[14]C DATING OF LAMINATED SEDIMENTS FROM LOCH NESS, SCOTLAND

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ABSTRACT. Radiometric and AMS radiocarbon dating of a 6-m sediment core from Loch Ness, Scotland, indicates that it represents perhaps the very end of the Late Pleistocene, and the first *ca.* 7500 yr of the Holocene. Counts of laminations observed in the Holocene section of the core suggest that they are present in sufficient number to constitute annual laminations (varves), an hypothesis consistent with the pollen record, which contains a sequence of zones representative of the Early, Middle and part of the Late Holocene regional vegetation history. On the basis of BSEM and X-ray studies of sediments, and modern seston trap data, the laminations are believed to be produced by winter floods, which introduce increased silt loading into the Loch. Sediment for the rest of the year is mostly composed of clay-sized material. This hypothesis is being further tested, however, by continuing sedimentological and microfossil studies.

Time-depth relations for the core based on calibrated ^{14}C dates and lamination counts, respectively, illustrate the close correspondence between the two sets of data. The latter are therefore now being used to develop a varve chronology for the Holocene for Loch Ness. This will then in turn be used for further chronological studies, and for investigations of palaeoclimatic variations over the eastern North Atlantic, to which the signal of lamination thickness in the sediments is thought to be particularly sensitive. They may also eventually be used for calibration studies, employing ^{14}C dating of specific carbon compounds, or groups of compounds extracted from the sediment using modern organic geochemical methods.

INTRODUCTION

Here we describe the results of ^{14}C dating of two long (> 5m) sediment cores from the deep northern basin of Loch Ness, Scotland. In this study, A. J. Shine is responsible for coring and sediment trap data, M. C. Cooper and P. E. O'Sullivan for lamination chronology and counting and measurement of laminations, D. Bull and A. E. S. Kemp for X-ray and backscatter electron microscopy (BSEM), D. D. Harkness for radiometric ^{14}C dating and one AMS date, E. M. Lawson for three AMS dates, R. I. Jones and A. J. Shine for sediment trap data, and S. M. Peglar and N. M. Matthews for preliminary pollen analysis respectively of Core 3 and Core 4.

SITE DESCRIPTION

Loch Ness (Fig. 1) is, by volume, the largest body of standing water in the United Kingdom (Maitland 1981). Its major limnological and other properties are listed in Table 1. The Loch is temperate, monomictic and unproductive, and occupies a deep, steep-sided, glacially scoured graben *ca.* 40 km long whose alignment southwest/northeast exposes it to prevailing southwesterly gales. Seiches and other wind-driven circulation patterns are common, but weak stratification develops during most summers (Smith, Lyle and Rosie 1981). The whole water column mixes during winter.

The Loch is divided into two basins, either side of Foyers (Fig. 1). In the south basin, minerogenic, mainly riverborne sediments are found (A. J. Shine, personal observation), whereas laminated lacustrine deposits are mostly confined to the north, at least partly because fewer rivers directly enter that

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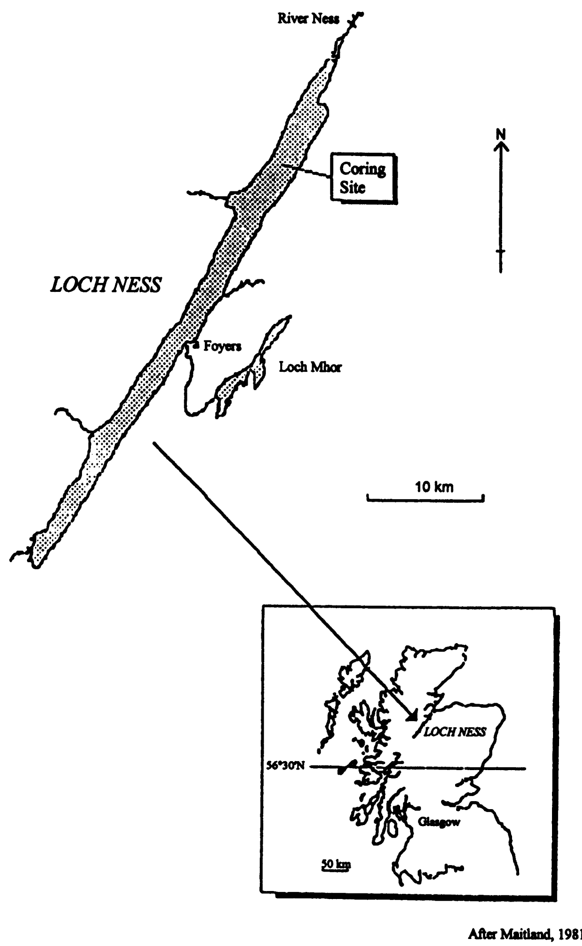

Fig. 1. Loch Ness, showing location of main coring station

TABLE 1. Characteristic Physical Features of Loch Ness and its Catchment (after Maitland 1981)

Latitude	57°15′N*
Longitude	4°30′W*
UK National Grid Reference	NH 285 429*
Length (L, km)	39
Mean breadth (B, km)	1.45
Area (A, km^2)	56.4
Volume (V, $m^3 \times 10^8$)	74.5
Hydraulic retention time (yr)	2.8
Catchment area (D, km^2)	1775
Maximum depth (Z_{max}, m)	230
Mean depth (Z, m)	132
Elevation (m)	15.8

*mean value only

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end of the Loch. Prevailing southwest winds also affect seasonal and spatial distribution of seston, concentrating it at the northern end of the Loch, from which the cores employed in this study were therefore collected.

METHODS

Two cores *ca* 5.75 m long, the uppermost *ca* 4.25 m of which are laminated, were recovered using purpose-built equipment modeled on the Kullenberg (1947) corer, designed and built by A. J. Shine. The sampling station is located at UK National Grid Reference NH 256779.286 832203.627 (Fig. 1), beneath 204 m of water, the same location at which the sediment trap data (see below) were recorded.

After extrusion, cores were sliced vertically, wrapped in polyurethane sheeting, and stored at 5°C. Sections for X-ray and BSEM (Fig. 2, below) were obtained using anodically-charged slab cutters (Schimmelman, Lange and Berger 1990). X-ray photography was carried out on the wet sections. Material for scanning electron microcope studies was prepared using the method described by Kemp (1990). Studies of images were conducted on X-radiographs prepared as above, or on fine-grained monochrome infrared plates obtained by cleaning and photographing the surface of fresh cores. Images were input to an analyzer (Quantimet 570, Leica/Cambridge Instruments, UK) using a CCD camera. Four scans were performed on each, and the average taken in order to produce a working digital image. This was calibrated by means of a scale included in the original photographs (Cooper 1998a). Plots of gray level against length (Fig. 3, below), showing the position of laminae as peaks or troughs (corresponding respectively to light or dark laminations) were then constructed. X-ray photographs were used for imaging finer laminations, and infrared photographs the coarser structures (*cf.* Walanus and Goslar 1993). Counts were then prepared by the use of image transforms (Cooper 1998a), which generate digitized information on lamination number, position, thickness and gray level/color. Results were compared with a predicted sedimentation rate obtained by reference to the preliminary pollen diagram (see below).

Six radiometric ^{14}C dates (SRR 5735-5740), and one AMS date (AA-21852), were carried out on material from Core 3 under the supervision of D. D. Harkness. Three further AMS dates from the same core (OZB 258U-260U) by E. M. Lawson. Samples for radiometric dating (and AMS date AA-21852) were selected on the basis of the preliminary pollen diagram (see below, Fig. 6), and were located approximately across major regional pollen zone boundaries. Material for the remaining AMS dates was removed from the core before this diagram became available, and so instead were positioned according to changes in overall gray level obtained by image analysis (Cooper and O'Sullivan, in press). No dates have yet been determined on material from Core 4.

Pretreatment

Radiometric Dates (plus AMS date AA-21852, D.D.H.).

Prior to isotope analyses, the raw samples were digested in 0.5M HCl at 80°C for 10 h, washed acid free, filtered, dried to constant weight in a drying oven, and converted to benzene. Counting took place at the NERC Radiocarbon Laboratory, East Kilbride, except for the single AMS date AA-21852, which was determined at the NSF–University of Arizona AMS Facility.

ANSTO AMS Dates (E.M.L.)

After extraction of macrofossils such as pollen, charcoal and twig fragments, the material was first treated in 2M HCL for 2 h at 60°C, then with 4% NaOH for 3 h at the same temperature, and finally once more with 2M HCl for 1 h, again at 60°C (the standard A-A-A procedure). It was then combusted and made into graphite for AMS determination.

Results

Sediment Composition and Structure

X-ray Photography and BSEM

One 15-cm section from Core 3 (but two more from adjacent short cores) has been analyzed using BSEM at the University of Southampton by D. Bull and A. E. S. Kemp. The results (Fig. 2) indicate

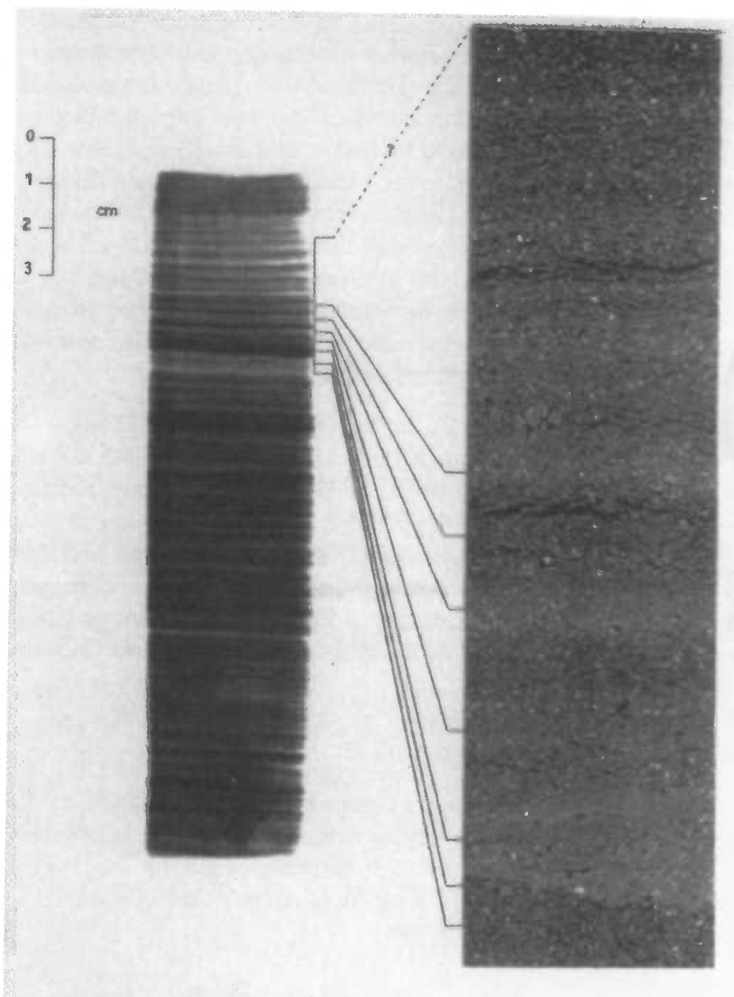

Fig. 2. Results of X-ray photography and backscatter electron microscopy of Loch Ness sediments (D.B.)

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that the matrix of the sediments of Loch Ness is composed mainly of couplets of alternating clay-rich and silt-rich laminae. Thickness of individual units varies between 0.5 and 0.75 mm, though some are only *ca* 0.25 mm thick. Superimposed upon the finer matrix is a sequence of irregularly spaced, thicker, more prominent silty-clay and silt layers, each exhibiting a decrease in particle size upwards.

In real color (not shown), clay-rich layers are dark brown to black, and silt-rich laminae, olive to brown. In X-radiographs (also Fig. 2), the relatively more opaque silt-rich laminae appear darker than less opaque clays. All sections examined are poor in organic matter and microfossils, notably diatoms. These appear, however, somewhat more abundant in the fine clay-rich laminae than in the corresponding silty layers. More analyses of sections of Core 3 are being prepared in the same laboratory by Dean (ms.). Relatively more diatoms are found in the lower sections of the core, dating from the Early Holocene.

Image Analyses

Figure 3 depicts a plot of gray level *vs.* length (depth) for a 15-cm laminated section of Core 3. The main peaks and troughs correspond to fine couplets 0.5–1.5 mm thick, so that the diagram may be used for counting fine laminae. Thirty (overlapping) sections from each long core were prepared in the same way, and counts fitted together in sequence, in order to develop measurements of lamination thickness throughout the entire sediment sequence. Two thin chaotic zones, one in each core, and which may represent slumps, could not be included in this analysis.

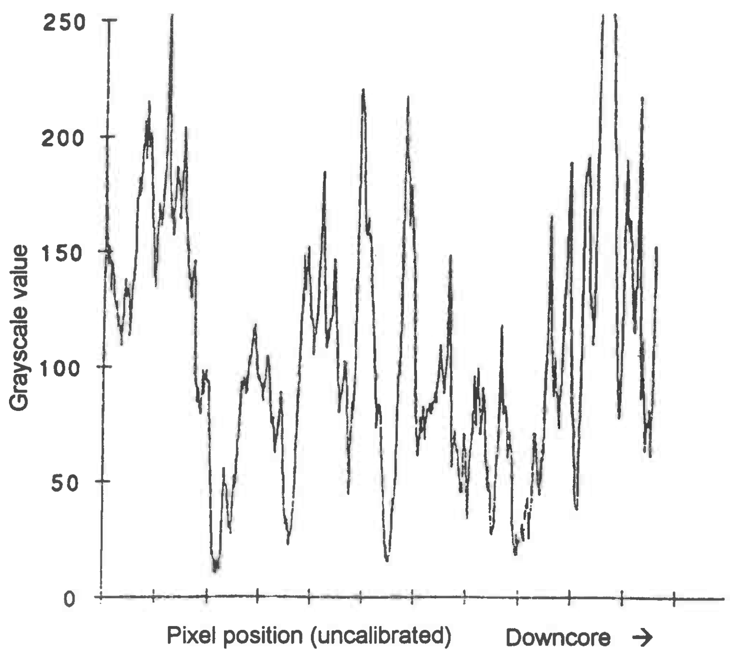

Fig. 3. Plot of gray level *vs.* depth for a 0.15-m section of Loch Ness sediments obtained by image analysis of X-ray photography (M.C.C)

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¹⁴C Dating

The results of all ^{14}C determinations, both radiometric and AMS, are summarized in Table 2, and plotted uncalibrated against depth in Figure 4. They indicate that Core 3 represents a period of some 7000 ^{14}C yr, with the basal sediments deposited *ca.* 9500 ^{14}C yr ago, and the uppermost sections from *ca.* 2800 ^{14}C yr BP onwards. The $\delta^{13}C$ measurements for all material dated lay in the range –25.1 to –28.7‰.

TABLE 2. Results of ^{14}C Dating of Selected Horizons from Loch Ness Core 3 (D.D.H. and E.M.L)

Depth (cm)	Lab code	Age (^{14}C yr BP)	Calibrated age (cal BP, 2σ)*	$\delta^{13}C$ (‰)
103	SRR-5735	2730 ± 50	2812 ± 68	–28.7
198	SRR-5736	3350 ± 60	3592 ± 131	–26.6
226	OZB-260U†	4000 ± 90		–26.9
326	SRR-5737	5305 ± 60	6096 ± 115	–25.6
358	SRR-5738	6050 ± 70	6933 ± 158	–25.1
383	OZB-259U†	7600 ± 110		–26.9
390	SRR-5739	6715 ± 70	7566 ± 98	–25.0
407	OZB-258U†	8580 ± 220		–26.9
430	SRR-5740	8435 ± 85	9371 ± 165	–27.2
433	AA-21852†	9450 ± 110	10,599 ± 320	–26.6

*Stuiver and Reimer 1983
†AMS date

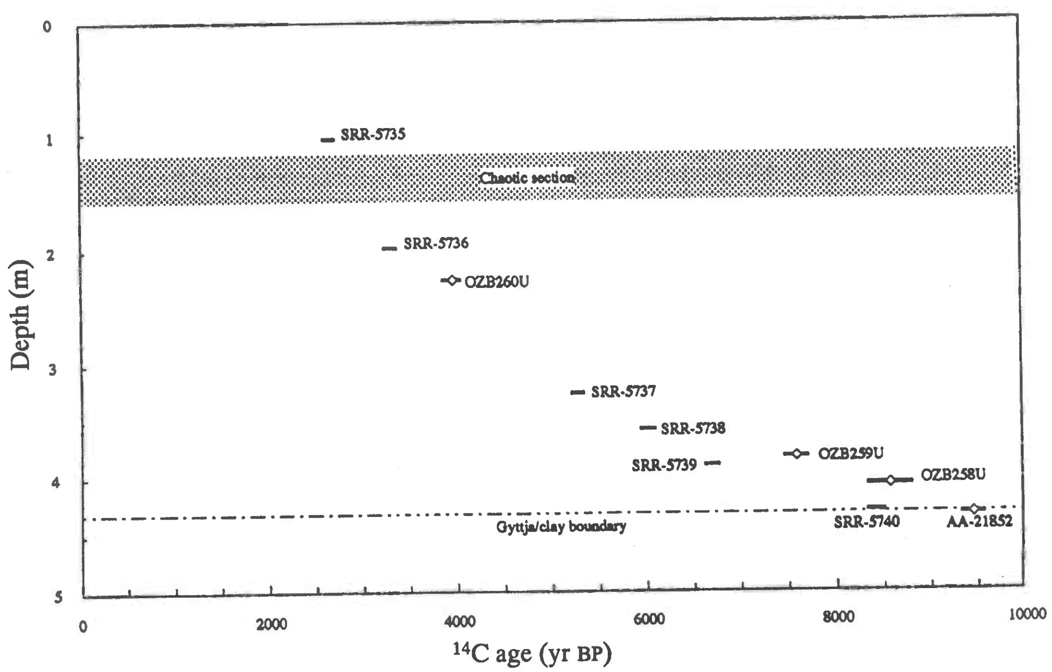

Fig. 4. Results of radiometric and AMS ^{14}C dating of Loch Ness Core 3

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Lamination "Chronology"

Figure 5 illustrates a time-depth relationship for Core 3 compiled from lamination counts. The curve is based on the assumption that the finer of the two sets of laminae present in the cores are varves, and that they therefore represent calendar years. Also plotted on the same diagram are the ^{14}C dates converted to calendar years by means of the Stuiver/Pearson calibration curve (Stuiver and Reimer 1993). As may be seen, a reasonable correspondence between the two sets of the data is obtained. An hypothesis was therefore developed that Core 3 contains a "floating" lamination chronology spanning the 11th to the 2nd calendar millennium BP.

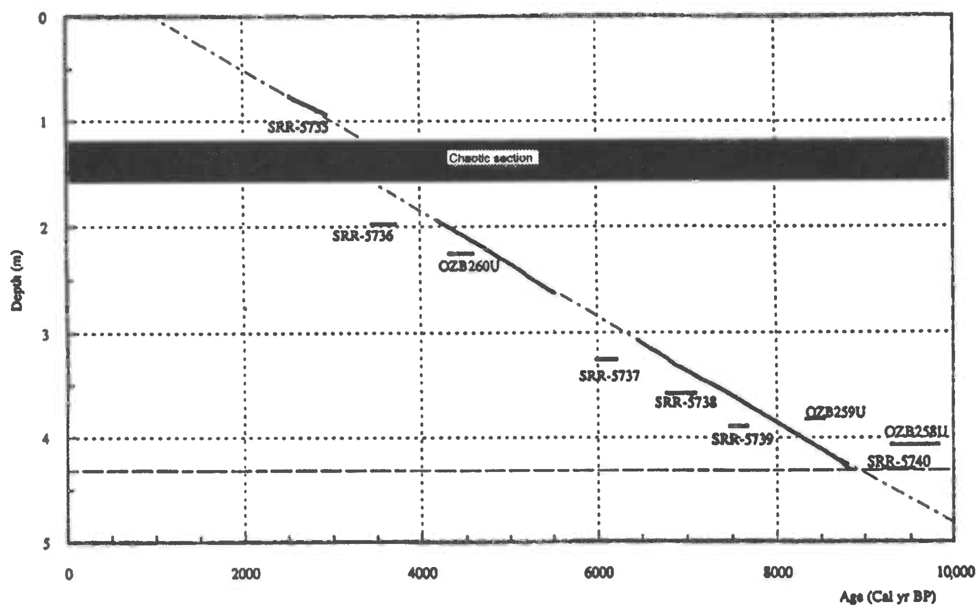

Fig. 5. Time-depth relationship for Loch Ness Core 3 based on lamination counts compared to calibrated ^{14}C dates (calendar years)

DISCUSSION

Results of ^{14}C Dating

Uncalibrated Dates

In terms of ^{14}C years (Fig. 4), the radiometric "bulk" determinations are somewhat younger than the AMS dates, except for OZB-260U (4000 ± 90 BP), which is quite close to SRR-5736 (3350 ± 60 BP) some 28 cm further up the core. The differences between the two sets of dates are partly explicable in terms of pretreatment. From the samples AMS-dated at ANSTO (OZB-258–260U), one alkali-soluble component, as well as two acid-soluble fractions (one before, one after alkali treatment), were removed. In contrast, the SRR dates (5735–5740) were performed on material pretreated only with acid. Therefore, they still contained, *e.g.*, humic compounds, which tend to give younger dates than some other fractions. AMS date AA-21852 (9450 ± 110 BP) is also slightly older than the radiometric dates, but was also carried out on material from which alkali-soluble compounds had not been removed.

One radiometric date (SRR-5735; 2730 ± 50 BP) is older than would be predicted from the rest of the data. However, this sample is located in that part of the core well above the horizons that denote the beginnings of human occupation of the catchment of Loch Ness, and may therefore be subject to the influence of radiometrically "old" carbon, washed in as a result of soil erosion. The ^{14}C dates as a whole, however, serve their intended strategic purpose quite well, in that they clearly demonstrate that the time interval occupied by the core spans some seven millennia, which is approximately the same as that predicted by the hypothesis that the fine laminae found within the sediments are indeed varves.

Calibrated Dates

In Figure 5, we depict the calibrated dates plotted against a time-depth curve for Loch Ness Core 3 compiled by lamination counting. This chronology by itself is floating, but when compared with the calibrated dates, it is clear that the total of pairs of fine laminae present in the core matches the number of calendar years quite closely, especially when we allow for the slumped zone that occurs in sediments dating from *ca.* 3000 ^{14}C yr ago. We therefore feel confident at present that the laminae we are are using to compile this chronology are indeed varves. For the moment, then, our hypothesis is accepted.

However, the slope of the curve in Figure 5 is obtained by assuming that the accumulation rate of the sediment remains uniform throughout the core, including the upper part (*i.e.*, that the line passes through the origin). This assumption may not be justified, and indeed, evidence from the accumulation rate of an adjacent short (< 1 m) core determined using ^{210}Pb (Jones *et al.* 1997) suggests that sedimentation rates in the Loch have accelerated during the later Holocene. When we have obtained more data, especially regarding the section between the top of the long cores (which, according to lamination counting, dates from *ca.* 1500 cal BP), and the bottom of the short cores we have studied (not discussed here; *ca.* 700 cal BP), we may be able to adjust the slope of this line to obtain a better fit to the calibrated ^{14}C dates.

Table 3 compares selected dates from this investigation obtained by lamination counting with those for regional pollen-zone boundaries as defined by Pennington *et al.* (1972). As can be seen, there is quite good agreement between the observed and the predicted dates, again corroborating the hypothesis that the laminae constitute varves.

TABLE 3. Comparison Between Selected Calibrated ^{14}C Dates from Loch Ness Core 3, and Dates of Regional Pollen Zone Boundaries as Defined by Pennington *et al.* (1972)

Horizon	Boundary age (cal BP)*	This study (cal BP) (Core 3)	Depth (Core 3, m)
Ulmus decline	5000	5100	3.25
Alnus rational limit	6500	7200	3.75
Pinus rational limit	8000	8100	4.20
Corylus + *Myrica* expansion	9000	8800	4.30

*Following Pennington *et al.* (1972)

Comparison with Proxy Data (Regional Pollen Diagrams)

Figure 6 represents a preliminary pollen analysis of Loch Ness Core 3 by S. M. Peglar. The samples are quite widely spaced, but depict a sequence of vegetation change consistent with what is already known of the forest history of the first seven millennia of the Holocene for that part of the Scottish

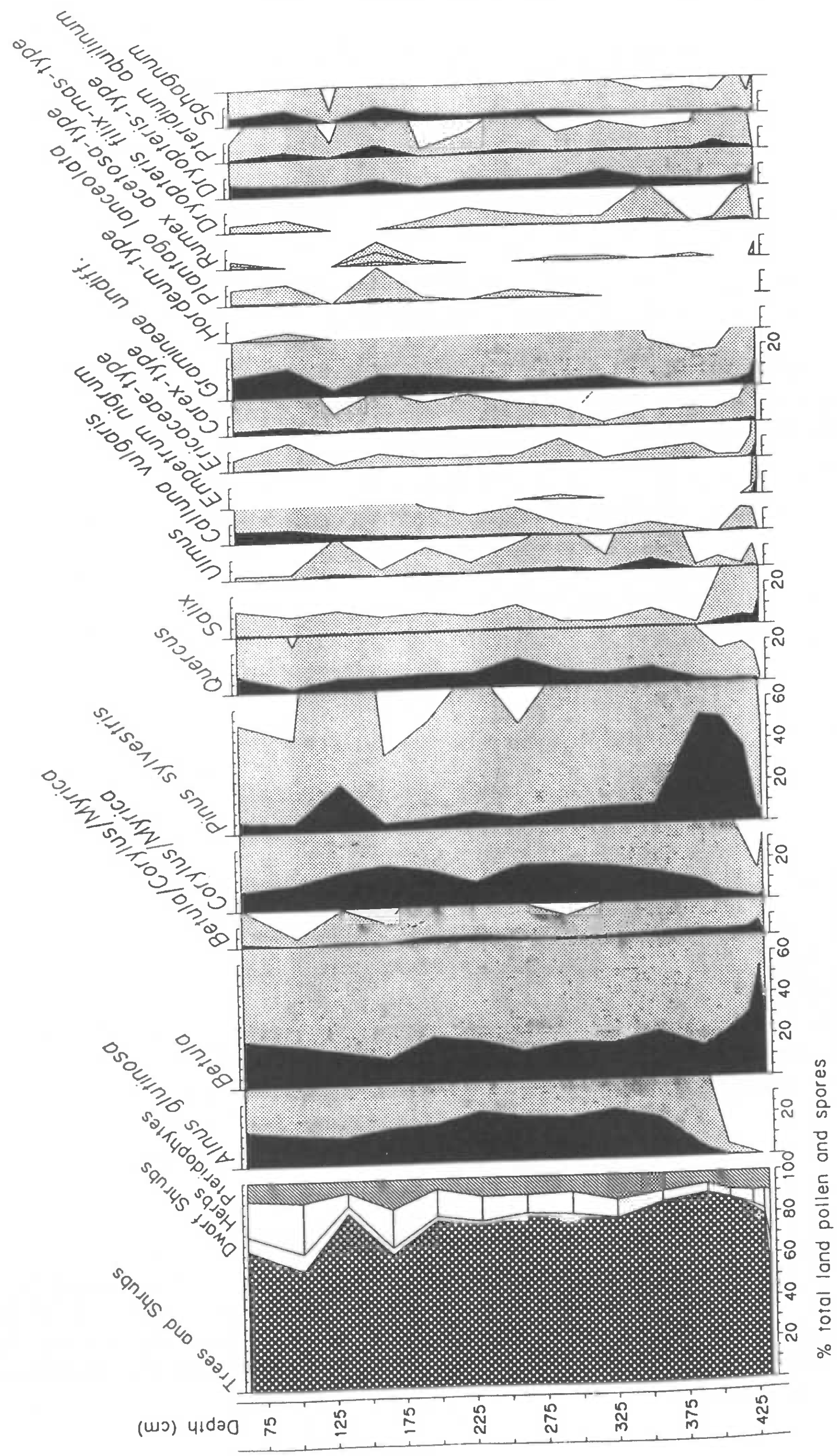

Fig. 6. Preliminary pollen diagram from Loch Ness Core 3 (S.M.P.)

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Highlands containing the drainage basin of Loch Ness, and adjacent areas (Bennett 1995; O'Sullivan 1977). The diagram shows that at the beginning of the Holocene, the catchment of Loch Ness was inhabited by relatively open vegetation, characterized especially by trees such as birch (*Betula* spp.), hazel (*Corylus avellana* L.) and willow (*Salix* spp.), along with shrubs such as juniper (*Juniperus communis* L.), dwarf shrubs such as crowberry (*Empetrum nigrum* L.), and many herbaceous taxa such as *Armeria* and *Artemisia*. The area was then colonized by the Scots pine (*Pinus sylvestris* L.), which invaded the region during the period 9600 to *ca.* 8000 cal BP. Some shrub, dwarf shrub and herbaceous taxa decline in the record, but others (*e.g., Calluna vulgaris* (L.) Hull., *Carex* spp., *Filipendula* sp., Rosaceae, *Dryopteris* spp., *Pteridium aquilinium* L.) persist or even expand slightly.

Expansion of pine was then followed (after 7800 BP) by that of alder (*Alnus glutinosa* (L.) Gaertn.), oak (*Quercus* spp.) and elm (*Ulmus* spp.). Shrubs such as willow and juniper declined. Then, at *ca.* 225 cm, values of *Ulmus* pollen decline, as do those of *Quercus*, even though this horizon probably corresponds to the classic elm decline. The pollen of various shrub, heathland and herbaceous taxa (*e.g., Juniperus, Calluna, Plantago lanceolata, Rumex acetosa*) expand, suggesting slight opening of the forests, or formation of limited clearings.

After 2500 BP, tree pollen declines slightly in the record, and moorland and mire spore and pollen taxa such as *Calluna*, Gramineae, *Carex*, and *Sphagnum* expand. These changes suggest not only the opening of the forests, but also renewed podsolization, or even the beginnings of peat development in catchment soils. A similar study of Core 4 carried out at Plymouth by N. M. Matthews records a similar sequence, but indicates that more recent vegetation changes than those found in the uppermost sections of Core 3 may be present.

Sediment Trap Studies

Data collected by R. I. Jones and A. J. Shine by trapping seston in the water column of Loch Ness (Fig. 7) indicates that a major peak in fine material (diameter 200 μm) entering the Loch occurs between November and March, coinciding with the annual maximum of precipitation, and also with annual snowmelt. This result applies equally to material trapped at 200 m and to that recovered at much shallower depths. Thus, despite its small size, such material is conveyed sufficiently rapidly to the bottom of the Loch to produce seasonal variations in both deposition rates and sediment quality.

On the basis of these findings, and the results of the X-ray and BSEM studies, a slightly more elaborate hypothesis can now be put forward, *viz.* that the paler, more silty laminations deficient in diatoms represent sediments laid down during winter, and the darker, more clay-rich laminae, in which they are somewhat more abundant, the rest of the year. This hypothesis implies that the finer of the two sets of laminations present in the sediments of Loch Ness constitute clastic varves (*sensu* Sturm 1979; O'Sullivan 1983), with the less abundant, thicker laminae recording floods.

Future work

Chronological Studies

In order to complete the chronology from the sediments of Loch Ness, it will be necessary to recover sediments dating from the period *ca.* 700–1500 cal BP. This interval represents the gap between the base of various short cores <1 m in length already studied (*e.g.,* Jones *et al.* 1997), and the top of long Cores 3 and 4. The exercise, then, probably requires the recovery of cores *ca.* 2 m in length, but also containing surface or near-surface sediments. If we can close that gap, then the varve chronology may be completed.

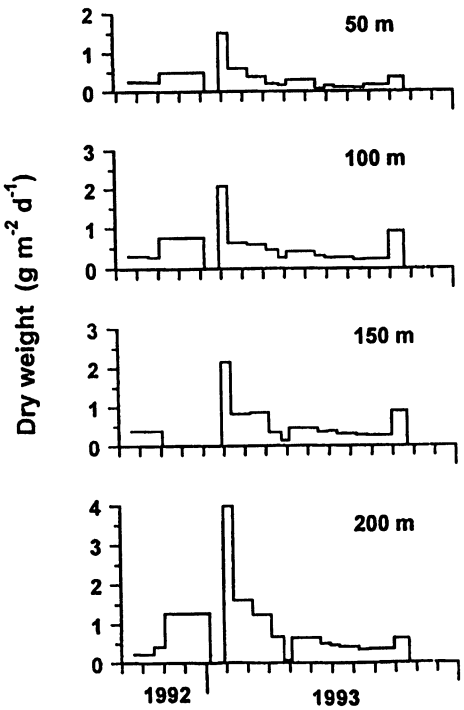

Fig. 7. Results of trapping of seston in the water column of Loch Ness, 1992–1993 (data by R.I.J. and A.J.S.).

Calibration

We can then proceed with the next stage of the chronological parts of the Loch Ness study, examining which fraction or fractions of the carbon present in the sediments give ^{14}C dates that are closest to the "true" calendar (*i.e.*, varve) age (O'Sullivan 1994). For this purpose, it will be necessary to discriminate between organic carbon synthesized in the terrestrial environment, and that originating in the water column, using, for example, chain length of respective molecules, carbon preference index, and maybe $\delta^{13}C$. To this end, it will be possible to take advantage of recent methodological advances in organic geochemistry, including identification of compounds specific to diatoms (Wraige *et al.* 1997), and of ^{14}C dating of individual compounds (O'Sullivan 1994; Eglinton 1998).

Palaeoclimatic Studies

The signal of lamination *thickness* in the sediments of Loch Ness is currently being compared with other sets of palaeoenvironmental data, especially certain palaeoclimatic indices (Cooper 1998b). These include the local instrumental record of precipitation and river discharge, various dendrochronologies (*e.g.*, the German and Belfast oak chronologies and a local chronology from the Scottish Highlands), data on sunspot frequency and number, and the Holocene record of $\delta^{18}O$ and $\delta^{14}C$. The data have also been analyzed for power spectra, by means of Fast Fourier transformation (FFT). Statistically significant correlations exist between thickness of individual pairs of laminations, local precipitation records from 1890 onwards, and annual sunspot frequency, especially for the period 1750 to the present. Episodes of change in thickness of varves may also be identified that appear to

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correlate with well-documented climatic phenomena such as the Little Ice Age, and with other events recorded both in local tree ring series and in the German oak chronology.

Gray level in Core 3 appears to vary directly with $\delta^{18}O$ for the Holocene, but inversely with $\delta^{14}C$. Periodicities in the data, tentatively identified by FFT analysis, appear also to correspond with well-documented indices such as the sunspot and double sunspot cycle. However, other signals are also seen which at present we cannot attribute to any known climatic series.

If generated by the incidence of winter floods, the formation and thickness of varves in the sediments of Loch Ness may be related to seasonal amounts of precipitation over its catchment. Clearly such effects are likely also to be associated with variations in sunspot frequency, and with changes in the mean position of the polar atmospheric front over the Eastern North Atlantic. These topics are therefore currently being investigated further.

Conclusion

1. ^{14}C dating of selected horizons from Loch Ness Core 3 indicates that the 4.5-m laminated section represents the period *ca.* 10,600 to *ca.* 1500 cal BP.
2. Counting of sediment laminae in the same section shows that sufficient pairs of fine (0.25–0.5 mm) laminations exist for the hypothesis to be put forward that they are clastic varves.
3. A preliminary pollen diagram from the same core records a sequence of vegetation history similar to that well documented for the first seven millennia of the Holocene of northern Scotland. This sequence is repeated in Core 4.
4. The cause of varve formation at present appears to be regular flooding, which is consistent with observations of changing abundance of suspended matter in the Loch, which exhibits pronounced seasonality, with a February maximum.
5. On the basis of their structure, minerogenic composition, and microfossil content, the fine, regular laminae in the sediments of the north basin of Loch Ness are believed to be clastic varves, with paler, siltier layers representing late winter and spring, when flooding occurs in the catchment of the Loch, and clay-rich laminae the rest of the year. Sporadic, thicker layers record major floods, as seems clear from their composition and internal physical structure.
6. Future detailed studies of these sediments will be used for the purposes of further development of the chronology, for calibration studies of ^{14}C dating of lake sediments, and for investigation of Holocene climatic variability of the Eastern North Atlantic.

Acknowledgments

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