological isolation contact
Loch nan Eala 1-2	UB3634	8743 ± 149	5.20	2.9	2.60	± 0.56	+	hydrological connection contact
Loch nan Eala 1-3	UB3633	10060 ± 86	5.20	2.9	2.60	± 0.56	–	hydrological isolation contact
Loch nan Eala 29	SRR4740	3600 ± 45	6.64				0	colonisation of sediment surface, sea level below the altitude of the sample
Loch nan Eala 66-1	SRR4741	4010 ± 50	6.27	2.9	3.67	± 0.25	–	hydrological isolation contact
Loch nan Eala 66-2	SRR4742	8195 ± 45	6.27	2.4	4.17	± 0.25	+	diatomological connection contact
Loch nan Eala 66-3	SRR4863	6630 ± 50	6.27	2.65	3.92	± 0.25	±	brief isolation of the upper basin, then connection
Loch nan Eala 67-1	SRR4865	10500 ± 100	6.27	2.65	3.92	± 0.25	–	diatomological and hydrological isolation contact
Loch nan Eala 67-2	SRR4864	8310 ± 45	6.27	2.65	3.92	± 0.25	+	diatomological and hydrological connection contact
Mointeach Mhor 11-1	SRR4857	6730 ± 45	6.95				0	radiocarbon date not supported by pollen data
Mointeach Mhor 11-3	SRR4856	3005 ± 45	7.23	2.6	4.93	± 0.20	–	regressive contact at exposed site
Mointeach Mhor 11-4	SRR4855	2565 ± 45	7.33	2.9	4.73	± 0.20	–	transition to bog
Mointeach Mhor 45-1	SRR4895	4640 ± 45	8.88	2.6	6.58	± 0.20	–	regressive contact at exposed site
Mointeach Mhor 45-3	SRR4896	6625 ± 45	8.61	4.1	4.81	+1.50 –0.20	+?	minimum date for marine incursion
Rumach Iochdar 5	SRR4862	10755 ± 90	9.3	2.9	6.70	± 0.25	–	hydrological isolation contact
Rumach Meadhonach	UB3643	11820 ± 145	17.8	2.9	15.20	± 0.25	–	hydrological isolation contact

ALT = Altitude of top of dated sample (0.02–0.04 m thick), or sill of isolation basin (m OD).
RWL = Present altitude of the reference water (tide) level (m OD).
rsl = Relative sea level (m above present mean tide level) calculated from the sea-level index point.
IR = Indicative range of the sea-level index point (includes error estimate for RWL and measurement error of ALT).
T = Tendency of sea-level movement: (+) positive, (–) negative, (±) negative followed by positive, (0) no tendency.

TABLE 2. Detailed stratigraphic record from core Kentra Moss 21. Notation follows Troels-Smith (1955). Ground altitude at +4.71 m OD

Altitude m OD	Depth cm	Stratigraphic description
4.71–3.73	0–98	Fresh herbaceous peat with *Eriophorum* Th^3 2,Th (*Erioph.*)^3 1, Sh1, nig 3, strf 0, elas 1, sicc 2
3.73–3.65	98–106	Humified herbaceous peat Th^3 2, Sh 2 nig 3, strf 0, elas 0, sicc 2, ls 0
3.65–3.59	106–112	Amorphous organic silt Ag 2, Th^3 1, Sh 1, Ga+ + + nig 2, strf 0, elas 0, sicc 2, ls 0
3.59–3.47	112–124	Organic sand silt, laminated Ag 3, Ga 1, Sh + nig 2, strf 2, elas 0, sicc 2, ls 0
3.47–3.41	124–130	Silt sand, slightly organic Ga 3, Ag 1, Sh + nig 2, strf 0, elas 0, sicc 2, ls 0

radiocarbon assay. The second is the transition to raised bog communities, defined from the pollen stratigraphy. Two locations above the limit of marine sedimentation were analysed. KM48 is close to the landward limit of marine sedimentation whereas KM32 is towards the central part of the transect. The base of the peat sequence at both is approximately +9.5 m OD and therefore provides a test of the model predicting a mid-Holocene sea-level maximum between +10 and +12 m OD.

For the cores with the organic silt at the base of the peat sequence the pollen changes are very similar at each site. Diatom preservation is good at KM21, but decreases at the higher altitude sites. In general, a simpler biostratigraphic succession is observed, which can be closely related to the contemporary vegetation succession in Kentra Bay. The typical biostratigraphic succession recorded below the limit of Holocene marine sedimentation is demonstrated in the description of site KM21, and then related to the observed contemporary sequences.

The study of the present day pollen and diatom flora gives a precise definition of the contemporary sedimentary environments of Kentra Bay. Sediment, pollen and diatom samples from 11 sites from the low water mark, across the saltmarsh, to the transition to raised bog vegetation define distinct environments (Innes *et al.*, 1993). Two specific boundaries are significant. Firstly, at approximately +2.6 m OD, which is ca. 0.2 m above the level of present mean high water of spring tides (MHWST), organic content increases significantly; the pollen of saltmarsh taxa, in particular *Plantago maritima*, are at a maximum; and the diatom assemblage is characterised by *Diploneis interrupta*. Secondly, at approximately the level of highest astronomical tide (HAT), +2.9 m OD, the pollen assemblages show an increase in mire taxa, particularly *Calluna*, with Gramineae, Cyperaceae and *Myrica* increasing and *Plantago maritima* decreasing in frequency; the diatom assemblage is dominated by oligohalobian species, with *Nitzschia fruticosa* dominant. The sediment at this altitude is highly organic with either only a trace or no clastic component. The samples from the zone between MHWST and HAT are transitional in most respects, but some features are perhaps diagnostic. The pollen spectra contain peaks of *Plantago coronopus*, *Aster*-type and *Taraxacum*-type and the diatoms include a peak of *Navicula pusilla*. These contemporary data provide an excellent analogue to assist the interpretation of the palaeoenvironmental data.

Kentra Moss Example: KM21

The lithostratigraphy at KM21 is similar to that recorded at most sites below the limit of organic sand silt sedimentation, and the detailed stratigraphic record from this core is shown in Table 2. Overlying sand with some silt is a grey sandy silt, which passes through a transitional organic silt into a well-humified *turfa* with an increasing *Eriophorum* content.

Diatom data (Fig. 4(a)) show a progressive reduction in salinity associated with the stratigraphic changes described above. First, there is a fall in the frequencies of polyhalobian species such as *Paralia sulcata* and *Diploneis incurvata*. This is associated with the sand and the lower part of the sand silt. There follows an increase in *Diploneis didyma* before a distinctive peak of the mesohalobian taxon *Diploneis interrupta* through the transitional organic silt to the base of the herbaceous peat. Finally there is an increase in oligohalobian species, in particular *Navicula pusilla*, followed by *Nitzschia fruticosa*. The sequence is interpreted as a change from intertidal sand flat, to salt marsh and then to the transition to mire communities, and is in very close agreement with the classification of assemblages proposed by Vos and de Wolf (1988).

This reduction in salinity is paralleled by the pollen data (Fig. 4(b)). Here high frequencies of *Plantago maritima* are found in the sand, the sand silt, as well as the transitional organic silt and into the base of the herbaceous peat. At the base of the latter stratigraphic unit there is a brief increase in the frequencies of *Taraxacum*-type. Frequencies of *Plantago maritima* decline in the well-humified *turfa*, and are replaced by high frequencies of Cyperaceae and then Gramineae. Continuing removal of the marine influence is shown by the gradual rise in frequencies of *Calluna*, *Myrica* and *Sphagnum* as acid raised bog communities became established.

In summary, the litho- and biostratigraphic successions recorded at KM21 show a progressive reduction in marine influence. The lithostratigraphy records a gradual shallowing of the depositional environment, with a reduction in particle size and increase in organic content. Pollen and diatom data show that this change in depositional conditions was associated with a reduction in salinity followed by the final isolation of the site from the marine influence. The morphology of the outwash sand and gravel along the transect (Fig. 3), the lithostratigraphy and biostratigraphy, and the age–altitude pattern of the dated samples (Table 1) suggest that this isolation from marine influence was caused by a fall in relative sea level.

The pollen and diatom assemblages from the lowest dated sample (Fig. 4) compare closely to the modern assemblages indicative of sediment accumulation at MHWST +0.2 m. The second sample dated at most of the sites in the Kentra Moss sequence is the transition to raised bog communities. At KM21 this transition, well reflected by the *Calluna* frequencies, occurs over a greater depth of sediment than at

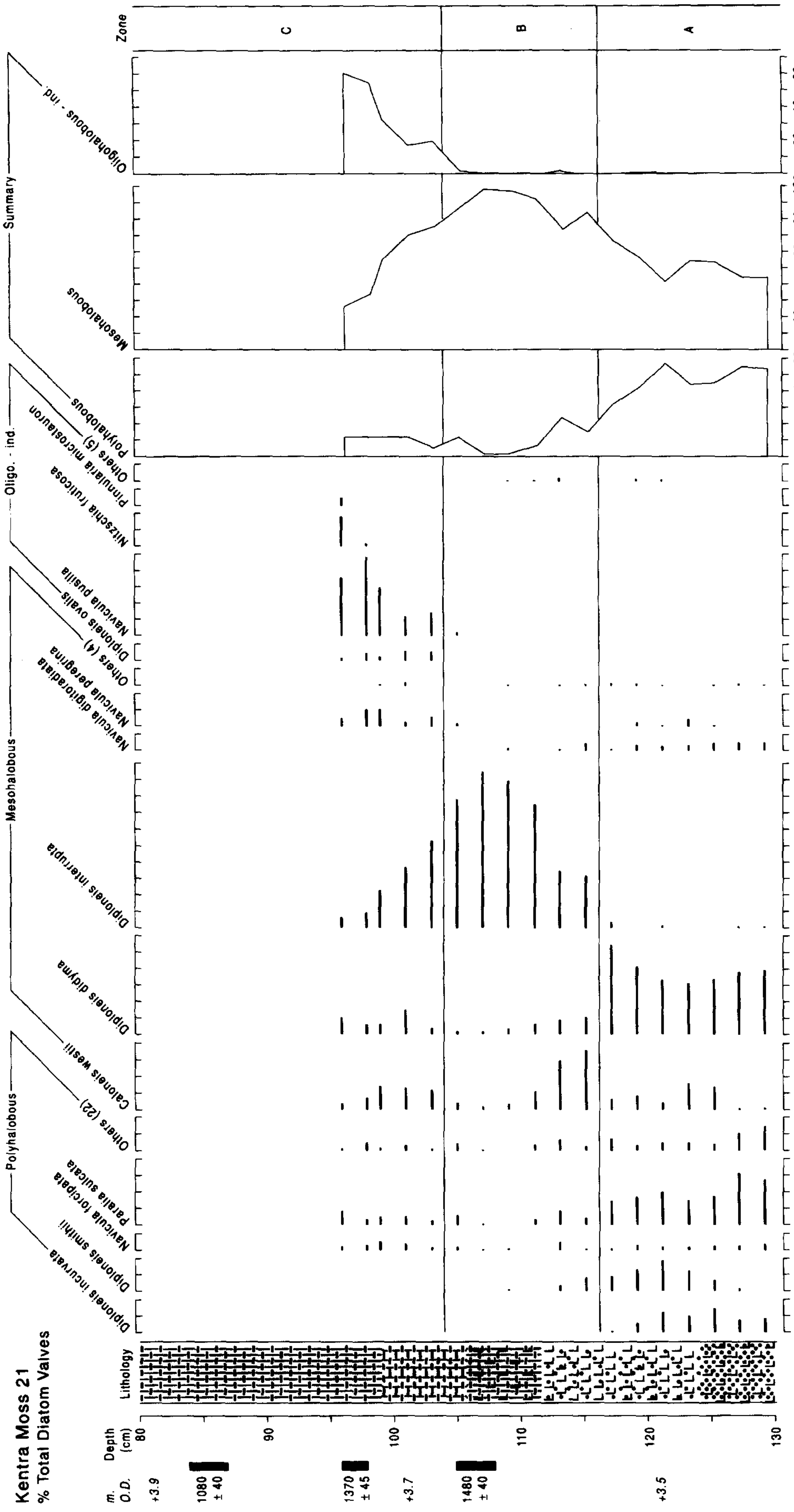

FIG. 4(a). Diatom diagram from Kentra Moss 21 showing taxa as a percentage of total diatom valves. The detailed stratigraphic record from core KM21 is presented as Table 2.

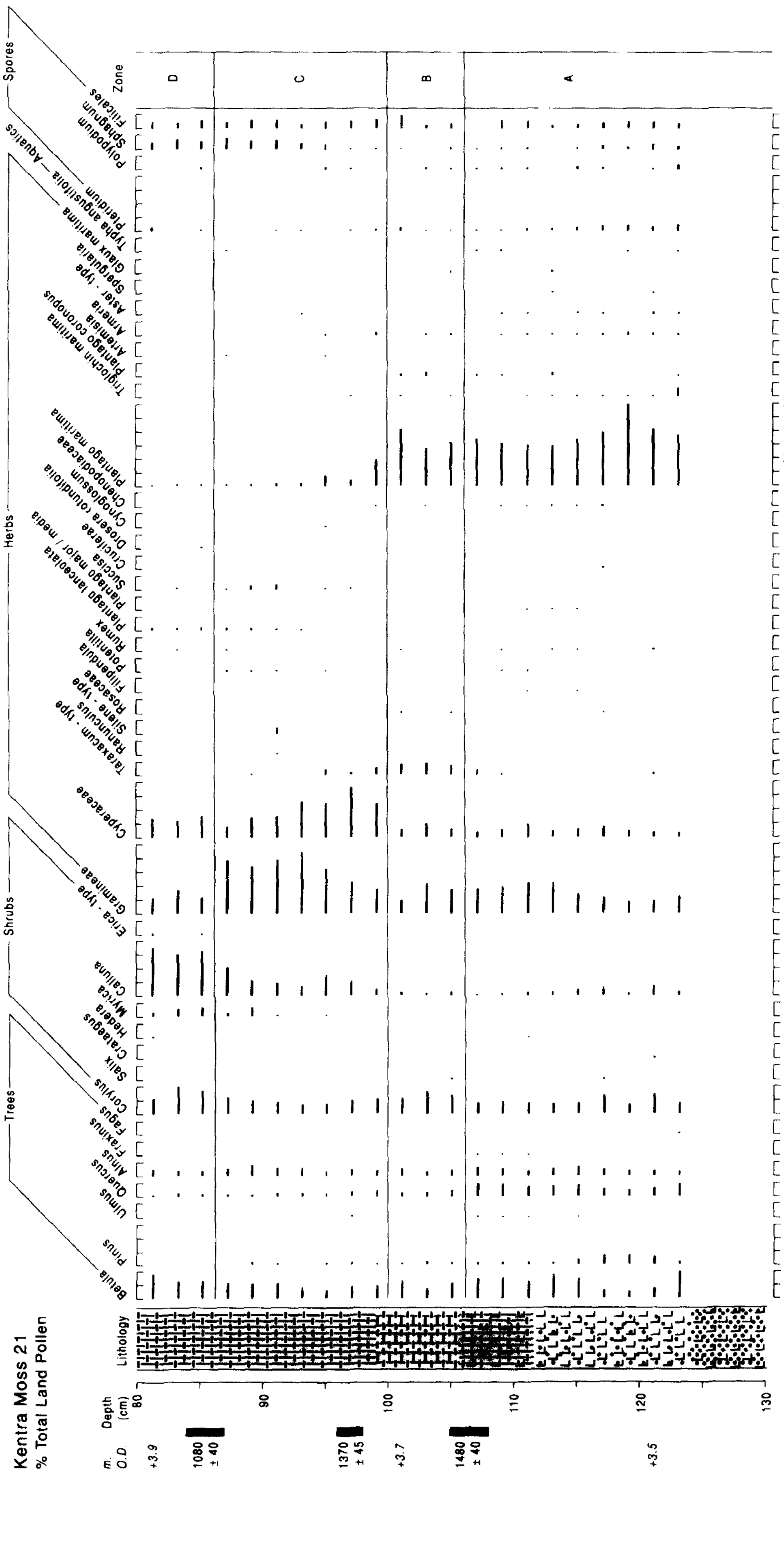

FIG. 4(b). Pollen diagram from Kentra Moss 21 showing taxa as a percentage of total land pollen. The detailed stratigraphic record from core KM21 is presented as Table 2.

other sites. Comparison with the modern diatom and pollen data suggest that the upper date represents sediment accumulation at HAT, and the middle date from a location between MHWST +0.2 m and HAT.

At KM32 the lithostratigraphy indicated that raised bog peat developed upon outwash sand and gravel which had not been reworked within an intertidal environment. The pollen stratigraphy (full details in Shennan *et al.*, 1995) shows the basal spectrum dominated by Gramineae. One centimetre above, the assemblage is characterised by *Sphagnum*, *Calluna, Betula* and Gramineae. The only tree pollen present are *Betula* and *Pinus*. These data support an early Holocene age, pre 8 ka BP (Table 1), but there is no pollen evidence of saltmarsh sedimentation.

At KM48 the pollen assemblage at the base of the peat sequence is dominated by *Calluna* (40–60% TLP) with subordinate *Betula, Alnus, Corylus* and Gramineae, and is comparable with KM21 zone d (Fig. 4(b)). There are low frequencies of *Plantago maritima* pollen (< 5% TLP), most probably reflecting the effects of salt spray, wind transport and possibly storm surges, since contemporaneous MHWST, defined by chronostratigraphic correlation with KM5 (Table 1), was over 3 m lower.

LOCH NAN EALA

The site (Fig. 5) occupies an area of lowlying land behind the Strath of Arisaig. In the mid-19th century the present loch was reduced in size by the construction of The Canal to drive a water mill and to improve drainage.

Transects of boreholes show that the site contains at least three distinct basins. The main basin occupies the area around the present loch. In the southwestern arm there is an upper basin. It is separated from the main basin by a peat-covered rock ridge with a lip identified at +6.27 ± 0.02 m OD. The northeastern basin is separated from the main basin by a rock ridge with a lip at +6.43 ± 0.05 m OD, but here alluvial fan deposits block the connection to the main basin and for this reason no detailed analysis of the sediments in the northeastern basin have been undertaken. The only connection to the sea is from the main basin and through the small valley in which The Canal runs. The Canal was cut through solid rock. As a result the lip between the sea and the main basin is not measured directly but a range of morphological, lithostratigraphic and biostratigraphic data indicate that the lip was at +5.2 ± 0.5 m OD (Shennan *et al.*, 1994). The western end of the upper basin is separated from the sea by a ridge at over 15 m OD.

Close to the present loch the sediment sequence is a surface herbaceous peat over a diatom-rich limnic sequence at least 950 cm thick. A sample from 950 cm (ca. –6 m OD) contained marine, brackish and fresh water diatoms, and a Flandrian III pollen assemblage (< ca. 5000 BP).

Away from the loch in the main basin and in both the upper basin and the northeastern basin there is a distinctive stratigraphic succession comprising four main units. Consistently there is a surface herbaceous peat, which away from basin edges grades into a thin limnic *detritus* peat, overlying a grey-blue clay silt. Below this there is a prominent limnic *detritus* peat layer and then a second clastic

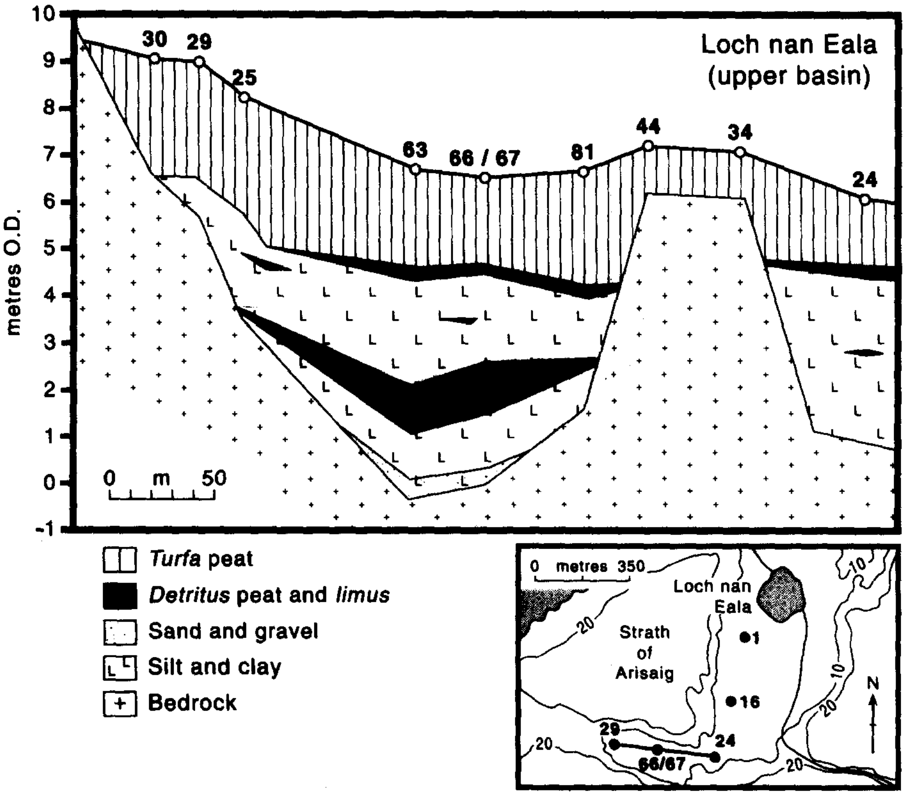

FIG. 5. Location of the borehole transect and generalised stratigraphy in the upper basin at Loch nan Eala. Cores 24, 16 and 1 are in the main basin.

layer. This lower clastic unit becomes coarser towards the base, containing sand and frequently gravel. In some boreholes another thin organic layer is recorded within the upper clastic unit but it is not possible to correlate this discontinuous layer between boreholes. Litho- and biostratigraphic analyses show that the basins have recorded relative sea-level changes in a manner comparable to the 'isolation basins' described from Scandinavia (e.g. Kjemperud, 1986; Palmer and Abbott, 1986; Svendsen and Mangerud, 1987). Both clastic units have diatom assemblages dominated by marine and brackish species, whilst the limnic *detritus* peat and the base of the surface peat unit contain freshwater microfossil assemblages.

The changes between fresh and marine conditions are related to the time when relative sea level crossed the rock lip in each basin. The change from marine to fresh at the regressive, or isolation, contact records a relative fall in sea level; the change from fresh to marine at the transgressive, or connection, contact records a relative rise in sea level. The effective reference water level at which these changes would have occurred is discussed below. Full details of the site are published elsewhere (Shennan *et al.*, 1994). For this paper the typical biostratigraphic succession is described from the upper basin.

Loch nan Eala Example: LNE66/67

The lower clastic sequence is a sand silt and silt clay with gravel component which fines to a silt clay at the transitional contact with the overlying limnic *detritus* peat. The layer containing gravel is a perched aquifer, and this caused temporary sampling difficulties during coring. Therefore the complete sequence at the deepest part of the basin is illustrated by the combination of data from two overlapping boreholes, 66 and 67, located 15 m apart. The detailed stratigraphic record from the relevant parts of these two cores are shown as Tables 3a and 3b respectively.

The clastic sequences and the limnic *detritus* peats represent the gradual infilling of the loch basin whereas the surface *turfa* peat represents the colonisation of the infilled loch by terrestrial communities.

The oldest sea-level index point, 10,500 ± 90 BP, is from the base of the limnic *detritus* peat, coincident with the change from polyhalobian to oligohalobian diatom assemblages (Fig. 6(a)). Diatom assemblage zone B represents the transition from connection to the sea to complete isolation in diatom assemblage zone C, which is coincident with the lithostratigraphic boundary from the clay silt to the limnic *detritus* peat.

The pollen data (Fig. 6(b)) from assemblage zone A, at the base of the limnic *detritus* peat, show high frequencies of *Rumex* and Cyperaceae, supported by high Gramineae values. *Artemisia, Myriophyllum alterniflorum* and Chenopodiaceae percentages are also high. A range of other open ground herb pollen types is recorded and tree and shrub pollen taxa are uniformly low. These data support the radiocarbon evidence of a Loch Lomond Stadial age.

The rise of sea level across the sill of the upper basin is dated at both cores: LNE66 8195 ± 45 BP; LNE67, 8310 ± 45 BP. The freshwater limnic *detritus* peat is overlain by a clay silt dominated by *Paralia sulcata* with subordinate *Fragilaria brevistriata* before a transition to a very species-rich assemblage, with a dominance of polyhalobian forms but also many mesohalobian and oligohalobian taxa (Fig. 6(a)). The pattern of changes in tree pollen frequency through the *detritus* peat are compatible with the radiocarbon data and with those from other sites in the area (Birks and Williams, 1983; Walker and Lowe, 1987). The connection of the basin to the sea is reflected by the rise of *Plantago maritima* pollen.

There is a brief episode of freshwater conditions, expressed by a 0.06 m thick limnic *detritus* peat in part of the upper basin, within the otherwise marine dominated period of sedimentation which laid down the main upper clay silt unit. The boundary between local pollen zones E and F (Fig.

TABLE 3a. Detailed stratigraphic record from the upper part of core Loch nan Eala 66, from which biostratigraphic data have been combined with data from the lower part of core Loch nan Eala 67. Notation follows Troels-Smith (1955). Altitude of the basin sill is +6.3 m OD

Altitude m OD	Depth cm	Stratigraphic description
6.27–4.61	0–166	*Turfa* peat with wood fragments Th^3 4, Dl + nig 3, strf 0, elas 0, sicc 2
4.61–4.37	166–190	Black *turfa* peat with *detritus* peat Th^3 4, Dh + nig 4, strf 0, elas 0, sicc 2, ls 0
4.37–4.19	190–208	*Detritus* peat and *limus* Dh 2, Ld^1 2 nig 3, strf 0, elas 0, sicc 2, ls 0
4.19–4.11	208–216	Clay silt with some *detritus* peat and *limus* Ag 2, As 1, Ld^1 1, Dh +, nig 2, strf 0, elas 0, sicc 2, ls 0
4.11–3.55	216–272	Organic clay silt Ag 3, As 1, Ld^1 + nig 2, strf 0, elas 0, sicc 2, ls 0
3.55–3.50	272–277	Silty *detritus* peat and *limus* Dh 1, Ld^1 2, Ag 1 nig 3, strf 0, elas 0, sicc 2, ls 0
3.50–2.69	277–358	Organic clay silt Ag 3, As 1, Ld^1 + nig 2, strf 0, elas 0, sicc 2, ls 0

Within this unit the core overlaps with core LNE67 down to 471 cm

TABLE 3b. Detailed stratigraphic record from the lower part of core Loch nan Eala 67, from which biostratigraphic data have been combined with data from the upper part of core Loch nan Eala 66. Notation follows Troels-Smith (1955). Altitude of the basin sill is +6.3 m OD

Altitude m OD	Depth cm	Stratigraphic description
Within this unit the core overlaps with core LNE66		
3.14–2.92	350–372	Slightly sandy, organic silt clay As 3, Ag 1, Ld^1 +, Ga + nig 2, strf 0, elas 0, sicc 2, ls 0
2.92–2.86	372–378	Clay *limus* with *detritus* peat Ld^1 2, Dh 1, As 1 nig 3, strf 0, elas 0, sicc 2, ls 0
2.86–1.63	378–501	*Detritus* peat and *limus* Dh 3, Ld^1 1 nig 3, strf 0, elas 0, sicc 2, ls 0
1.63–1.34	501–530	Blue-grey silt clay with gravel As 3, Ag 1, Gg(maj) + nig 2, strf 0, elas 0, sicc 2, ls 0
1.34–1.14	530–550	Sand silt Ag 3, Ga 1 nig 2, strf 0, elas 0, sicc 2, ls 0

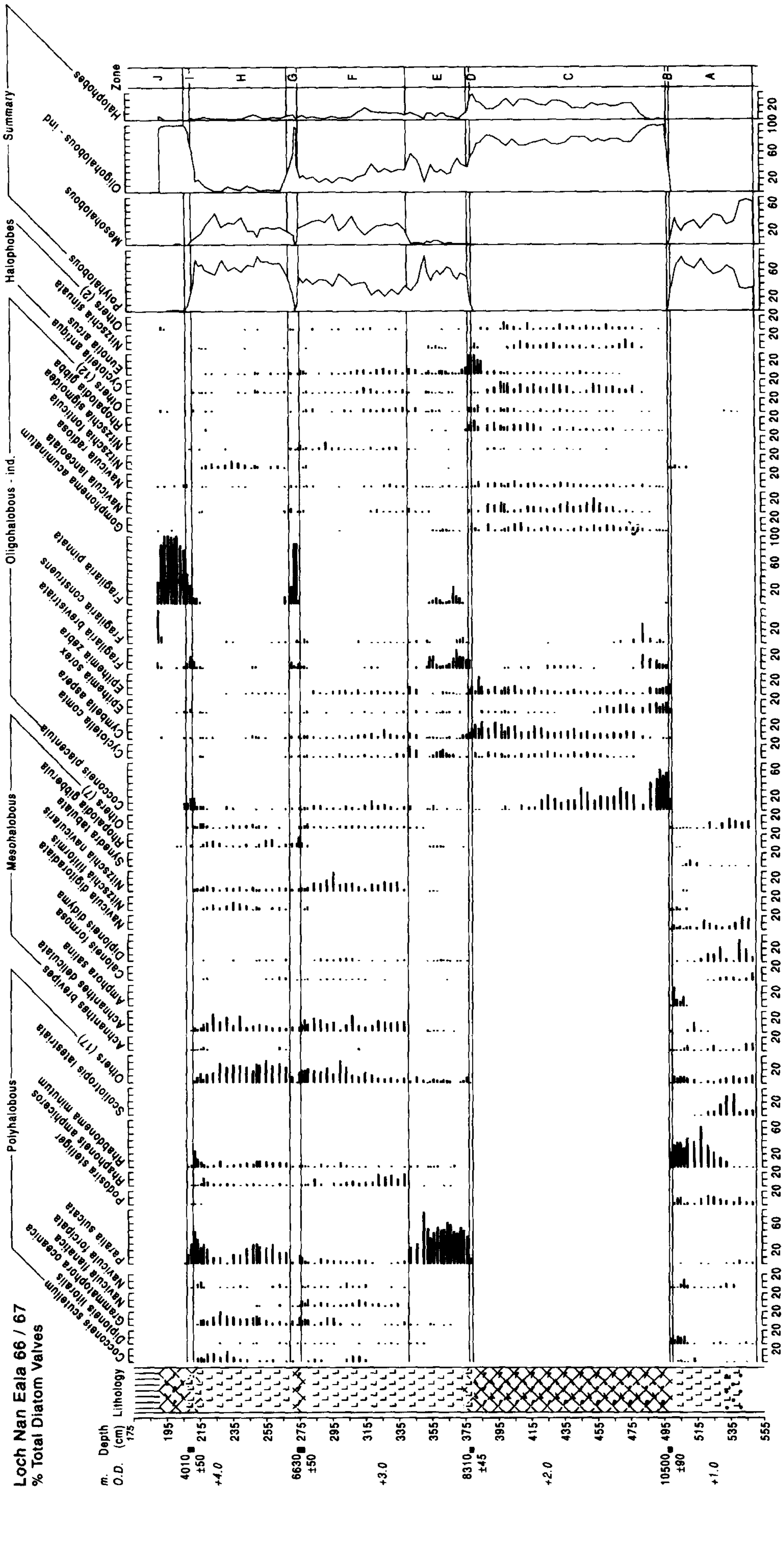

FIG. 6(a). Diatom diagram from Loch nan Eala 66/67 showing taxa as a percentage of total diatom valves. The detailed stratigraphic record from the relevant parts of cores LNE66 and LNE67 are presented as Tables 3a and 3b.

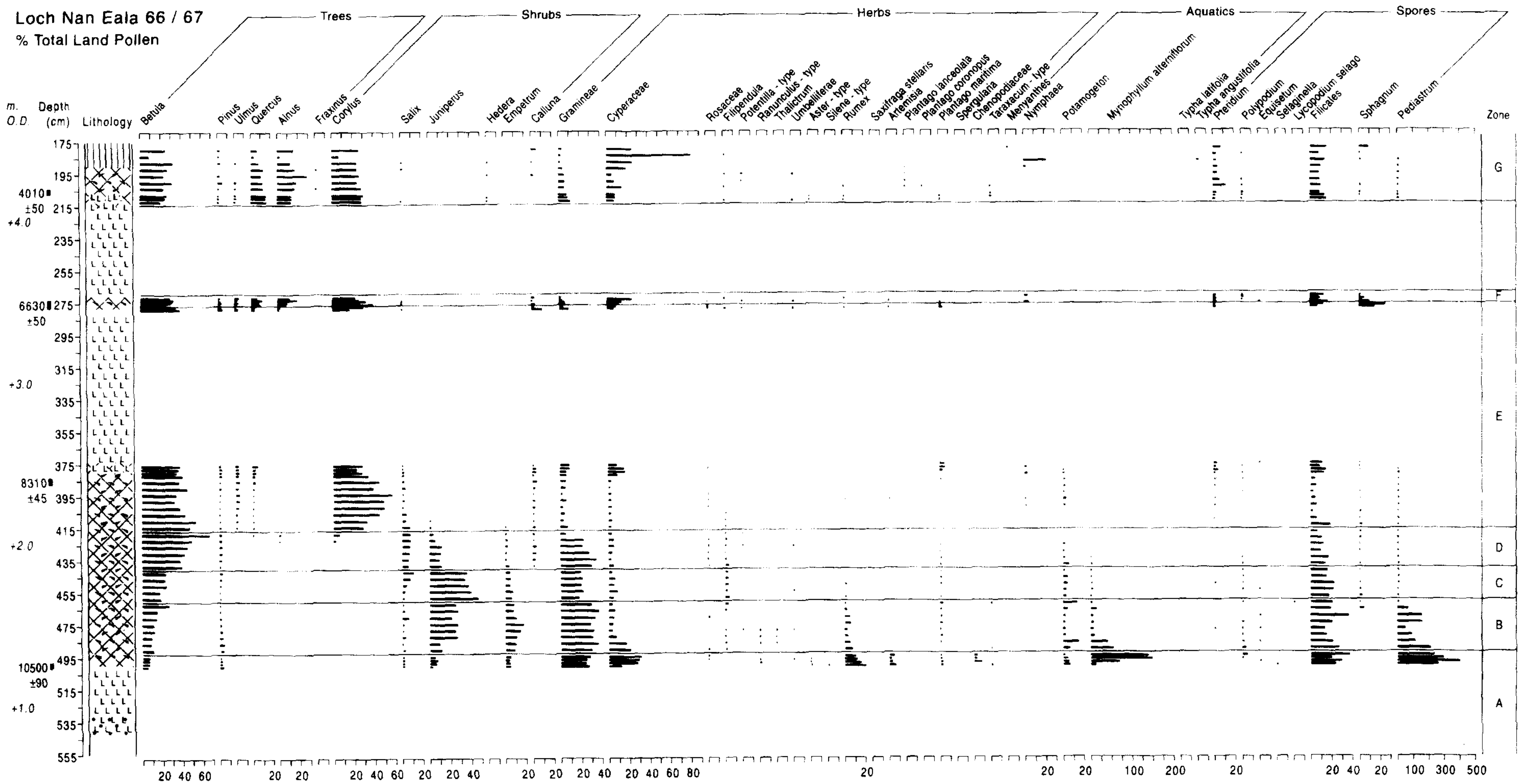

FIG. 6(b). Pollen diagram from Loch nan Eala 66/67 showing taxa as a percentage of total land pollen. The detailed stratigraphic record from the relevant parts of cores LNE66 and LNE67 are presented as Tables 3a and 3b.

6(b)) is within this thin limnic *detritus* peat and correlates with the rise of *Alnus* pollen. The radiocarbon date, 6630 ± 50 BP, accords with this biostratigraphic feature since the *Alnus* rise in this part of Scotland is dated at other sites to about 6500 BP (Tallantire, 1992). The pollen flora suggests a mixed environment, with saltmarsh types such as Chenopodiaceae, *Spergularia, Artemisia* and *Plantago maritima* prominent, but with freshwater aquatics, especially *Nymphaea*, also occurring. Beneath the limnic *detritus* peat layer marine conditions are recorded by the diatom flora in local diatom assemblage zone F. In the organic layer, in zone G, the assemblage records a transition to freshwater conditions reaching a peak at 273 cm. This is the most organic part of the layer and the assemblage is dominated by *Fragilaria pinnata*. At the upper boundary of the organic sediment the diatom flora shows a transition back to marine conditions into the overlying clay silt.

The final sea-level index point, 4010 ± 50 BP, is the regressive contact from the marine clay silt to the surface peat sequence. The pollen data (Fig. 6(b)) agree with this date by clearly showing this transition to be of post-*Ulmus* decline, Flandrian Chronozone III (< ca. 5000 BP), age. Saltmarsh pollen types *Plantago maritima, Taraxacum*-type and *Aster*-type at the base of pollen zone G confirm this regressive contact as an index point. The basal 20 cm of the peat sequence is an herbaceous limnic *detritus* peat. Having formed under limnic conditions, the transition from clastic to organic sedimentation records the isolation of the upper basin by relative sea-level fall. This is confirmed by the diatom data (Fig. 6(a)), which show a brief transition (zone I), characterised by *Cocconeis placentula* and *Fragilaria brevistriata*, between marine sediments containing high frequencies of *Paralia sulcata* (zone H) and the freshwater limnic *detritus* peat dominated by *Fragilaria pinnata* (zone J).

Pollen, diatom and lithostratigraphic data from LNE29, in the upper basin, show that this sample dates the colonisation of the clastic sediment by semi-terrestrial communities, there is no intervening limnic *detritus* peat, and is not related to the timing of isolation (full discussion in Shennan *et al.*, 1994).

The sea-level index points from the main basin, LNE1 and LNE16 (Table 1), are all supported by pollen and diatom data (Shennan *et al.*, 1994) and fit in the correct sequence with those from the upper basin. With a lower sill, the main basin records the falls in sea level after, and the rise in sea level before, the upper basin. As yet, no distinct layer equivalent to the thin limnic *detritus* peat dated ca. 6600 BP in the upper basin has been identified in the main basin, although horizons with an increased organic content have been noted in some hand cores.

Detailed analysis of the diatom data defines different types of isolation and connection contacts (for full discussion see Kjemperud, 1986; Shennan *et al.*, 1994). These refer to different stages in the isolation or connection process and to different reference water levels during the process of relative sea-level movement. Our initial analysis suggested reference water levels between MHWST and HAT (Shennan *et al.*, 1994). These figures are used in Table 1, but are re-evaluated later.

RUMACH

This site is comparable with Loch nan Eala in being a sequence of isolation basins with sills of definable altitudes and infilled with Late Devensian and Holocene sediments. The site lies near the end of the Ru peninsula to the west of Loch nan Eala (Figs 1 and 7). The individual basins are much smaller, being less than 100 m in diameter at the widest point. A comprehensive series of boreholes was made to establish the height of the basin lip as well as to investigate the sedimentary record (Fig. 7). There are at least six separate basins. Investigation of two, Rumach Iochdar (lower Rumach) and Rumach Meadhonach (middle Rumach), is complete. The crest of the rock sills of these two basins are at +9.3 ± 0.06 m OD and +17.8 ± 0.05 m OD respectively.

Rumach Iochdar and Rumach Meadhonach reveal comparable lithostratigraphies. The most complete sequences are from the deepest parts of the basins, whereas the margins reveal evidence of slopewash, erosion and sediment mixing. Typically there are four main lithostratigraphic units. The lower clastic unit (summarised as one unit in Fig. 7) comprises a basal laminated stiff silt clay overlain by a sand, with shells and gravel in some cores, then a grey clay silt. The second unit is a thin limnic *detritus* peat. Above this there is another clastic unit, a grey clay silt, slightly sandy in some cores, and finally the surface peat sequence, comprising a thick *detritus* peat layer at the base which grades into an herbaceous peat with bryophyte and ericaceous remains.

Rumach Example: Rumach Iochdar 5

The detailed stratigraphic record from core RI5 is shown in Table 4. Diatom analysis (Fig. 8(a)) shows that the grey clay silt above the shelly sand in RI5 is of marine origin. *Paralia sulcata, Navicula digitoradiata* and *Nitzschia punctata* are common in this clay silt, but the assemblage switches sharply to freshwater as the boundary between this deposit and the limnic *detritus* peat is reached, with *Fragilaria brevistriata* dominant initially. This change is confirmed by the pollen data (Fig. 8(b)), for the limnic *detritus* peat contains some evidence of saltmarsh and coastal taxa, including Chenopodiaceae and *Plantago maritima*. The transition between the grey clay silt and the thin limnic *detritus* peat is therefore an isolation contact, dating a relative fall in sea level at 10,755 ± 90 BP. The pollen data indicate an age for the isolation just prior to the Lateglacial Interstadial/Loch Lomond Stadial boundary.

A pronounced peak in frequencies of *Fragilaria construens* occurs within the upper clastic unit, a sandy grey clay silt, showing that the deposit is of freshwater origin. Pollen, lithostratigraphy and radiocarbon data (Shennan *et al.*, 1993) correlate this clastic unit with the Loch Lomond Stadial. Diatom data from the rest of the core show no evidence of marine conditions, demonstrating that the site was not directly affected by marine conditions following the original isolation.

A similar sequence of events is recorded at Rumach Meadhonach, except that the isolation occurs earlier, 11,820

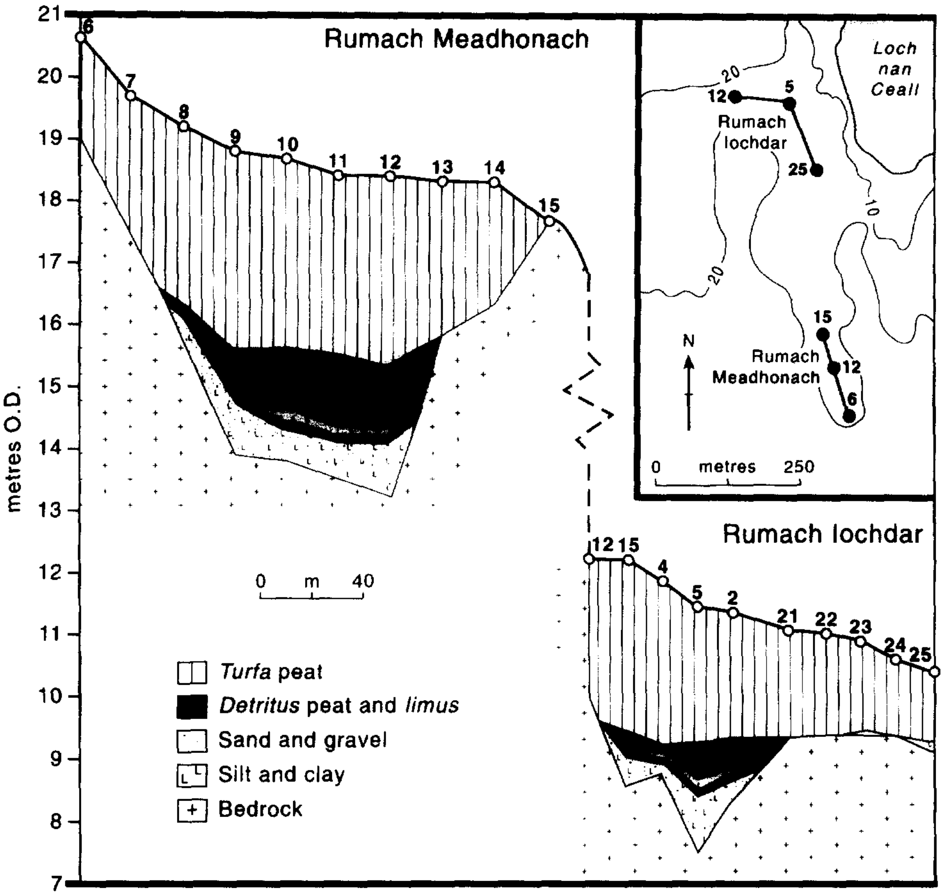

FIG. 7. Location of the borehole transects and generalised stratigraphy at Rumach Iochdar and Rumach Meadhonach.

± 145 BP, during the Lateglacial Interstadial (Shennan *et al.*, 1993).

MOINTEACH MHOR

The site, previously described by Peacock (1970), resembles Kentra Moss in being a large outwash fan covered in peat, the fan surface sloping seawards from the Loch Lomond Stadial ice contact limit at the present shore of Loch Morar (Figs 1 and 9). In contrast to the three preceding sites Mointeach Mhor is exposed to the westerly storm wave environment with active dune systems at the present coast.

A long borehole transect was made along the central axis of the outwash fan, and ditch sections were also observed (Fig. 9). Towards the seaward end of the section there is an arcuate fossil sand dune, at MM4. A similar feature, with a slightly lower surface altitude, occurs just to the east of MM13. Peacock (1970) maps these features as storm beach ridges. Throughout the site the surface deposit is a humified herbaceous peat which rests conformably upon sand. The transition is frequently a sandy organic silt or sandy silty peat. In most cores this sand overlies a lower peat, which in turn overlies a coarse sand. The upper contact of the lower peat appears sharp, probably eroded, in all handcores. This was confirmed in the cleaned ditch section, but in addition loading and dewatering structures were also observed. The landward limit of the upper sand unit remains to be identified.

Mointeach Mhor Example: MM11

A detailed pollen diagram (Fig. 10) was completed from core MM11 to establish the environmental conditions under which the organic deposits recorded at Mointeach Mhor accumulated. The detailed stratigraphic record from MM11 is shown in Table 5. Only occasional diatom fragments are preserved in the sand and peat units.

Peat initiation above basal outwash sand is dated 6730 ± 45 BP. This age is not supported by the pollen data. High frequencies of Gramineae and Cyperaceae, declining frequencies of *Juniperus*, increasing *Betula* and the absence of *Corylus*, *Ulmus* and *Quercus* suggest an earlier Holocene age for the deposit.

There is no indication of approaching marine conditions in the upper part of this peat, either at MM11 or at MM45 where similar biostratigraphic analyses have been undertaken, suggesting either erosion of the peat or instantaneous inundation of freshwater wetland. The pollen data from MM11 indicate a mid-Holocene age for the top contact of the peat, and provide a maximum age estimate for the erosive or inundation episode. Similar pollen data occur

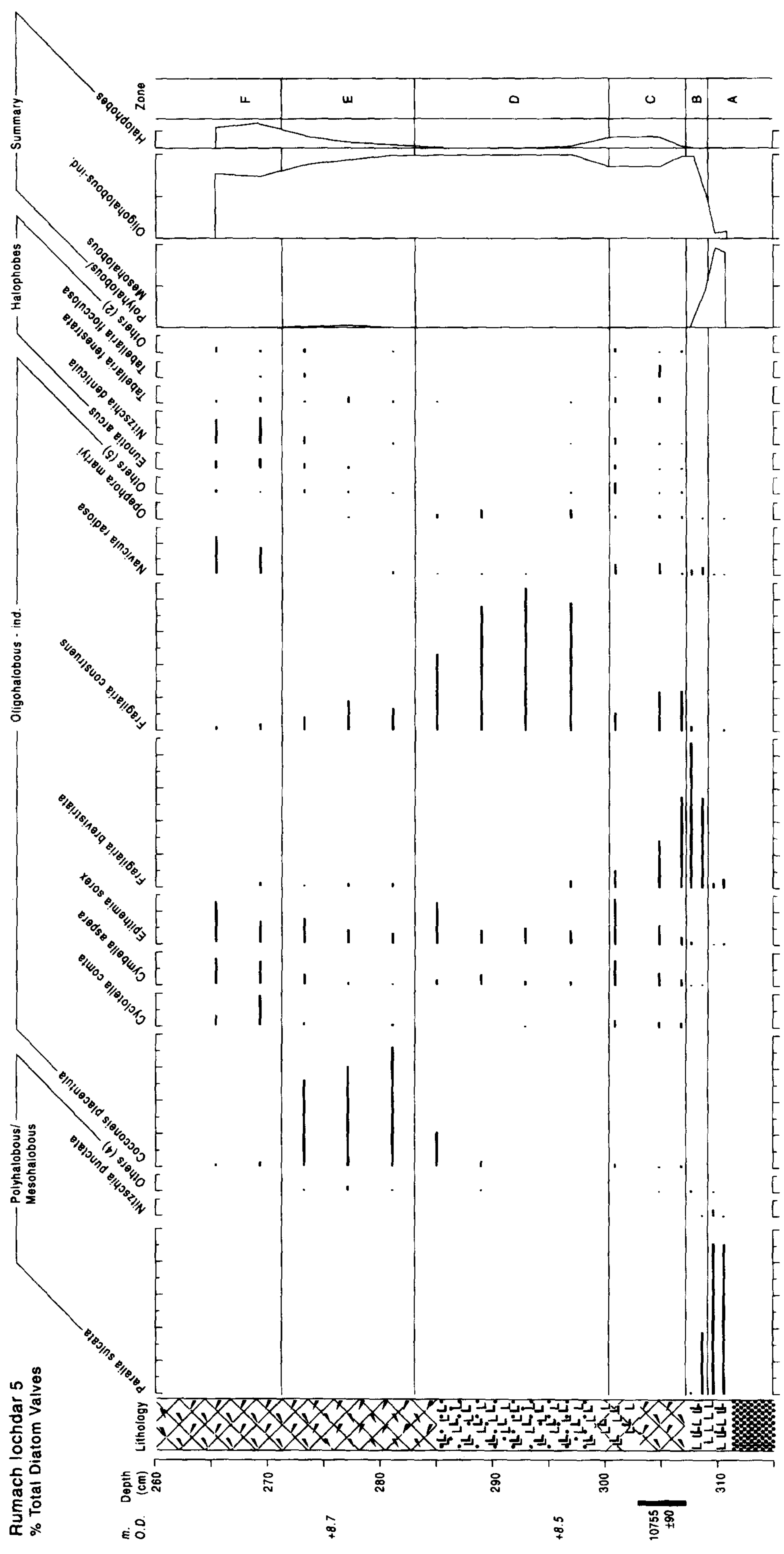

FIG. 8(a). Diatom diagram from Rumach Iochdar 5 showing taxa as a percentage of total diatom valves. The detailed stratigraphic record from core RI5 is presented as Table 4.

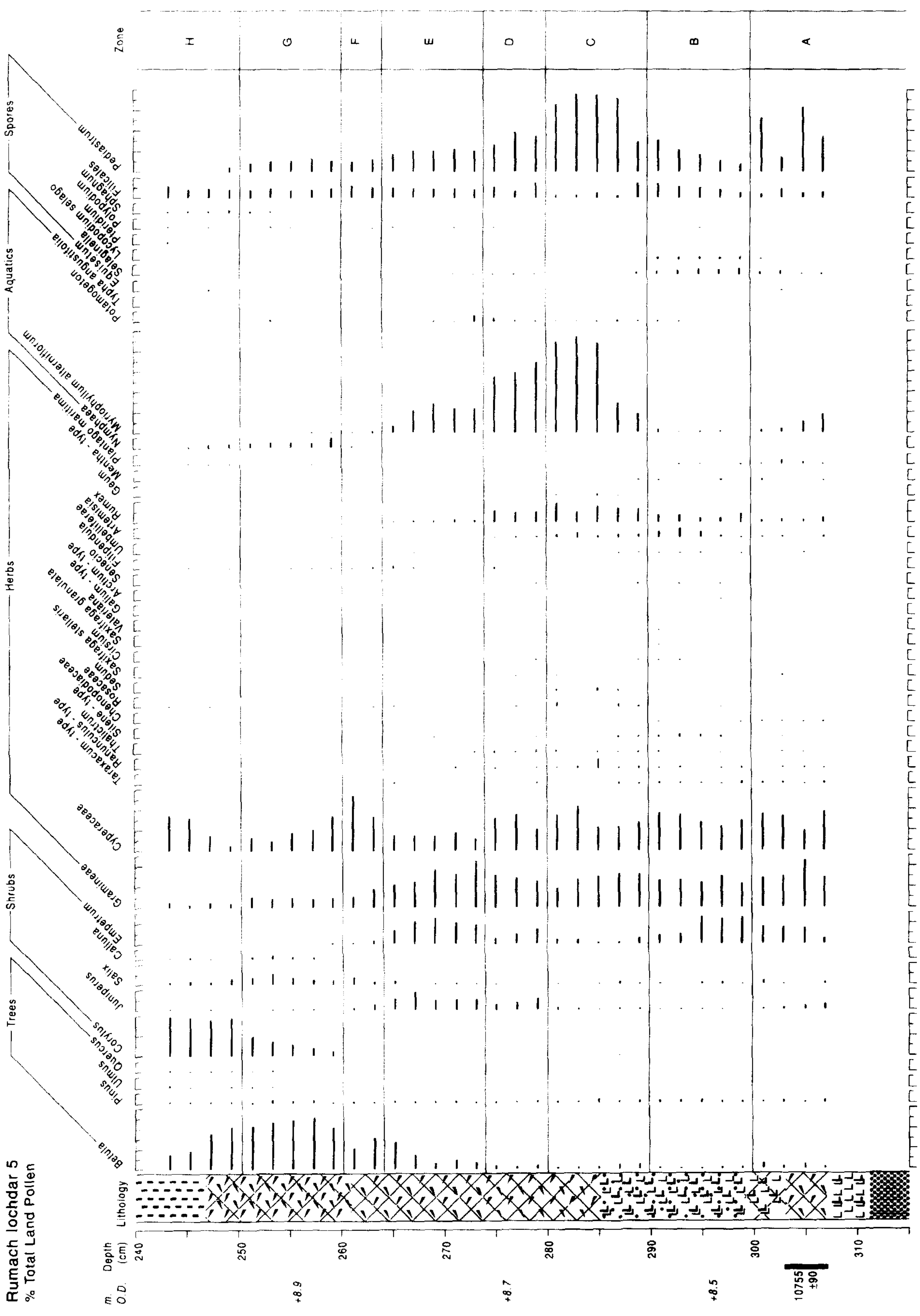

FIG. 8(b). Pollen diagram from Rumach Iochdar 5 showing taxa as a percentage of total land pollen. The detailed stratigraphic record from core RI5 is presented as Table 4.

TABLE 4. Detailed stratigraphical record from core Rumach Iochdar 5. Notation follows Troels-Smith (1955). Altitude of the basin sill is +9.3 m OD

Altitude m OD	Depth cm	Stratigraphic description
11.46–8.99	0–247	Well humified peat with wood fragments Th^3 4, Dl +, Tb(*Sphag.*)^3 + nig 4, strf 0, elas 0, sicc 2
8.99–8.85	247–261	Humified *detritus* peat with some *turfa* Dh 3, Ld 1, Th^2 + nig 3, strf 0, elas 0, sicc 2, ls 0
8.85–8.74	261–272	Fresh *detritus* peat and *limus* Dh 2, Ld^2 2 nig 2, strf 0, elas 1, sicc 2, ls 0
8.74–8.69	272–277	Humified *detritus* peat and *limus* Dh 2, Ld^3 2 nig 3, strf 0, elas 0, sicc 2, ls 0
8.69–8.67	277–279	Fresh *detritus* peat and *limus* Dh 2, Ld^2 2 nig 2, strf 0, elas 1, sicc 2, ls 0
8.67–8.61	279–285	Humified black *detritus* peat and *limus* Dh 2, Ld^3 2 nig 4, strf 0, elas 0, sicc 2, ls 0
8.61–8.47	285–299	Grey clay silt with *limus siliceus organogenes* and fine sand Ag 2, As 1, Ga 1, l.s.o + nig 2, strf 0, elas 0, sicc 2, ls 0
8.47–8.43	299–303	Grey clay silt with *limus* and *limus siliceus organogenes* Ag 2, As 1, Ld^3 1, l.s.o. + nig 2, strf 0, elas 0, sicc 2, ls 0
8.43–8.39	303–307	Humified *detritus* peat and *limus* Dh 2, Ld^3 2 nig 3, strf 0, elas 1, sicc 2, ls 0
8.39–8.35	307–311	Grey clay silt with some sand Ag 3, As 1, Ga + nif 2, strf 0, elas 0, sicc 2, ls 0
8.35–8.30	311–316	Sand with some silt and gravel Ga 4, Ag +, Gg(maj) + nig 2, strf 0, elas 0, sicc 2, ls 0
8.30–8.26	316–320	Gravel Gg(maj) 4 nig 2, strf 0, elas 0, sicc 2, ls 1
8.26–7.81	320–365	Sand with shell fragments Ga 4, *part test. (moll)* + nig 2, strf 0, elas 0, sicc 2, ls 0
7.81–7.19	365–427	Laminated grey silt clay As 4, Ag + nig 2, strf 3, elas 0, sicc 2, ls 0

TABLE 5. Detailed stratigraphic record from core Mointeach Mhor 11. Notation follows Troels-Smith (1955). Ground altitude at +8.11 m OD

Altitude m OD	Depth cm	Stratigraphic description
8.11–7.29	0–82	Well humified *turfa* peat Th^2 3, Sh 1 nig 3, strf 0, elas 0, sicc 2
7.29–7.20	82–91	Sandy amorphous peat, silty near base Sh 3, Ag 1, Ga + Th^3 + nig 3, strf 0, elas 0, sicc 2, ls 0
7.20–7.01	91–110	Organic sand Ga 4, Sh ++, nig 2, strf 0, elas 0, sicc 2, ls 0
7.01–6.91	110–120	Amorphous peat, some *turfa* Sh 4, Th^3 + nig 3 +, strf 0, elas 0, sicc 2, ls 4
6.91–6.83	120–128	Coarse and fine sand with some *turfa* Ga 3, Gs 1, Th^2 + nig 2, strf 0, elas 0, sicc 2, ls 0

at the top of the peat at MM45, and agree with the radiocarbon date of 6625 ± 45 BP from the contact.

The pollen and radiocarbon data from the basal 0.16 m of the surface peat at MM11 record the reduction and final removal of any marine influence on sedimentation from 3005 ± 45 BP to 2565 ± 45 BP. The marine influence is indicated by saltmarsh pollen types such as *Plantago maritima*, Chenopodiaceae, *Armeria* and *Aster*-type. In contrast to Kentra Moss the succession is not immediately to *Calluna* bog communities, but temporarily to fen wood, with *Alnus*, *Quercus* and *Betula*.

The base of the upper peat sequence at MM45 is an organic sand silt, lithologically similar to the regressive contacts recorded at Kentra Moss, and is dated 4640 ± 45 BP.

The relationship between sedimentation and past sea levels is hard to establish at Mointeach Mhor because of the complicating factor of the presence of past and present sand dune barrier systems at the entrance to the wetland-filled lowland embayment. With the currently available data the following explanation is offered. The tapering sand wedge represents the sudden inundation of a freshwater peat community arising from breaching of a coastal sand dune system. This event caused Mointeach Mhor to become

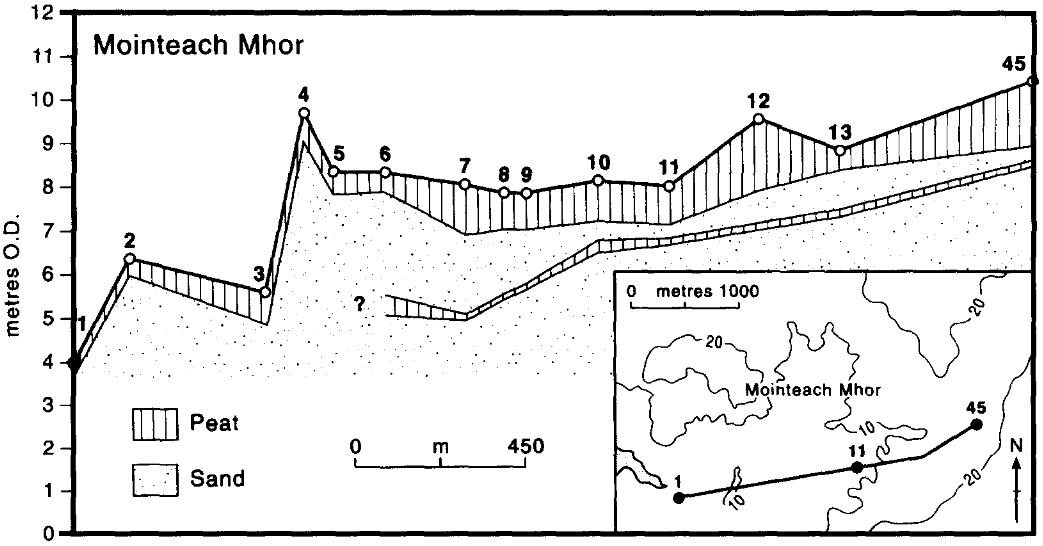

FIG. 9. Location of the borehole transect and generalised stratigraphy at Mointeach Mhor.

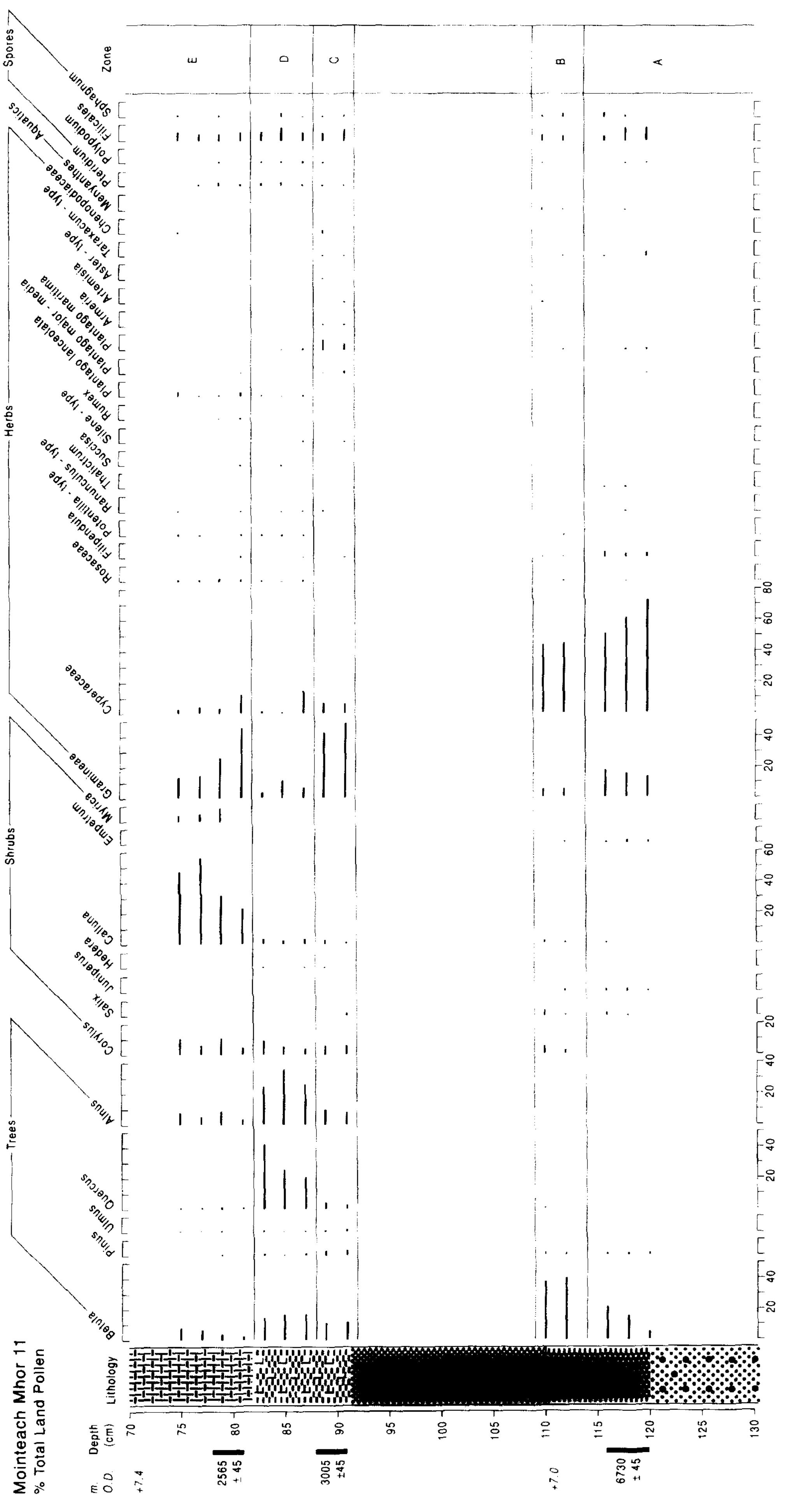

FIG. 10. Pollen diagram from Mointeach Mhor 11 showing taxa as a percentage of total land pollen. The detailed stratigraphic record from core MM11 is presented as Table 5.

occupied by marine water during the mid-Holocene, broadly equivalent to chronozone Flandrian II, until progressively the marine influence was reduced and freshwater peat environments redeveloped prior to a transition to bog communities. The presence of a transitional silt-dominated layer at the regressive contact between the sand wedge and the surface peats at MM45, a high silt component at this contact at MM11, and the significant time-lag between the radiocarbon dates for this contact at the two cores, suggests a gradual withdrawal of marine influence similar to that recorded at Kentra Moss. The pollen data, with *Plantago maritima* and other saltmarsh indicators, are also analogous to the Kentra Moss situation. These factors suggest that during the withdrawal of marine conditions Mointeach Mhor was functioning as a tidal marsh in the same way as at Kentra Bay and, as at Kentra, the reduction in marine influence was probably caused mainly by a progressive relative sea-level fall from the maximum achieved locally during the mid-Holocene. On Table 1, therefore, the regressive contacts at Mointeach Mhor are interpreted as having the same reference water level and indicative range as at Kentra Moss. The eroded contact of the basal peat at MM45 is not a precise or reliable sea-level index point, but gives a minimum age for the incursion.

At Mointeach Mhor, however, there is the possibility that the sedimentary record has been affected by the periodic re-establishment of the coastal dunes and so its interpretation must remain equivocal. The site's exposure to westerly storms further complicates the meaning of sediment altitudes. Levelling of the contemporary saltmarsh communities at the coast immediately west of Mointeach Mhor reveals that in a relatively sheltered location the lower limit of the raised bog *Calluna* community and the upper saltmarsh community with *Plantago* spp. occurs within the same altitudinal range as that recorded at Kentra Bay. However, at an exposed site a *Plantago coronopus*-Gramineae community, growing upon sand, was recorded at +4.03 m OD. This is 1.3 m above the altitude of the nearby upper saltmarsh community and 1.1 m above HAT. No site with freshwater peat currently accumulating behind a dune or storm ridge was found in the vicinity of Mointeach Mhor. Without a complete range of modern analogues there remains some doubt about the reference water levels and indicative ranges for the Mointeach Mhor index points in Table 1.

GLENANCROSS

This site is a small embayment within the rocky coast south of Morar (Figs 1 and 11), and at present is almost cut off from the coast by a belt of blown sand which in places forms high dunes and elsewhere is draped upon solid rock. Small streams flow into the embayment and cut through a fossil sand ridge to reach the sea. The entrance to the embayment faces west and is frequently affected by storm waves, but in places rock outcrops make it quite narrow and the embayment's degree of exposure is hard to define. While areas of the embayment are sand filled, there have clearly been opportunities within it during the mid-Holocene for quiet water deposition in sheltered areas. In places sediments within this embayment are similar to those at Mointeach Mhor and Kentra Moss in having sand and silt sand overlain by an organic sequence, grading from a silty amorphous peat into a fresh herbaceous bog peat.

Glenancross Example: GL2

The regressive contact between the lower silt sand and the overlying silty peat is dated 5805 ± 50 BP at +9.03 m OD. The silt sand unit comprises numerous layers, 0.05–0.16 m thick, of variable proportions of sand, silt and organic material. The detailed stratigraphic record from core Glenancross 2 is shown in Table 6. Pollen analyses (Fig. 12) show saltmarsh indicators such as *Armeria*, Chenopodiaceae, *Spergularia* and *Plantago maritima*

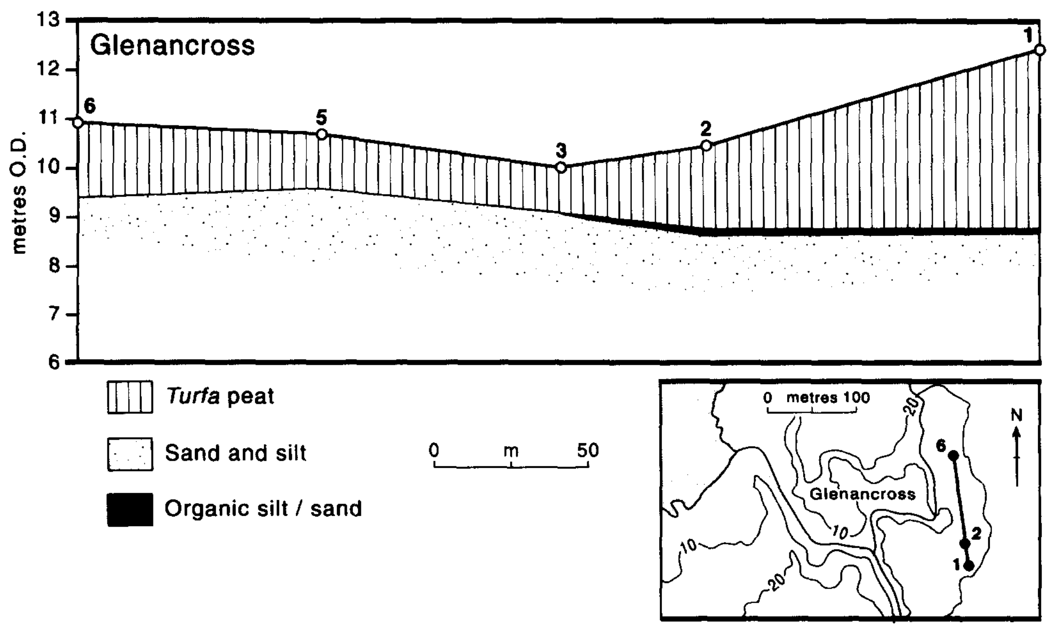

FIG. 11. Location of the borehole transect and generalised stratigraphy at Glenancross.

TABLE 6. Detailed stratigraphic record from core Glenancross 2. Notation follows Troels-Smith (1955). Ground altitude at + 10.53 m OD

Altitude m OD	Depth cm	Stratigraphic description
10.53–9.31	0–122	Fibrous brown herbaceous peat Th² 4 nig 3, strf 0, elas 1, sicc 2
9.31–9.22	122–131	Herbaceous peat with wood Th² 3, Sh 1, Dl + nig 3, strf 0, elas 1, sicc 2, ls 0
9.22–9.17	131–136	Black well humified peat Sh 3, Th³ 1 nig 4, strf 0, elas 0, sicc 2, ls 0
9.17–8.98	136–155	Silty amorphous peat Sh 2, Ag 2, Th² +, Ga + nig 3, strf 0, elas 0, sicc 2, ls 0
8.98–8.93	155–160	Slightly organic sand Ga 4, Sh + nig 2, strf 0, elas 0, sicc 2, ls 1
8.93–8.88	160–165	Sand with organic material and silt Ga 4, Sh +, Th² +, Ag + nig 2, strf 0, elas 0, sicc 2, ls 0
8.88–8.85	165–168	Slightly organic silt sand Ga 3, Ag 1, Sh + nig 2, strf 0, elas 0, sicc 2, ls 0
8.85–8.69	168–184	Slightly organic sand with some silt laminations Ga 3, (Ag + Sh) 1 nig 2, strf 1, elas 0, sicc 2, ls 0
8.69–8.62	184–191	Sand Ga 4 nig 2, strf 0, elas 0, sicc 2, ls 0

associated with the regressive contact. The removal of marine conditions and the development of freshwater peat-forming communities is shown in the pollen diagram by the disappearance of the saltmarsh indicators and the increase in frequencies of *Alnus*. This event is dated 5285 ± 45 BP.

The exposure of the site to westerly storms and the presence of blown sand across the mouth of, and extending into, the embayment make it difficult to establish the relationship between sedimentation and contemporaneous tide levels. The silt sand and silt peat probably accumulated behind the fossil sand ridge or the rock knoll which exists in the centre of the embayment. Quiet-water sedimentary environments are unlikely to exist without some kind of protection from westerly storms and waves. It is unclear whether the sand represents a fossil dune or beach ridge. Furthermore the effect of wave run-up, in raising sedimentation above stillwater high tide levels is unknown. This is significant because the highest regressive overlap recorded in this project is from Glenancross, +9.26 m OD at GL3. The date on the regressive contact represents a negative tendency of sea-level movement. The gradual nature of the fall in saltmarsh pollen indicators and the fine grained highly organic character of the regression contact sediments suggests that they may have been caused by a relative fall in sea level in a tidal marsh situation comparable with those at Kentra Moss and Mointeach Mhor. The reference water level and indicative range at Glenancross would therefore be the same as at those sites, and is shown as such on Table 1.

The nature of the Glenancross embayment, however, means that changes in coastal geomorphology, particularly the size and position of dunes and beach ridges, are also likely to have influenced past sedimentation. The altitude of past reference water levels cannot be established precisely with the present data. Levelling of present day coastal environments in exposed locations near Glenancross has shown that *Plantago* spp., may grow upon sand at up to one and a half metres above the upper saltmarsh limit. If such exposure were a factor in the Glenancross embayment in the mid-Holocene, the Glenancross index point may represent a level above that of highest tides.

RELATIVE SEA-LEVEL CHANGES

Relative sea-level change is reconstructed by defining the following variables for each sea-level index point: age, altitude, tendency of sea-level movement and indicative meaning.

Age

The dating of each index point is presented in Table 1.

Altitude

For index points from dune, beach ridge or tidal marsh palaeoenvironments, Glenancross, Mointeach Mhor and Kentra Moss, the measured altitude of the dated sample is used. To compare sea-level index points from different stratigraphic positions and palaeoenvironments the measured altitude is modified using the indicative meaning defined for the specific type of index point (see below). For isolation basins, Loch nan Eala and Rumach, the relevant altitude for each index point is the sill of the appropriate basin, rather than the altitude of the dated sediment. These data are presented in Table 1.

Tendency of Sea-Level Movement

A positive tendency of sea-level movement represents the increase in marine influence at the sampling site; a negative tendency is a decrease. Tendencies of sea-level movement are defined for each dated sample from the morphostratigraphic, lithostratigraphic and biostratigraphic data and form the basis for correlation of processes operating at individual sites to identify regionally significant processes (Shennan, 1986b; Shennan *et al.*, 1983) such as relative sea-level change. All sites need not show the same sea-level tendency at the same time since local processes, such as changes in sediment supply, can obscure the regional signal. Correlation of tendencies between sites allows the balance between local and regional processes to be investigated.

Indicative Meaning

This is composed of the reference tide (water) level and the indicative range of the sea-level index point. The latter is an estimate of how accurately the tide level can be defined from the morphostratigraphic, lithostratigraphic and biostratigraphic data, and typical values range between ±0.2 m and ±0.6 m (Shennan, 1986b; Shennan *et al.*, 1994/1995). Reference tide levels, between HAT and MHWST, and indicative ranges suggested by Shennan (1982, 1986b), based on tidal marsh palaeoenvironments from sites mostly in England, are consistent with the observations from the contemporary environments described from Kentra Bay (see previous section).

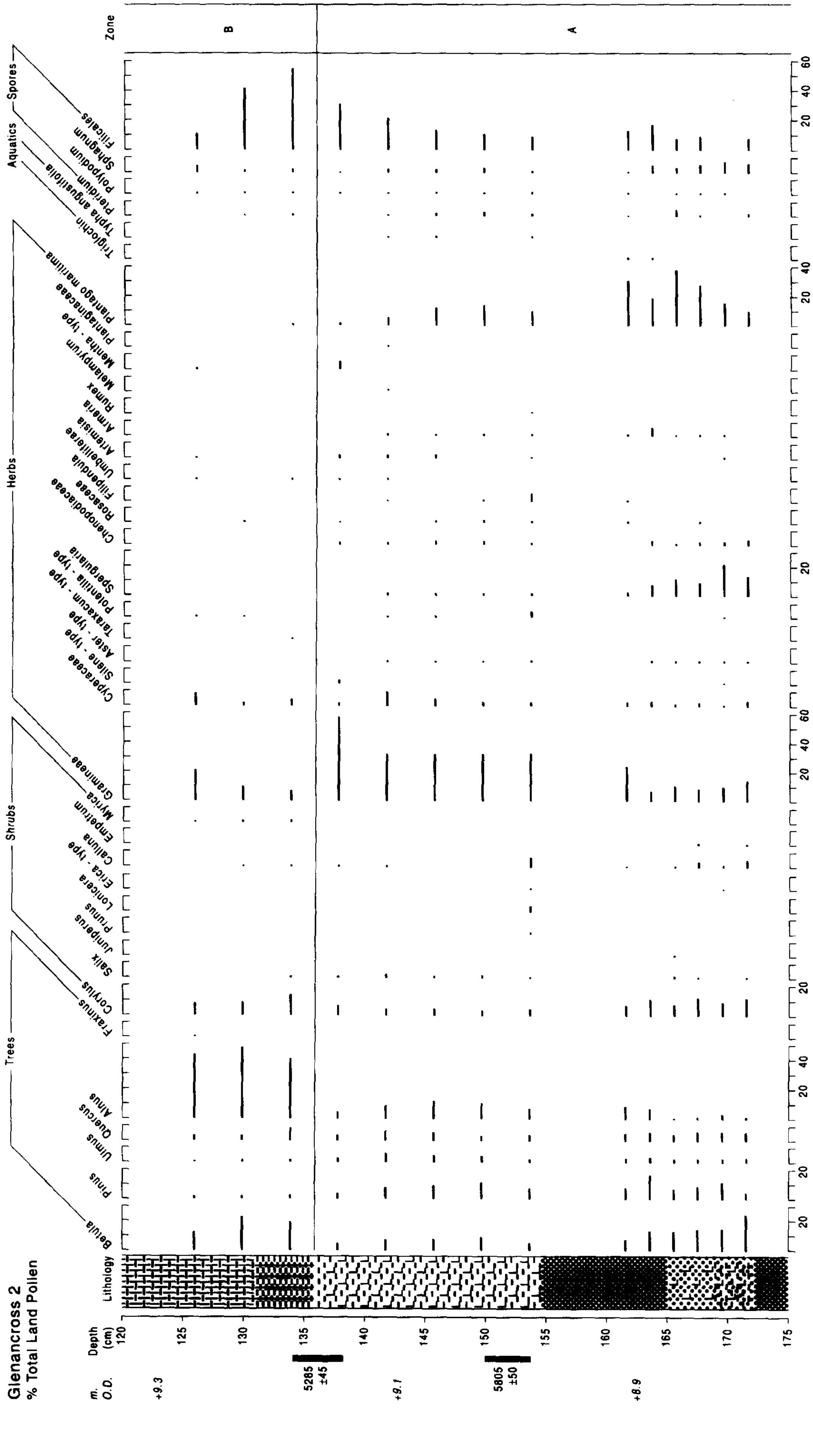

FIG. 12. Pollen diagram from Glenancross 2 showing taxa as a percentage of total land pollen. The detailed stratigraphic record from core Glenancross 2 is presented as Table 6.

Kjemperud (1986) suggests that stratigraphic and microfossil data from isolation basins illustrate different stages during the isolation process, as the sill changes from an intertidal level to where there are no marine incursions into the basins. Shennan *et al.* (1993, 1994) estimate that the latter stage, the hydrological isolation contact, represents approximately highest astronomical tides (HAT), and the earlier stage, the diatomological isolation contact, about 0.5 m lower, around mean high water spring tides (MHWST).

Current mean tide level is +0.3 m OD (Admiralty Tide Tables, 1986). This value and the indicative meanings for each index point are combined to calculate the relative mean sea-level changes shown in Fig. 13 and Table 1 as differences from present mean sea level. No discrimination is made between mean sea level and mean tide level.

Relative Sea-Level Change at the Sites

The relative sea-level record from Kentra Moss shows a fall of around 5 m since 4 ka BP. The two outliers are the samples from KM32 and KM48 (see earlier discussion) from which the lithostratigraphic and biostratigraphic evidence suggested that they were not indicative of the contemporary sea level. This conclusion is endorsed by the age–altitude diagram (Fig. 13(A)).

Loch nan Eala and the two Rumach sites are plotted together in Fig. 13(B). There is clear evidence for a fall in relative sea level from ca. 15 m above present at 11.8 ka BP to around 2 m above present ca. 10 ka BP. This rapid Late Devensian fall in relative sea level is supported by morphological evidence from near to Loch Morar (Peacock, 1970). In the present study the Late Devensian fall is recorded by the sequence of four isolation basins each recording only one negative tendency of sea-level movement. The subsequent relative rise in sea level is first dated ca. 8.7 ka BP in the main basin at Loch nan Eala, and then at ca. 8.3 ka BP in the upper basin (Table 1).

The series of isolation basins is unable to define precisely the age and altitude of the maximum Holocene relative sea level since there is approximately 4000 years with only one index point, that from the thin intercalated peat at LNE66/67 in the upper basin which represents a minor oscillation in relative sea level across the sill of the basin. The highest clastic sediments at Loch nan Eala are ca. 0.30 m above the altitude of the sill of the upper basin and the pollen data show that they post-date the thin intercalated peat. Therefore the Holocene maximum is dated between 6.6 ka BP and 4.0 ka BP. The presence of Holocene marine sediments at Loch nan Eala and their absence from Rumach Iochdar suggests that the altitude of this maximum is between ca. 4 m and 6.2 m above present (Fig. 13(B)). However, it is possible that peat growth in the Rumach Iochdar basin filled it with sediment which then prevented the incursion of seawater into the basin. There are two lines of evidence which support this argument. The highest regressive contact at Glenancross is

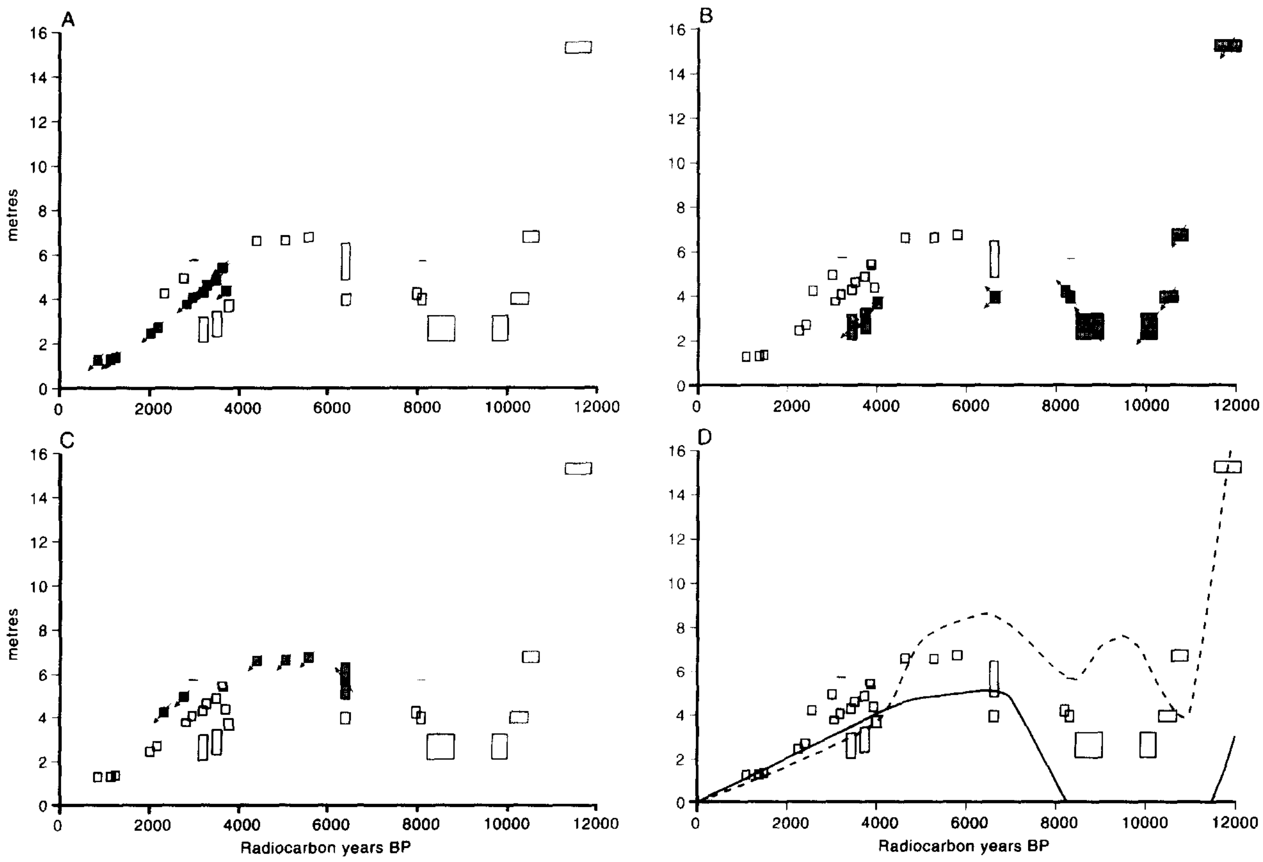

FIG. 13. Relative sea-level index points for Kentra Moss (A); Loch nan Eala and Rumach (B); Mointeach Mhor and Glenancross (C); and comparison with the empirical and rebound models (D). All altitudes are related to present mean tide level. Sea-level index points for the individual sites are shaded in sections A–C; the data from other sites are unshaded. Tendencies of sea-level movement are given by arrows, positive (up) or negative (down). The horizontal bars are those samples which formed above the contemporaneous sea level. All data are presented in Table 1.

only 0.04 m below the altitude of the sill of Rumach Iochdar, and the transition from open water to semi-terrestrial peat-forming communities at Rumach Iochdar occurred prior to the *Alnus*-rise (Shennan *et al.*, 1993). The *Alnus*-rise is dated ca. 6.6 ka BP at Loch nan Eala (Fig. 6(b)). Three index points from Loch nan Eala record a fall in relative sea level from 4.0 ka BP.

The data points from Glenancross (Fig. 13(C) and Table 1) fall within the period of the Holocene maximum identified from the Loch nan Eala sequence but there remains some uncertainty over the indicative meanings of the two samples. Therefore it is unclear whether the Holocene sea-level maximum is dated as early as 6 ka BP, the regressive overlap at Glenancross, or around 4 ka BP, the cluster of dates showing negative tendencies of sea-level movement at Loch nan Eala and Kentra Moss.

At Mointeach Mhor the age of the top of the basal peat, from MM45, suggests that the sudden inundation of the freshwater marsh occurred during a rise in sea level. The three samples showing a negative sea-level tendency conform with the general trends from Kentra Moss and Loch nan Eala, but at higher altitudes. Significantly, they plot closest to the Kentra Moss data rather than those from Loch nan Eala, which is only 2 km south of Mointeach Mhor. This altitudinal separation of the Loch nan Eala and Mointeach Mhor index points may be evidence of the storm influence at the latter, but may also reflect differences in reference water levels between isolation basins and the other, tidal marsh, types of site, as discussed below.

DISCUSSION

Diversity in Coastal Evolution

Northwestern Scotland is an ideal research area to evaluate diversity in Holocene coastal evolution. There is no dominant palaeoenvironment, so the pattern of relative sea-level change must be established from a diverse set, providing a measure of intercalibration, independent of the limitations of analyses dependent on one dominant palaeoenvironment.

The methodology of analysing relative sea-level changes based on high resolution lithostratigraphic, biostratigraphic and chronostratigraphic analyses of quiet-water depositional environments, developed initially on sites in England and Wales, is enhanced here through the study of three types of depositional environments — isolation basins, dune-fronted wetlands and raised tidal marshes. There are a number of novel aspects to this project: the integration of this range of data in this manner in Scotland; the detailed and systematic analysis of isolation basins in Scotland; and the reconstruction of relative sea-level changes in northwestern Scotland using a radiocarbon chronology rather than an over-riding dependence upon morphological data.

Each of the different palaeoenvironments has particular problems in providing relative sea-level data, but by following the consistent methodology of identifying the age, altitude, indicative meaning and tendency for each index point a diverse data set is used to resolve the local and regional pattern of sea-level change. It is apparent that high energy depositional environments characterised by dune systems are difficult to work with, due to the difficulty of defining the indicative meaning and sea-level tendency of potential index points. For all the palaeoenvironments more studies of the modern analogues are needed to assist in the interpretation of fossil data (e.g. Innes *et al.*, 1993), but this need is perhaps most pressing with regard to reference water levels during the isolation and connection process in isolation basin sites.

Isobase Models

The radiocarbon age of the "Main Lateglacial Shoreline" is equivocal (see Dawson, 1984; Sutherland, 1984, 1988; Gray and Ivanovich, 1988). Most current opinion favours the argument suggesting formation during the latter part of the Lateglacial Interstadial and through most of the Loch Lomond Stadial, approximately 11 ka BP to 10.3 ka BP. A key element of this argument is that during this period relative sea level either fell very slowly or was approximately stable, thus allowing sufficient time for shoreline formation (Sutherland, 1984). The isobase map published by Firth and Haggart (1989) shows a predicted altitude of +5 m OD for this shoreline in the Arisaig area, while Sutherland (1984) proposes a higher altitude, perhaps + 8 ± 1 m OD, but this figure is based upon extrapolation of a model for the area immediately south of Arisaig. Data from Rumach and Loch nan Eala (Table 1 and Fig. 13(B)) show that relative sea level fell from +17.8 m OD to +9.3 m OD in approximately the final 1000 radiocarbon years of the Lateglacial Interstadial and a further 3 m in the next 250 radiocarbon years, into the Loch Lomond Stadial. Therefore, while the relative sea-level index point from Loch nan Eala at +6.3 m OD dated 10.5 ka BP fits the isobase model for the "Main Lateglacial Shoreline" within the broad context of age and altitude, the full sequence of dates does not support the stable or slowly falling relative sea level proposed as necessary for the formation of the rock platforms correlated with the "Main Lateglacial Shoreline".

The highest Holocene marine deposits are recorded at +8.88 m OD and +9.26 m OD at Mointeach Mhor and Glenancross respectively. In contrast, at sites sheltered from westerly storms Holocene marine deposits are only found up to +6.60 m OD, at LNE29 in the upper basin of Loch nan Eala, and at +7.67 m OD at Kentra Moss. Although the "Main Postglacial Shoreline" has been predicted to lie between +10 and +12 m OD, no evidence has been found in the present study for marine deposits at these altitudes. Holocene marine sediments are absent from the basin at Rumach Iochdar where the altitude of the sill is at +9.3 m OD, although as noted above if this basin were full of sediment before the time of the sea-level maximum it may have no longer been capable of registering a sedimentary sea-level signal. Overall, however, the currently available data show the maximum Holocene relative sea level, represented by quiet-water sedimentation, constrained between +6.6 m OD and +9.3 m OD in the Arisaig area and around +7.7 m OD at Kentra Moss.

When the indicative meanings of the different features are taken into account, the discrepancy between the new data presented in this paper and the published isobase models is increased, not reduced. The index points from Kentra Moss, Mointeach Mhor and Glenancross have reference water levels which range from approximately MHWST to HAT, or possibly higher for the latter two sites. In contrast, the estuarine flats used to produce the most precisely constrained isobase maps, for eastern Scotland (Cullingford *et al.*, 1991), refer to 0.8–1.2 m below MHWST. It is equivocal whether the isobases on the west coast (e.g. Jardine, 1982; Sissons, 1983; Firth and Haggart, 1989; Firth *et al.*, 1993) are reduced to a reference water level comparable to the east coast sites although Sissons and Dawson (1981) show that adjustment for different sea-level indicators and their location is necessary. The new results presented here suggest that further reappraisal of the isobase models, including the age and indicative meaning of the different features used as index points in their construction is needed. For example, the difference between HAT and 1.2 m below MHWST is 1.7 m. A consistent bias of this magnitude would represent a horizontal shift of the isobases for the Main Postglacial Shoreline in the order of 12–30 km (Firth *et al.*, 1993, Fig. 4(a)).

Age–Altitude Empirical Model

The age–altitude model for the Forth valley and comparable patterns described for other parts of Scotland (e.g. Sissons and Brooks, 1971; Dawson, 1984; Sutherland, 1984; Firth and Haggart, 1989) show a sequence of fall–rise–fall between ca. 12 ka BP and the opening of the Holocene (Fig. 13(D)) which is not supported by the data from Loch nan Eala and Rumach. There is no evidence for anything other than a fall in relative sea level from 11.8 ka BP to at least 10.1 ka BP. The early Holocene minimum is recorded between 10.1 ka BP and 8.7 ka BP in the main basin at Loch nan Eala. This is earlier than proposed in the model.

The five sites described are insufficient to define precisely the age and altitude of the maximum Holocene relative sea level. It is dated between ca. 6.6 ka BP and 4.0 ka BP and slightly below the model prediction.

Rebound Models

The new data show general trends which are similar to curves predicted by quantitative rebound models (Lambeck, 1991a, 1993), although details of the predicted curves show spatial variation and depend on the input parameters to the models. The predictions, using the ice model giving the best fit for Great Britain (Lambeck, 1993, Fig. 24(a)), place the Late Devensian relative fall in sea level earlier than recorded by the field data from Rumach and Loch nan Eala (Fig. 13(D)) and the models predict relative sea level falling below present before 11 ka BP and below –4 m at 10 ka BP. These predictions are not supported by the new sea-level index points. The prediction for the mid-Holocene maximum is below the range of new data (Fig. 13(D)). The magnitude of different model predictions between Kentra Moss and the Arisaig area cannot be deciphered from the original figures (Lambeck, 1991a, Fig. 3; 1993, Fig. 24(a)).

Overall, the field and laboratory data generate a relative sea-level curve consistent with the general trends predicted by Lambeck (1991a, 1993) but quantitatively the pattern is closer to the curves predicted for areas covered by a greater thickness of ice at the glacial maximum and/or at stages during deglaciation. Lambeck (1993) suggests that an increase in ice load, by about 17%, over northern Scotland is required to give a better regional fit between the predictions and published observations for northeastern Scotland. This regional solution (Lambeck, 1993, Fig. 24b) shows relative sea level at ca. +3 m above present at 10.5 ka BP and ca. +7 m at 6 ka BP. This is more consistent with the data from the Arisaig area (Fig. 13(B)).

The new relative sea-level data, showing a fall since the mid-Holocene, support the interpretation of isostatic uplift continuing through the late Holocene to the present (Shennan, 1989).

Indicative Meanings, Isolation Basins and Relative Sea-Level Change

It is significant that, using the reference water levels shown in Table 1, where the records overlap in age, the Loch nan Eala index points lie consistently below those from Kentra Moss. In contrast the youngest two index points from Mointeach Mhor are higher. There may have been a measure of differential glacioisostatic, hydroisostatic and gravitational effects between Kentra Moss and the other sites in particular, but this will not explain the differences between Loch nan Eala and Mointeach Mhor. Therefore, the reference water levels of the sea-level index points must be re-evaluated.

The lithostratigraphic and biostratigraphic data from Loch nan Eala, and Rumach (above and Shennan *et al.*, 1993, 1994), are consistent with the stages of isolation proposed by Kjemperud (1986). However, the present spring tidal range around Scandinavia is 1–2 m or less, whereas between Kentra Bay and Loch Morar it is over 4 m (Admiralty Tide Tables, 1986). This difference may be significant. The salinity of water in the photic zone of the basin in each stage of the isolation, or connection, process will depend upon factors such as the tidal range, freshwater input, and the size and morphology of both the basin and its connection to the sea. Regular, perhaps as much as daily, penetration by marine water is probably required to produce a diatom assemblage dominated by polyhalobous taxa, preserved in complete chains of valves as was observed for many samples in both basins at Loch nan Eala, even though there is significant freshwater input into the system. In this situation the reference water levels associated with the hydrological and diatomological isolation, and connection, contacts will be lower than those in small basins with little freshwater input. At or below mean high water of neap tides (MHWNT) may be a more realistic estimate under these circumstances.

Much more work, including study of present day examples and hydrological modelling, is required on Scottish isolation basins in macrotidal environments. A Holocene record from isolation basins adjacent to Kentra Moss would be particularly useful for cross-correlation with other types of sea-level index points. All this work is at present in progress and the importance of quantifying the reference water level is illustrated by Fig. 14. Here Rumach and Loch nan Eala reference water levels are reduced by 1.7 m, the present day difference between HAT and MHWNT. The sea-level index points now overlap with those from

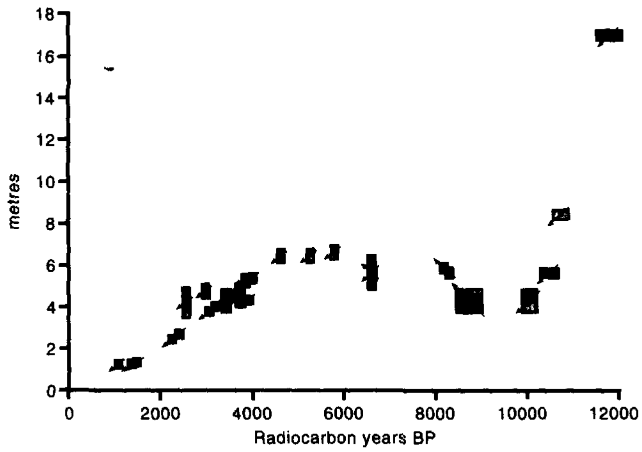

FIG. 14. Relative sea-level index points, calculated with revised indicative meanings for some types of site (see text for details). All altitudes are related to present mean tide level.

Kentra Moss. Similarly, the larger error boxes given for the Glenancross and Mointeach Mhor samples, in contrast to Fig. 13, show the uncertainty whether they represent storm levels rather than MHWST to HAT.

The work in progress will show in which situations indicative ranges must be increased (Fig. 14, Glenancross and Mointeach Mhor samples) and when different reference water levels can be specified whilst retaining a small indicative range (Fig. 14, Loch nan Eala and Rumach samples). With our current data we present the relative sea-level changes calculated with the modified indicative meanings (Fig. 14) as the next model to be evaluated using an independent data set.

It is significant that none of these changes alters the general evaluations of the existing isobase, empirical and rebound models. Although some of the differences in altitude are less certain the tendency of each index point is unaffected, therefore the trend of relative sea-level change remains the same.

CONCLUSIONS

The methodology outlined in this paper is applicable to a range of coastal palaeoenvironments from which sea-level index points are recorded in a form suitable for between-site correlation. The new sea-level data allow the objective and independent assessment of previous models.

The empirical model is not supported as a model for the area between Kentra Bay and Loch Morar. In particular, the relative rise in sea level during the mid- to late Loch Lomond Stadial is not evident. More data are needed from northwestern Scotland but reappraisal of the original evidence for this rise in sea level is merited. This involves further consideration of the age and indicative meaning of the "Buried Gravel Layer" and the "Buried Beach" sequence in the Forth Valley (e.g. Sissons, 1969, 1983), proposed equivalent features in the Beauly Firth (e.g. Firth and Haggart, 1989), and the processes controlling formation of the "Main Lateglacial Shoreline" in western Scotland (e.g. Gray, 1978; Dawson, 1984; Sutherland, 1984). Furthermore, this rise in relative sea level is central to the developing debate upon whether the Loch Lomond Stadial ice cap caused any measurable crustal loading (e.g. Firth *et al.*, 1993; Lambeck, 1993).

The general form of the relative sea-level curve predicted by rebound models is supported by the new data, but the timing and magnitude of the major changes are closer to those predicted for an ice model with greater ice load over northern Scotland (Lambeck, 1993). The relative fall in sea level from the mid-Holocene to the present is consistent with a model of continuing isostatic uplift in the area (Shennan, 1989).

The major discrepancies with both the empirical model and the rebound model are for the Late Devensian and early Holocene. This is not too surprising since the present project represents the first investigation to date sea-level index points with small age and altitude error bands within that time frame. The sea-level record from ca. 12 ka BP to the present, even with the sparse data for the mid-Holocene, probably represents the longest relative sea-level history, derived with quantified accuracy, in the U.K.

The results presented here require independent verification since significant reappraisal of existing models will be needed before they can be applied at any regional scale. The priorities for future research should focus on the further analysis of the mid-Holocene maximum and the Late Devensian/Holocene transition. Future research must also address the precision of the methods needed to establish all the parameters of a sea-level index point: age, altitude, tendency of sea-level movement, reference water level and indicative range. Excessive reliance on a methodology which focuses on only some of these is too limiting. The methodology adopted in this study is flexible, and so applicable to a diverse range of coastal environments and coastal evolution. The opportunities exist to extend this approach over a much wider area to resolve local and regional scale questions and so address the adopted aims of IGCP Project 274 described earlier.

ACKNOWLEDGEMENTS

The work was completed under European Community funded projects "Climate Change, Sea-Level Rise and Associated Impacts in Europe" (EPOC CT90-0015) and "Relative Sea-Level Changes and Extreme Flooding Events around European Coasts" (EV5V-CT93-0266).

Thanks are expressed to Professor I. Hutchinson of Simon Fraser University, Canada, and to Dr A. Nelson of the United States Geological Survey, Colorado, for help in the field and valuable discussions. We are also grateful to James Carnegie, Matt Corney, Alistair Kirk, Chris Puhr and Ian Sproxton for assistance with fieldwork, and to all the landowners for access to sites. Most of the radiocarbon data were provided by NERC, allocation 455/0591.

REFERENCES

Admiralty Tide Tables (1986). *European waters including the Mediterranean Sea (Vol. 1)*. Taunton, Hydrographer to the Navy, Admiralty Hydrographic Department.

Ballantyne, C.K. and Gray, J.M. (1984). The Quaternary geomorphology of Scotland. *Quaternary Science Reviews*, **3**, 259–289.

Birks, H.J.B. and Williams, W. (1983). Late Quaternary vegetational history of the Inner Hebrides. *Proceedings of the Royal Society of Edinburgh*, **83B**, 269–292.

Cullingford, R.A. and Smith, D.E. (1966). Late-glacial shorelines in eastern Fife. *Transactions of the Institute of British Geographers*, **39**, 31–51.

Cullingford, R.A., Smith, D.E. and Firth, C.R. (1991). The altitude and age of the Main Postglacial Shoreline in eastern Scotland. *Quaternary International*, **9**, 39–52.

Dawson, A.G. (1980). The low rock platform in western Scotland. *Proceedings of the Geologists' Association*, **91**, 339–344.

Dawson, A.G. (1984). Quaternary sea-level changes in western Scotland. *Quaternary Science Reviews*, **3**, 345–368.

Donner, J.J. (1970). Land/sea level changes in Scotland. *In*: Walker, D. and West, R.G. (eds), *Studies in the Vegetational History of the British Isles*, pp. 23–39. Cambridge University Press, Cambridge.

Farmer, B.H. (1966). Special number on the vertical displacement of shorelines in highland Britain. *Transactions of the Institute of British Geographers*, **39**, i–vii, 1–145.

Firth, C.R. and Haggart, B.A. (1989). Loch Lomond Stadial and Flandrian shorelines in the Inner Moray Firth area, Scotland. *Journal of Quaternary Science*, **4**, 37–59.

Firth, C.R., Smith, D.E. and Cullingford, R.A. (1993). Late Quaternary glacio-isostatic uplift patterns for Scotland. *In*: Owen, L.A., Stewart, I. and Vita-Finzi, C. (eds), *Neotectonics: Recent Advances*, pp. 1–14. Quaternary Proceedings No. 3, Quaternary Research Association, Cambridge.

Gray, J.M. (1974). The Main Rock Platform of the Firth of Lorn, western Scotland. *Transactions of the Institute of British Geographers*, **61**, 81–99.

Gray, J.M. (1978). Low-level shore platforms in the south-west Scottish Highlands: Altitude, age, and correlation. *Transactions of the Institute of British Geographers New Series* **3**, 151–164.

Gray, J.M. and Ivanovich, M. (1988). Age of the Main Rock Platform, western Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **68**, 337–345.

Gunn, W. (1900). The geology of Belford, Holy Island and the Farne Islands, Northumberland. *Memoirs of the Geological Survey, England and Wales New Series*, **4**, H.M.S.O., London, 155 pp.

Haggart, B.A. (1986). Relative sea-level change in the Beauly Firth, Scotland. *Boreas*, **15**, 191–207.

Haggart, B.A. (1989). Variations in the pattern and rate of isostatic uplift indicated by comparison of Holocene sea-level curves from Scotland. *Journal of Quaternary Science*, **4**, 67–76.

Haggart, B.A. and Sutherland, D.G. (1992). Moine Mhor. *In*: Walker, M.J.C., Gray, J.M. and Lowe, J.J. (eds), *The South-West Scottish Highlands Field Guide*, pp. 143–152. Quaternary Research Association, Cambridge.

Haggett, P. and Chorley, R.J. (1967). Models, paradigms and the new geography. *In*: Chorley, R.J. and Haggett, P. (eds), *Models in Geography*, pp. 19–41. Methuen, London.

Innes, J.B., Shennan, I. and Zong, Y. (1993). The Contemporary Diatom and Pollen Flora of Kentra Bay, Argyll. Unpublished Report, Scottish Natural Heritage.

Jamieson, T.F. (1865). On the history of the last geological changes in Scotland. *Quarterly Journal of the Geological Society*, **21**, 161–203.

Jardine, W.G. (1982). Sea-level changes in Scotland during the last 18,000 years. *Proceedings of the Geologists' Association*, **93**, 25–42.

Kirk, W., Rice, R.J. and Synge, F.M. (1966). Deglaciation and vertical displacement of shorelines in Wester and Easter Ross. *Transactions of the Institute of British Geographers*, **39**, 65–78.

Kjemperud, A. (1986). Late Weichselian and Holocene shore displacement in the Trondsheimfjord area, central Norway. *Boreas*, **15**, 61–82.

Lambeck, K. (1991a). Glacial rebound and sea-level change in the British Isles. *Terra Nova*, **3**, 379–389.

Lambeck, K. (1991b). A model for Devensian and Flandrian glacial rebound and sea-level change in Scotland. *In*: Sabadini, R., Lambeck, K. and Boschi, E. (eds), *Glacial Isostasy, Sea Level and Mantle Rheology*, pp. 33–62. Kluwer Academic Publishers, Dordrecht.

Lambeck, K. (1993). Glacial rebound of the British Isles — II. A high-resolution, high-precision model. *Geophysical Journal International*, **115**, 960–990.

Long, A.J. (1992). Coastal responses to changes in sea-level in the East Kent Fens and southeast England. *Proceedings of the Geologists' Association*, **103**, 187–199.

McCann, S.B. (1966). The main post-glacial raised shoreline of western Scotland from the Firth of Lorne to Loch Broom. *Transactions of the Institute of British Geographers*, **39**, 87–99.

Moore, P.D. and Webb, J.A. (1978). *An Illustrated Guide to Pollen Analysis*. Hodder and Stoughton, London.

Palmer, A.J.M. and Abbott, W.H. (1986). Diatoms as indicators of sea-level change. *In*: van de Plassche, O. (ed.), *Sea-Level Research: A Manual for the Collection and Evaluation of Data*, pp. 457–488. GeoBooks, Norwich.

Peacock, J.D. (1970). Some aspects of the glacial geology of west Inverness-shire. *Bulletin of the Geological Survey of Great Britain*, **33**, 43–56.

Plassche, O. van de (ed.) (1986). *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. GeoBooks, Norwich.

Shennan, I. (1982). Interpretation of Flandrian sea-level data from the Fenland, England. *Proceedings of the Geologists' Association*, **93**, 53–63.

Shennan, I. (1983). Flandrian and Late Devensian sea-level changes and crustal movements in England and Wales. *In*: Smith, D.E. and Dawson, A.G. (eds), *Shorelines and Isostasy*, pp. 255–283. Academic Press, London.

Shennan, I. (1986a). Flandrian sea-level changes in the Fenland I. The geographical setting and evidence of relative sea-level changes. *Journal of Quaternary Science*, **1**, 119–154.

Shennan, I. (1986b). Flandrian sea-level changes in the Fenland II. Tendencies of sea-level movement, altitudinal changes and local and regional factors. *Journal of Quaternary Science*, **1**, 155–179.

Shennan, I. (1987a). Holocene sea-level changes in the North Sea. *In*: Tooley, M.J. and Shennan, I. (eds), *Sea-Level Changes*, pp. 109–151. Blackwell, Oxford.

Shennan, I. (1987b). Global analysis and correlation of sea-level data. *In*: Devoy, R.J.N. (ed.), *Sea Surface Studies: A Global View*, pp. 198–230. Croom Helm, London.

Shennan, I. (1989). Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science*, **4**, 77–89.

Shennan, I. (1992). Late Quaternary sea-level changes and crustal movements in eastern England and eastern Scotland: An assessment of models of coastal evolution. *Quaternary International*, **15/16**, 161–173.

Shennan, I., Tooley, M.J., Davis, M.J. and Haggart, B.A. (1983). Analysis and interpretation of Holocene sea-level data. *Nature*, **302**, 404–406.

Shennan, I., Innes, J.B., Long, A.J. and Zong, Y. (1993). Late Devensian and Holocene relative sea-level changes at Rumach, near Arisaig, northwest Scotland. *Norsk Geologisk Tidsskrift*, **73**, 161–174.

Shennan, I., Innes, J.B., Long, A.J. and Zong, Y. (1994). Late Devensian and Holocene relative sea-level changes at Loch nan Eala, near Arisaig, northwest Scotland. *Journal of Quaternary Science*, **9**, 261–283.

Shennan, I., Innes, J.B., Long, A.J. and Zong, Y. (1995, *in press*). Holocene relative sea-level changes and coastal vegetation history at Kentra Moss, Scotland. *Marine Geology*.

Sissons, J.B. (1966). Relative sea-level changes between 10,300 and 8,300 B.P. in part of the Carse of Stirling. *Transactions of the Institute of British Geographers*, **39**, 19–29.

Sissons, J.B. (1967). *The Evolution of Scotland's Scenery*. Oliver and Boyd, Edinburgh.

Sissons, J.B. (1969). Drift stratigraphy and buried morphological features in the Grangemouth–Falkirk–Airth area, Central Scotland. *Transactions of the Institute of British Geographers*, **48**, 19–50.

Sissons, J.B. (1983). Shorelines and isostasy in Scotland. *In*: Smith, D.E. and Dawson, A.G. (eds), *Shorelines and Isostasy*, pp. 209–226. Academic Press, London.

Sissons, J.B. and Brooks, C.L. (1971). Dating of early Post-glacial land and sea-level changes in the western Forth valley. *Nature Physical Science*, **234**, 124–127.

Sissons, J.B. and Dawson, A.G. (1981). Former sea-levels and ice limits in Wester Ross, northwest Scotland. *Proceedings of the Geologists' Association*, **92**, 115–124.

Smith, D.E. and Dawson, A.G. (eds) (1983). *Shorelines and Isostasy*. Academic Press, London. 387 pp.

Smith, D.E., Cullingford, R.A. and Brooks, C.L. (1983). Flandrian relative sea-level changes in the Ythan valley, northeast Scotland. *Earth Surface Processes and Landforms*, **8**, 423–438.

Smith, D.E., Firth, C.R., Turbayne, S.C. and Brooks, C.L. (1992). Relative sea-level changes and shoreline displacement in the Dornoch Firth area, Scotland. *Proceedings of the Geologists' Association*, **103**, 237–257.

Smith, D.E., Sissons, J.B. and Cullingford, D.E. (1969). Isobases for the Main Perth raised shoreline in south-east Scotland as determined by trend-surface analysis. *Transactions of the Institute of British Geographers*, **46**, 45–52.

Sutherland, D.G. (1984). The Quaternary deposits and landforms of Scotland and the neighbouring shelves: A review. *Quaternary Science Reviews*, **3**, 157–254.

Sutherland, D.G. (1988). Glaciation and sea-level change in the south-west Highlands. *In*: Dawson, A.G. (ed.), *INQUA Field Excursion and Symposium on Late Quaternary Sea-Levels and Crustal Deformation*, pp. 15–27. Coventry Polytechnic, Coventry.

Svendsen, J.I. and Mangerud, J. (1987). Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *Journal of Quaternary Science*, **2**, 113–132.

Tallantire, P.A. (1992). The alder (*Alnus glutinosa* (L.) Gaertn.) problem in the British Isles: A third approach to its palaeohistory. *New Phytologist*, **122**, 717–731.

Tooley, M.J. (1982). Sea-level changes in northern England. *Proceedings of the Geologists' Association*, **93**, 43–51.

Troels-Smith, J. (1955). Characterization of unconsolidated sediments. *Danmarks Geologiske Undersogelse Series IV*, **3**, 38–73.

Vos, P.C. and de Wolf, H. (1988). Methodological aspects of palaeo-ecological diatom research in coastal areas of the Netherlands. *Geologie en Mijnbouw*, **67**, 31–40.

Vos, P.C. and de Wolf, H. (1993). Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands; Methodological aspects. *Hydrobiologia*, **269/270**, 285–296.

Wain-Hobson, T. (1981). Aspects of the Glacial and Post-glacial history of north-west Argyll. Unpublished Ph.D. Thesis, University of Edinburgh.

Walker, M.J.C. and Lowe, J.J. (1987). Flandrian environmental history of the Isle of Mull, Scotland. III. A high resolution pollen profile from Gribun, western Mull. *New Phytologist*, **106**, 333–347.