

**DISPLAY
ONLY**

ISSN 1366-7300



**ENVIRONMENTAL CHANGE
RESEARCH CENTRE**

University College London

RESEARCH REPORT

No. 23

**Proxy records of climatic change in the UK over the
last two millenia**

**R.W. Battarbee, K.E. Barber, F. Oldfield, R. Thompson,
A.C. Stevenson, G. Eglinton, E.Y. Haworth, S.J. Brooks,
J. Holmes, N.G. Cameron, N.L. Rose & D. Maddy**

Final Report for NERC Special Topic Grant: GST/02/701

April 1996

**Environmental Change Research Centre
University College London
26 Bedford Way
London
WC1H 0AP**

TIGGER IIa FINAL REPORT
April 1996

PROXY RECORDS OF CLIMATE CHANGE IN THE UK OVER
THE LAST TWO MILLENIA

A NERC SPECIAL TOPIC GRANT : GST /02/701

Principal Investigators:

Rick Battarbee, UCL (joint co-ordinator)
Keith Barber, Southampton (joint co-ordinator)
Frank Oldfield, Liverpool
Roy Thompson, Edinburgh
Tony Stevenson, Newcastle
Geoff Eglinton, Bristol
Liz Haworth, IFE Windermere
Steve Brooks, NHM London

Sub-project leaders and co-workers:

Nigel Cameron, UCL
Neil Rose, UCL
Jonathan Holmes, Kingston
Roger Hutchinson, Edinburgh
Bill Austin, Edinburgh
Rob Stoneman, Southampton
Darrel Maddy, Southampton
Paul Golding, UCL
Kath Ficken, Bristol
Doug Harkness, East Kilbride
Peter Appleby, Liverpool
Jean Lishman, Windermere
D.P. Hewitt, Windermere
Clive Pinder, Monks Wood
D. Leach, Monks Wood

Executive Summary

The TIGGER 2a (last 2000 years) project has established an instrumental record of temperature for Edinburgh back to 1764 that shows an overall warming trend of 0.5°C and a period of more oceanic climate in the 1920s. Comparison with records from other stations show that temperature, but not precipitation records are spatially coherent. In addition several lines of proxy evidence have indicated:

- (i) cool, wet decades between 1700-1850 AD (from peats);
- (ii) cooler conditions (from diatoms) and more storminess (from rock magnetism) during the Little Ice Age, and
- (iii) temperature cycling (from organic matter, diatoms and chironomids) on a periodicity of approximately 200 years over the last 4000 years.

Key aspects of methodological progress include:

- (i) stable isotope analysis (^{18}O , ^{13}C) of ostracod shells from lowland marl lake sediments;
- (ii) confirmation of humification and macrofossil analysis as valid proxy-climate signals from both lowland and montane peats, and the linkage of the signals using ordination methods;
- (iii) use of high resolution analysis of lowland lake sediments for comparison with plankton and weather records;
- (iv) use of diatoms and chironomids as indirect and direct indicators respectively of past temperature;
- (v) use of remote mountain lakes to obtain sediment records free from human impact;
- (vi) development of techniques for tephra analysis of lake sediments and as a method for chrono-stratigraphic correlation between lake and bog sequences.

Introduction

1. Importance of the last 2000 year record

It can be argued that climate records of the recent past (last 2000 years) are the most relevant to the immediate problem of future climate change as they deal with:

- (i) decadal to century time-scale studies of natural climate variability;
- (ii) similar natural environments; and
- (iii) issues of enhanced greenhouse effect detection.

Moreover, this period is methodologically important for palaeoclimatologists as climate changes over the last few hundred years are quite well known from independent instrumental and documentary records. This allows:

- (i) the sensitivity of proxy methods of climate reconstruction to be tested; and
- (ii) the validation of transfer functions against instrumental records.

2. Potential difficulties

Despite the attractiveness and relevance of this time period, there are a number of key difficulties that are encountered in a search for climate signals from sediment records:

- (i) compared with glacial-interglacial transitions the amplitude of climate change is small (c. 0.5°C): methods need to be very sensitive;
- (ii) in north-west Europe many of climate-change signals potentially recorded by sediments are confused or obscured by stronger human impacts: sites and methods need to be chosen very carefully;
- (iii) parts of the period are difficult to date accurately;
- (iv) it is a period for which there are few or no prior palaeoclimate research studies in the UK, or elsewhere to build on.

3. Aims of the project

- (i) to review, improve and extend instrumental records of climate change for upland Britain;
- (ii) to determine which methods (microfossil, isotope, physical etc) at which sites (montane lake, marl lake, raised bog, montane bog) gives the least ambiguous signal over this time period;

(iii) to explore the possibility of improving chronology for this period;

(iv) to attempt to link sequences between sites using tephra and other chronological techniques, and to use tephra to link to tree-ring time series (this latter element was not funded).

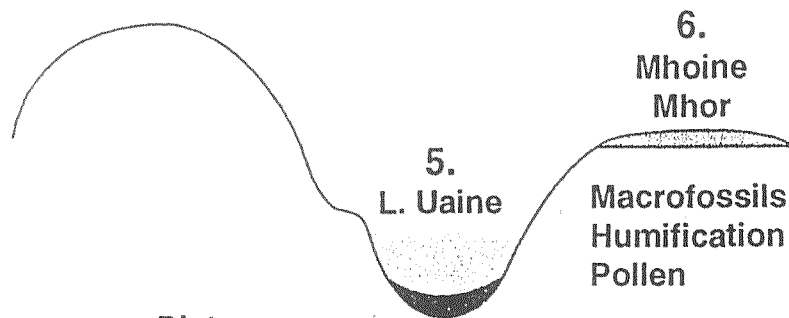
Field sites included in the project (Figure 1) are located in the Scottish Cairngorms, Northern Ireland and the English Lake District, and these are the subject of five of the sub-projects. Other sub-projects are concerned with instrumental records and with tephrochronology.

Results are presented by sub-project, and the colour diagram attempts to show how the various sub-projects, sites and methods are related.

Tigger IIa

Site Types and Techniques

Montane lakes and bogs



Diatoms
Chironomids
Particle size
Magnetics
 ^{210}Pb , ^{241}Am , ^{137}Cs , AMS ^{14}C , Tephra

Lowland lakes and bogs



Ostracods (^{18}O , ^{13}C)
Magnetics
Pollen

Macrofossils
Humification
Tephra, AMS ^{14}C
Pollen

7. Windermere - Diatoms
Cladocera
Plankton records

links to:
2. tree ring data
1. instrumental record
8. tephra

Sub-projects

1. Historical climate records (Project leader, Roy Thompson)

Aim: to improve the long Edinburgh temperature series, and to analyse other British instrumental records for temperature and precipitation, and to make comparisons between them.

Approach: splicing, homogenisation and time series analysis of raw data; use of filtering techniques to identify patterns in records and to assess spatial and temporal coherence of temperature and precipitation records between sites.

Results and Conclusions:

(i) **time series analysis** of instrumental data shows clear 6 month and 1 year cycles, but no longer strictly periodic cycles;

(iii) **The Edinburgh temperature series** has been homogenised back to 1764: it shows a 0.5°C warming (Figure 2), and a clear change in continentality with the 1920s being more oceanic;

(iv) **comparison with other temperature records** shows that these features are found in Central England (Manley) and the Netherlands (de Bilt) series, showing temperature records have remarkable spatial coherence (Figure 3);

(v) **the longest precipitation record** in Scotland comes from Eallabus (from 1800);

(vi) **comparison with other precipitation records** shows that there is little spatial coherence between them, even those as close as Wick, Gordon Castle and Eallabus within Scotland (Figure 4), making it impossible to build a long homogenised series for precipitation.

Future work

(i) to extend the Scottish temperature record by retrodicting the Edinburgh historical series using longer instrumental and tree-ring records from further away e.g Central England, Switzerland and Sweden.

(ii) to study phase changes associated with the yearly temperature cycle and changes in continentality as a method of identifying the onset of anthropogenic greenhouse gas induced warming.

2. Tree ring records and tephra in Ulster

This part of the project was not funded.

3. Proxy-climate indicators in lowland lake sediments (Project leader, Frank Oldfield)

Aim: to assess the value of stable carbon and oxygen isotopes in ostracod carapaces in lake sediments as proxy climate indicators in relation to historical climate records

Site: Lough-na-Shade in Co. Armagh, a hard-water lake with marly sediments suited to the preservation of carbonate microfossils, and for which a detailed pollen-based study had recently been completed.

Approach: To identify the late 17th - early 18th century section of sediment that spans the period of greatest and most rapid variation in annual to hemi-decadal temperature change within the Manley series using a variety of dating techniques (^{210}Pb , ^{137}Cs , ^{14}C , pollen, tephra); and to pick ostracods for stable oxygen and carbon isotope analysis.

Results:

(i) **Core section dating** using a combination of ^{137}Cs , pollen analysis (rise of pine in the late 18th/early 19th century and the peak of *Cannabis* and *Linum usitatissimum* pollen in the early 18th century) and associated magnetic evidence (greigite peak probably caused by reducing conditions in the lake as a result of flax and hemp retting (Figure 5)).

(ii) **The stable isotope data** (Figure 6) from ostracods show a clear trend in increasingly less negative values of delta ^{18}O possibly showing either increasing air temperature, wetter climate, or reduced water temperature or any combination of these. The considerable scatter at each level where replicate samples have been analysed may reflect seasonal or inter-annual variations in hydrology.

Future work:

(i) improve chronology for the remaining parts of the core using AMS ^{14}C on seeds and tephra where possible;

(ii) extend the isotope analysis for the remaining parts of the core sequence;

(iii) carry out trace element (Mg/Ca and Sr/Ca) determinations on ostracod valves in order to reinforce the interpretation of the stable isotope record;

(iv) compare data with instrumental record, with similar data from other sites (e.g. Little Hawes Water);

(v) calibrate ostracod-isotope relationships from modern sampling and measurements at the site

4. Proxy-climate indicators in raised bogs (Project leader Keith Barber)

Aim: to reconstruct a high-resolution proxy-climate record for the last 2,000 years from a lowland area close to the lake chosen for sub-project 3.

Site: Fallahogy Bog, a large virtually-intact site in the Bann Valley was selected, having the advantage of being the site of previous palaeoenvironmental work by Hall & Pilcher (1992 et seq.).

Methods: Contiguous interval humification and macrofossil analyses. Dating using spheroidal carbonaceous particles (SCP) and pollen / land-use correlations for the recent peat; radiocarbon age estimates and tephrochronology for the older peat; various multivariate analyses.

Chronology: there were problems with the dating of the upper 40cm of peat due to the penetration of bomb ^{14}C . The pollen and SCP counts confirm that the top 30 cms accumulated at 5yrs/cm. The complete profile of 160 cm (FAL 1) covers the last 2,000 years. The radiocarbon date from 145 cm is CAL. AD160 and a distinctive tephra at 86 cm dates to AD860 +/-20.

Results:

(i) The humification profile is driven by bog water level. There is a very significant decline from values touching 50% in the early part of the last 2,000 years, down to lows in the 20-30% range after about AD600. The least humified part of the profile (apart from the fresh surface material) around 35 cm is coincident with the wet period in the macrofossils. The period is in the last part of the Little Ice Age and has very low humification values.

(ii) The macrofossil diagram shows changes between peat components and different *Sphagnum species*. The two wettest periods are pre-Medieval, ca. AD725 - 800 and between AD1685-1845. The extinction of *Sphagnum imbricatum* is dated to Cal AD 1450.

(iii) Detrended Correspondence Analysis (DCA) of the macrofossil data (Figure 7) indicates similar periodicity to that found at Bolton Fell Moss, Cumbria. Severe wet and/or cold conditions are indicated between Cal. AD 1685 - 1845.

(iv) The compound specific $\delta^{13}\text{C}$ data for the n-alkanes isolated from the selected layers show marked consistency and no major shifts. Much further work would be required on matters such as the species signal to evaluate this method fully.

Future work: to improve the chronology with the 10 remaining radiocarbon assays and perform Time Series analyses.

5. Proxy climate indicators in montane lake sediments (Project leader, Nigel Cameron)

Aim: To assess the usefulness of sediments from remote undisturbed mountain lakes in studies of climate change

Site: Lochan Uaine (Cairntoul), Scottish Cairngorm Mts., a soft-water slightly acidified by acid deposition over the last century, but otherwise and for the remainder of the Holocene entirely undisturbed by human impact.

Methods: To use a full range of physical (grain-size, magnetics), chemical (major cations) and biological (diatoms, chironomids, pollen) analyses of contiguous 2mm thick sediment slices to identify possible climate variation, especially changes potentially associated with the Little Ice Age and the Medieval Warm Period. Methods to be assessed were:

- (i) the use of **diatom-pH transfer functions** for mountain lakes to reconstruct possible temperature related variations in alkalinity
- (ii) the use of **chironomid assemblages** as direct temperature indicators
- (iii) the use of **loss on ignition, magnetics, grain size and base cation analysis** as indicators of climate change, especially catchment erosion
- (iv) the use of **tephra analysis** for chronology of lake sediments

Chronology:

- (i) **^{210}Pb dating** showed results in agreement with ^{137}Cs and established an excellent chronology for the last 100 years (top 2 cm), with a constant but very slow sediment accumulation rate of about 0.3 mm yr^{-1} .
- (ii) **AMS ^{14}C dating** of 36 samples were obtained from East Kilbride. Extension of the age-depth curve to the sediment surface, however, suggested that the ^{14}C dates contained an average older age error of about 550 years. A temporary chronology has been established by fitting a quadratic curve to the dates and matching it to the base of the ^{210}Pb chronology (Figure 8).

Results:

- (i) **Loss on ignition** measurements of contiguous 2 mm samples show a series of quasi-periodic cycles of approximately 200 year duration over the last 4000 years (Figure 9). The source and composition of the organic matter is not yet fully understood, but the cycles probably reflect temperature-driven fluctuations in primary productivity.
- (ii) **Analysis of a single cycle** shows that this interpretation is supported by the good correlation between the organic matter content and higher less negative ^{13}C values (data courtesy of Roy Switsur), the higher concentration of chironomid head capsules, and higher diatom-inferred pH values (Figures 10,11).

(iii) Particle grain size analysis also reveals cycles also appear to correlate with the organic matter cycles. However, as almost all particles are diatoms this must reflect cycling in diatoms of different size or systematic variations in diatom breakage, not variations in catchment-derived clastic material (Figure 12).

(iv) The magnetic data are also cyclical, but they have a different, longer periodicity. One of the main features is the striking increase in "hard" IRM in the uppermost 17 cm. This is interpreted as an increase in the concentration of haematite and possibly of an indication of increased catchment erosion during the Little Ice Age (Figure 13).

(v) The diatom data show few major changes in relative abundance throughout the analysed section of the core, except for the uppermost section (top 2 cm) where there is clear evidence of an acid rain effect (Figure 14). This is also apparent from the chironomid data (Figure 15).

(vi) Below this level it is difficult to identify clear patterns. However, diatom-inferred pH values from these data reveal striking cycles that appear to be in phase with the loss on ignition cycles. A swing to lower pH values during what is assumed to be the period of the Little Ice Age (between 10 and 17 cm depth) (Figure 16) is consistent with the hypothesis that pH in mountain lakes is dependent on temperature related alkalinity generation.

(vi) the chironomid study represents the first of its kind in the UK.

(vii) larval head capsules were present in all samples, often in high numbers. However, preservation was often poor, which meant that identification of Tanytarsini even to generic level was not possible in most cases. Other groups were readily identifiable.

(viii) the main chironomid diagram (Figure 15) shows cyclical changes in the chironomid head capsule concentrations that largely follow the loss on ignition cycles.

(ix) a significant change in the chironomid assemblage occurs at 59 cm (ca. 2,200 BC). At this point the cold intolerant taxa, *Microtendipes* and *Heterotanytarsus* decline, indicating a cooling of the climate after this time. However, the change was gradual judging from the progressive increase in the relative abundance of Tanytarsini from 110 cm upwards.

(x) below 110 cm colder conditions than those above 59 cm are suggested by the abundance of Tanytarsini and *Sergentia*, although this conclusion is tentative as the number of head capsules in these samples is very low.

Future work:

(i) organic geochemical and stable carbon isotope analyses are required to identify the main carbon sources in the sediment and to assist in explaining the loss on ignition cycles;

(ii) dating of tephra peaks is needed to improve the chronology;

(iii) analyses of the mineral fraction are required to separate biogenic (diatom and chrysophyte) and abiogenic (catchment clastic) silica fractions

(iv) a chironomid-temperature calibration training set is urgently needed for the UK—to develop a transfer function for temperature reconstruction using chironomids

(v) more detailed studies of the climate changes and patterns apparent from the data e.g. the chironomid change at 59 cm, and the organic matter and diatom cycles are required. Replication of these changes in other Cairngorm corrie lochs would be especially useful.

6. Proxy climate indicators from montane bogs (Project leader, Keith Barber)

Aim: to assess the utility of montane blanket bog as a climatic archive; to produce a proxy-climate record using humification, macrofossil and other analyses from a peat site within a few kilometres of the montane lake, and to compare the record with that of the lowland raised bog.

Site: the high and extensive blanket bog of Moine Mhor is about 6 km west of Lochan Uaine, and represents the largest area of high-level relatively untouched bog in Britain. A water-shedding part of the bog complex was chosen.

Methods: bulk density and humification analyses, followed by plant macrofossil analyses when these were found to be present in abundance. Tephra, SCP and radiocarbon assays for dating.

Chronology: no major problems were encountered with the exception of one "rogue date" in the 1200s which is being checked with the three remaining assays. Fitting a 4th-order polynomial to the 17 dates gave a curve with a R-squared value of 0.98.

Results:

(i) The bulk density and humification profiles show substantial and largely coincident changes, the most recent of which is dated to AD1715-1850. This profile is thought to be representative, test cores showed up the banded nature of the top 25 cm of peat over quite a large area of bog.

(ii) Plant macrofossils in the peat were abundant, unusual for a blanket bog, and the banded upper peat shows abrupt shifts between *Racomitrium* and *Sphagnum* domination. This lasted until very recently when sedge began to replace moss.

(iii) Tephra analyses show three very similar peaks to those found at Fallahogy; the particle size profile of the main layer is identical, possible allowing a direct chronological pinning-point between the two bogs and possible the montane lake. Due to the small size of the shards it was not possible for them to be geochemically typed.

(iv) DCA again demonstrated a striking signal (Figure 17) with the later pulse of the LIA being contemporaneous (within the limits of the dating methods) with that at Fallahogy.

Future work: to improve the chronology with the 3 remaining radiocarbon assays and perform Time Series analyses.

7. High resolution plankton records from Windermere sediments (Project leader, Liz Haworth)

Aim: To assess the extent to which plankton changes for Windermere over the last 40 years are faithfully recorded in the sediments, and to relate those changes to weather patterns, especially temperature and windiness.

Approach: High resolution analysis of a core from the north basin of Windermere for cladocera and diatoms, sequence slotting between plankton records and sediment records, comparison with local weather records.

Results and conclusions:

(i) Comparisons between the plankton records and the sediment record show a relatively poor relationship between cladocerans, but an excellent relationship between diatoms. Not only does the succession relating to lake eutrophication show clearly but the underlying year to year changes in the various populations also show through (Figure 18). Various factors dictate species success or failure and the eventual fate of the very high population of *Aulacoseira subarctica* following the 1967 Langdale flood can be clearly seen within a 1 cm horizon of sediment. Most taxa show distinct cycles of change within the record.

(ii) Computed slot sequencing between the algal records and sediment diatom records shows that the sediments can be dated from the algal history with a +/- 3 year accuracy or even better.

(iii) ^{210}Pb dating and the dates derived from algal history are in excellent agreement;

(iv) These data show that sediment mixing is limited and that the Windermere sediment is suited to high resolution analysis;

(v) Weather records include a series of datasets within which several long-term trends have been observed, notably the decline in late summer sunshine and increase in winter precipitation. So far algal changes have not been related to any clearly identified seasonal changes in averaged datasets.

Future work:

(i) Within the precise stratigraphic record of Windermere it is now necessary to seek the signature of the recent climatic extremes of warmer waters and very low flow. Such a signature could then be used to identify similar events in earlier periods for which there are no documentary records.

8. Tephra analysis (Project leader, Neil Rose)

Aim: to develop a new method for extracting and enumerating tephra shards from lake sediments, to apply the method to Lochan Uaine and Lough-na-Shade sediments and to correlate tephra peaks between lake and peat sediments.

Approach: to remove selectively by chemical digestion organic, biogenic silica and carbonate fractions of lake sediments and prepare microscope slides for shard counting, to characterise shards according to size and chemistry, and where possible to relate tephra peaks to known volcanic eruptions.

Results:

(i) a new method for **tephra extraction** from lake sediments has been developed successfully, and is now in press in *The Holocene* (copy attached);

(ii) a detailed **tephra diagram** has been produced for the Lochan Uaine core (Figure 19). Tephra occurs in most samples, but there are two main peaks. The upper peak has the same size distribution of shards as the main peaks in the peat sequences from Fallahogy and Moine Mhor (Figures 20, 21), but these are different from the size distribution in the lower peak.

(iii) the shards in the upper peak, and in the peat sequences are too small for ion microprobe analysis. The larger shards in the lower peak have been submitted for microprobe analysis, and may represent Hekla 4 (c. 2300 BC). Confirmation of this will help to calibrate the radiometric dating.

(iv) the Cairngorm data represent the first potential tephra correlation between adjacent peat and lake sediment sequences.

(v) tephra were not found at the Lough-na-shade site although only a small section of sediment, possibly not containing tephra, was selected for study.

Future work:

(i) need to develop characterisation techniques for small shards;

(ii) need to explain the complex stratigraphic distribution of shards in relation to primary material from volcanic sources and reworked or resuspended material within the lake and its catchment;

(iii) need to make further correlations between lake sites and peat sequences to establish a regional framework for core correlation, and to contribute to the development of a tephrochronology for the UK as a whole;

(iv) need, with other researchers, to determine the geographical extent, especially the southern limits.

Conclusions and Recommendations

1. Historical and proxy climate methods

(i) Homogenisation techniques can allow long-time series of instrumental records to be built for temperature by combining data from different stations. However, this approach is not appropriate for precipitation as precipitation records are not spatially coherent

(ii) Stable isotope analysis of ostracod valves preserved in marl lake sediments is a potentially powerful means of climate reconstruction, although detailed work on the relationships between climate variables and the stable isotope geochemistry of lakewaters in the UK is urgently needed.

(iii) A Climate Response Model (CRM) was developed as part of previous work at Bolton Fell Moss, Cumbria, where excellent dating control was available. With the solution of the dating problems referred to earlier it should be possible to develop CRMs for both of these sites, with the prospect of at least regional climatic records. There are also indications of periodicity in the DCA data, as has been found in previous work, and a more secure chronology will allow time series analysis.

(iv) Both bog sites demonstrate striking changes in response to climatic forcing over the last 2,000 years. Within the uppermost peat the most dramatic change, especially well shown on the DCA axis 1 plots, is synchronous between the two bogs and of a similar magnitude - it must represent change driven by the climate of the period AD1700 - 1850, and can therefore be related to the instrumental record and other proxy-data.

(v) In the absence of catchment disturbance or eutrophication from anthropogenic causes, the loss on ignition record of lake sediments is an extremely simple but powerful proxy climate indicator. In remote mountain lakes it is hypothesised that primary productivity (organic matter generation) is controlled by the length of the ice-free season that in turn is controlled by temperature.

(vi) Also, in the absence of human disturbance of the catchment, erosion indicators in the sediment, especially rock magnetic records and base cation profiles, may indicate changes in erosion intensity associated with the frequency and magnitude of storms.

(vii) In low alkalinity lakes diatoms can be very sensitive indicators of temperature change, not directly, but indirectly according to the relationship between temperature, in-lake alkalinity generating processes and pH. Consequently the climate signals are best revealed using diatom-pH transfer functions.

(viii) Chironomids are also sensitive to temperature change and, if appropriate modern training sets are available, can be used to reconstruct temperature directly. Moreover the relationship between chironomid head capsule concentration and organic matter shown in the Lochan Uaine study suggests that chironomid abundance may also be correlated to temperature.

2. Chronology

(i) Radiocarbon dating appears to perform extremely well when applied to ombrotrophic mire samples. However, the dates from Lochan Uaine confirm that it is less reliable when applied to lake sediments, even sediments where there is no hard-water effect and where there is no evidence of catchment soil or peat erosion.

(ii) ^{210}Pb dating performed perfectly well on the Lochan Uaine and Windermere cores, but was of little value for the Lough-na-Shade core. The reason for this is not fully understood.

(iii) For this time period pollen analysis can be a very useful method for dating, where distinctive changes in pollen diagrams can be clearly related to known historical vegetation changes.

(iv) The most important chronological advance of this project has been the development of a tephra extraction technique for lake sediments to complement existing methods for peats. If a tephrochronology for the British uplands can be worked out, tephra can be used not only to calibrate other dates at a site, but also be used to correlate stratigraphic sequences between lakes and bogs and between regions. Accurate correlations with tree-ring and instrumental series should then also become possible.

(v) Spheroidal carbonaceous particle analysis has been used extensively as a technique for dating recent lake sediments. This study has also confirmed its use as a technique for dating recent peats.

3. Sites

(i) The sediments of marl lakes have great potential for climate change studies as they almost always contain well preserved assemblages of ostracods, whose valves can be used for stable isotope analysis. Marl lakes are quite abundant in Britain and Ireland, and studies of the kind begun at Lough-na-shade could be usefully replicated at other sites. A key problem is the difficulty of dating marl sediments over the Holocene period using conventional methods. Again tephrochronology probably represents the most promising way forward.

(ii) Unfortunately lowland sites with high sediment accumulation rates and, in some cases, laminated sediments have catchments that are usually strongly disturbed by human influence and in many respects are inappropriate for climate change studies. However, data from Windermere suggest that variations in weather patterns do exert an influence on the plankton populations and that evidence for such relationships are potentially preserved in the sediments.

(iii) the Lochan Uaine results suggest that remote mountain lakes are excellent sites for climate change research. Although they have low sediment accumulation rates, the sediment does not suffer from bioturbation and high resolution analyses are possible if sampling is carried out at fine intervals (e.g. 2 mm).

(iv) The linking via DCA of the records of bogs 300 km apart, with a 900m difference in altitude, and with different species composition, in such a direct and convincing way is a

great advance. The implications of this are far-reaching and reinforce the view that the remaining raised and blanket bogs of Britain and Ireland contain a valuable archive of past climates covering at least half of Holocene time. The analysis of contiguous 0.5 - 1 cm samples gives a high-resolution record of the last 2,000 and more years. More blanket bogs, particularly at high altitudes, may contain contain countable plant macrofossils than has hitherto been thought.

4. Climate

Although this project was primarily concerned with developing methods and ideas a number of climate change features have been revealed:

- (i) the instrumental temperature records show a 0.5°C warming trend over the last 200 year;
- (ii) temperature records, but not precipitation records, are similar between stations. This conclusion suggests it may be more effective to focus on proxy temperature rather than proxy precipitation techniques when developing new proxy climate methods;
- (iii) the 1920s was a period of more oceanic climate;
- (iv) most of the proxy data support the idea of a Little Ice Age, the magnetic record at Lochan Uaine suggests there was an increase in catchment erosion, the diatom record suggests water pH values were lower.
- (v) Both the lowland raised bog and the montane blanket bog demonstrate a clear proxy-climate signal, with many similarities between the changes in the DCA plots, some of them synchronous within the limits of the dating models. The cool wet decades between ca. AD 1700 and 1850 show up very well, as they do in many other bog sites, and there appears to be some similarities in the records since AD 1850; in the period prior to AD 1700; AD 860 (tephra-dated), and before AD 725. The relatively wet conditions on Moine Mhor between AD 1020 and 1290 is unexpected and may point to cooler conditions during Medieval times compared to the lowland record.
- (vi) the loss on ignition data from Lochan Uaine indicate that there has been many low amplitude cycles in temperature over the last 4000 years with a mean periodicity of about 200 years;
- (vii) the chironomid data from Lochan Uaine indicate a period of gradual cooling at the end of the Bronze Age

5. Recommendations

- (i) the continued development of calibration techniques to allow better quantification of the climate record;
- (ii) an improved understanding of bog and lake responses to climate variability, including the

development of appropriate dynamic models;

(iii) development of chronological methods needed to produce more accurate dates, to allow correlation between sites and to allow comparisons with tree-ring and instrumental records;

(iv) to generate climate reconstruction from physico-chemical proxy methods so that the fossil record can be used independently to assess the biological response of ecosystems to climate change;

(v) a major effort to expand the number of proxy-climate records from raised and blanket bogs, since it is clear that a strong signal exists, over and above any "ecological noise", and that this could give a framework for natural climate change over a greater part of the Holocene.

(vi) replication of the Lochan Uaine study at other mountain sites to assess the extent or "availability" of such excellent sites in the UK.

(vii) to integrate these approaches and researchers and develop a coherent multi-proxy approach to climate variability studies during the Holocene in Britain.

Contribution to wealth creation and quality of life

Climate records of the recent past (last 2000 years) are the most relevant to the immediate problem of future climate change as they deal with:

- (i) decadal to century time-scale studies of natural climate variability;
- (ii) similar natural environments; and
- (iii) issues of enhanced greenhouse effect detection.

This project so far has shown that significant natural changes in British climate have taken place over the last two millenia, but that there is no evidence, as yet, that anthropogenic influences on climate have caused changes beyond the range of those that might be expected from natural variations.

TIGGER IIa

Last Two Millenia

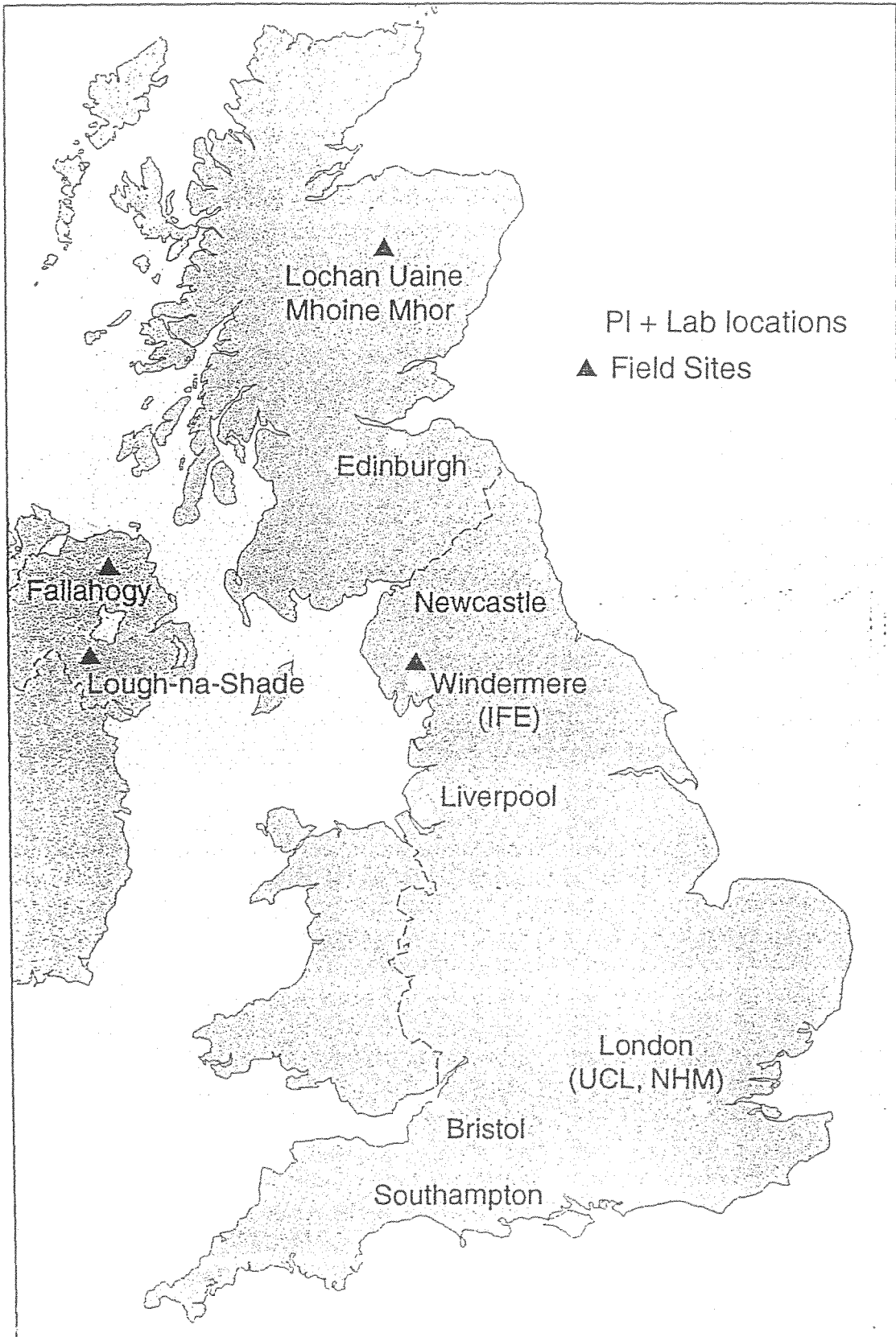
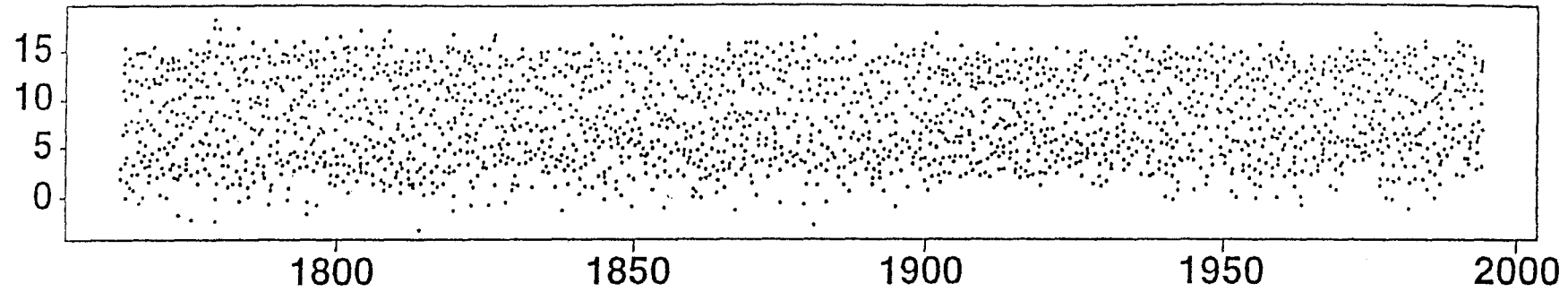
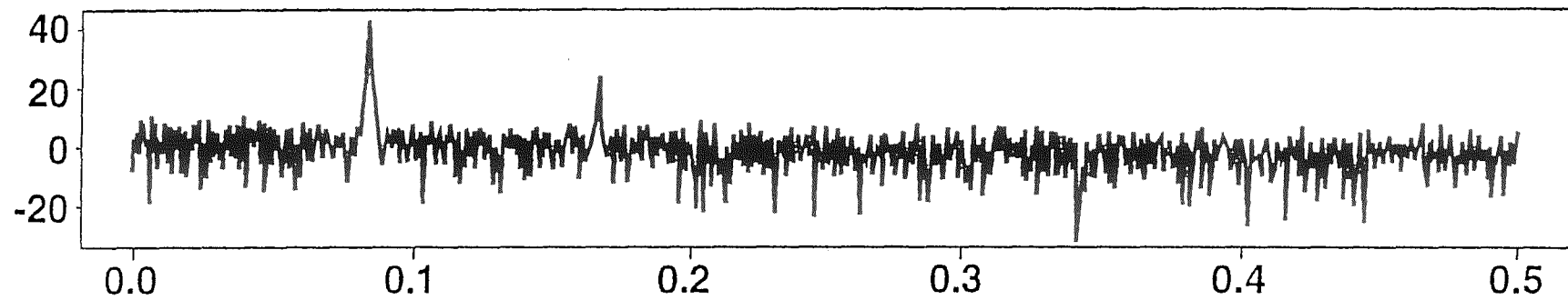


Figure 1

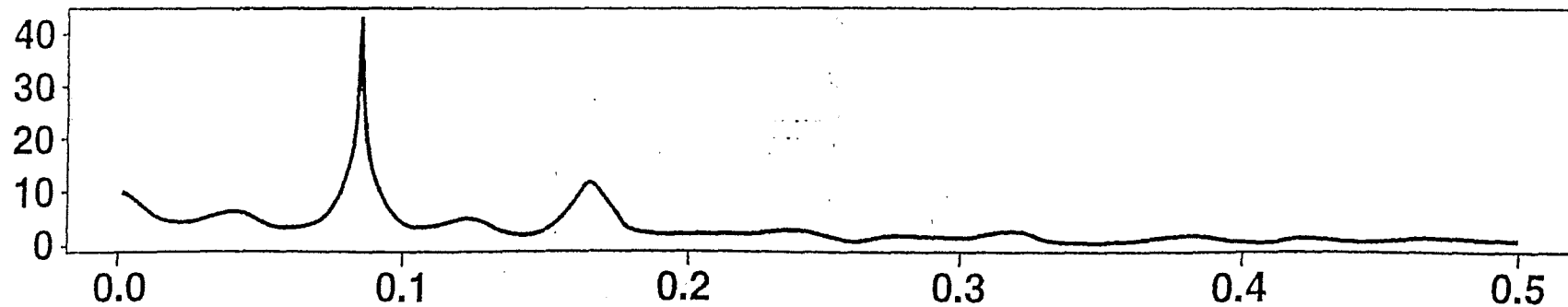
Edinburgh Series



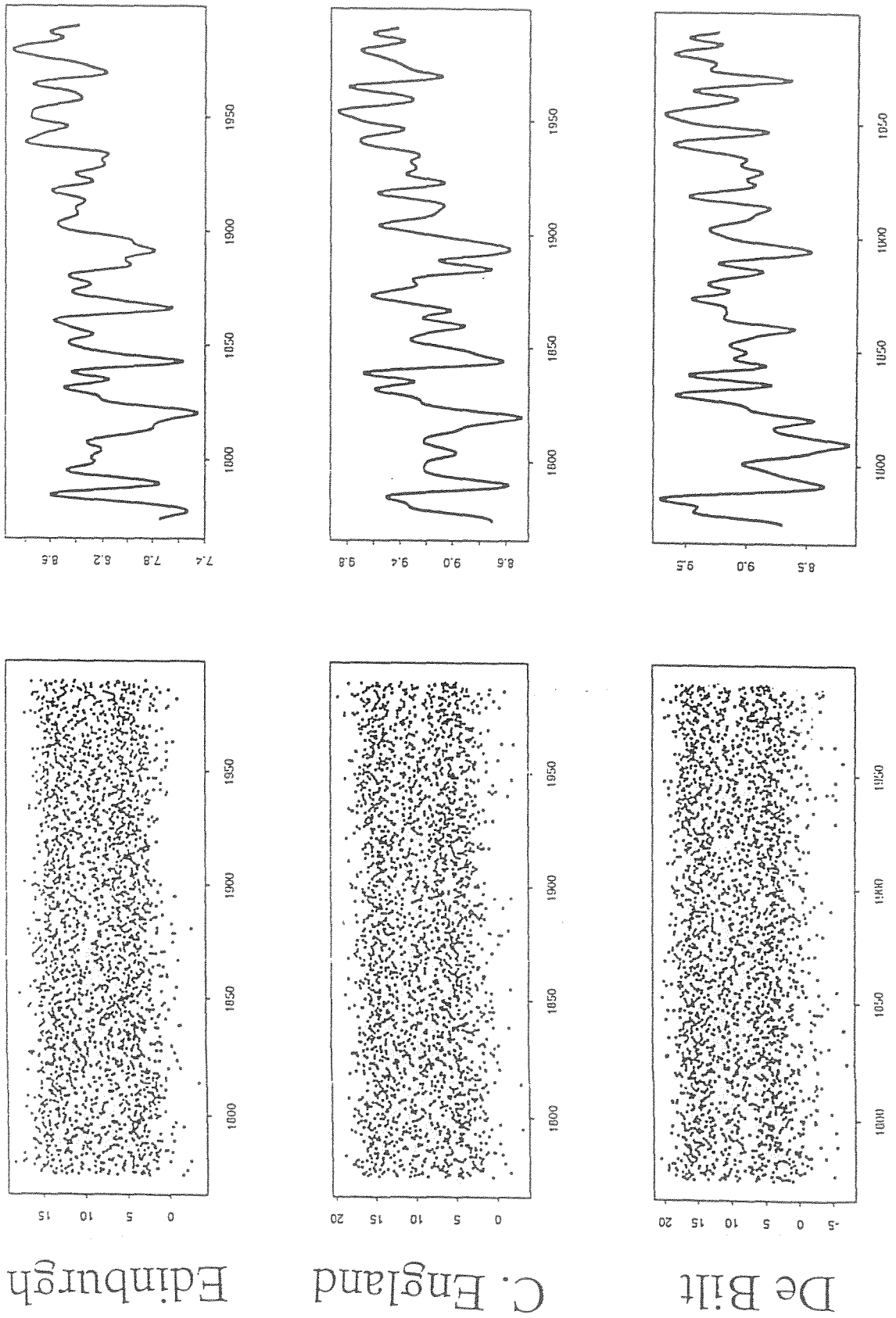
Raw Periodogram



Frequency Spectrum

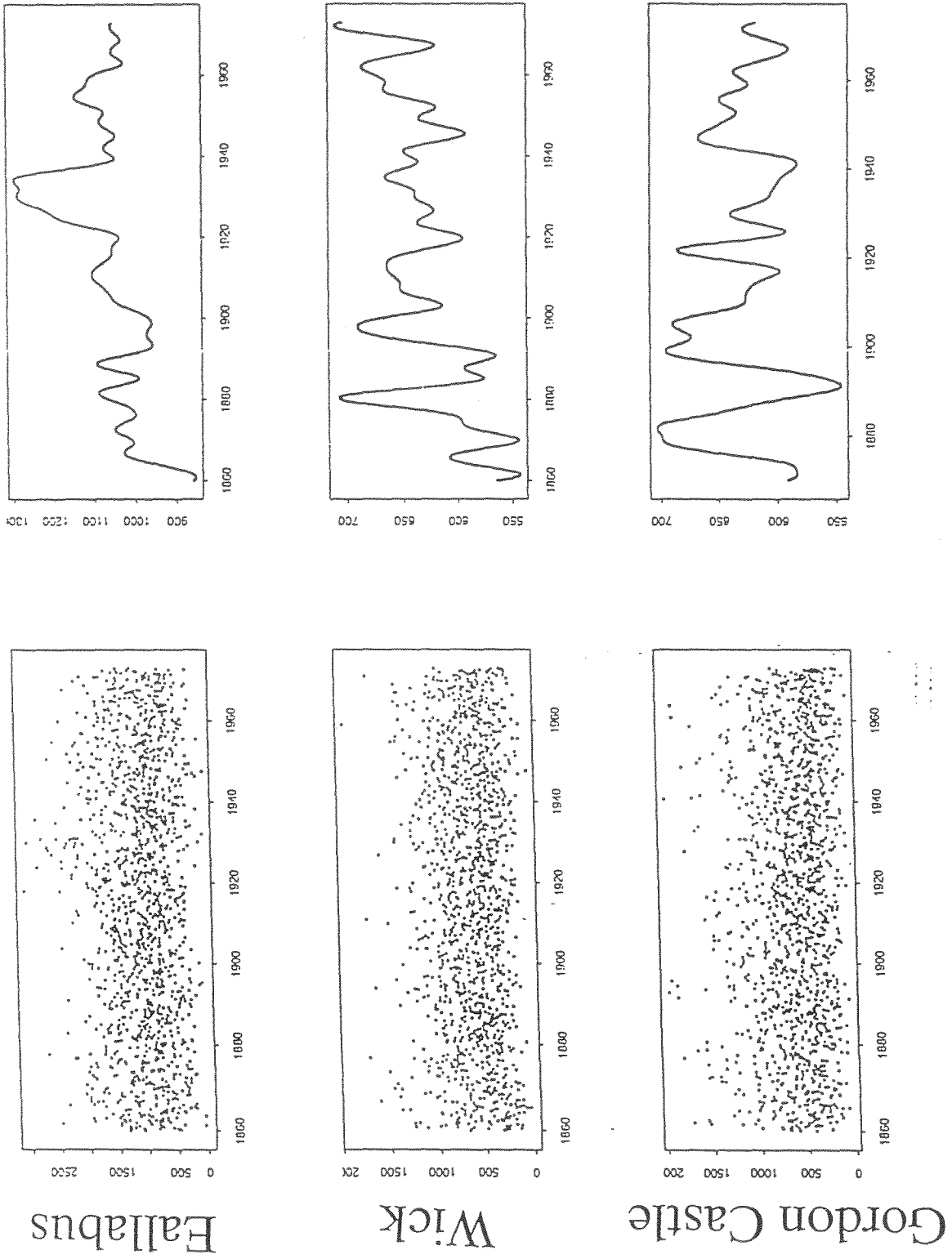


Temperature Data



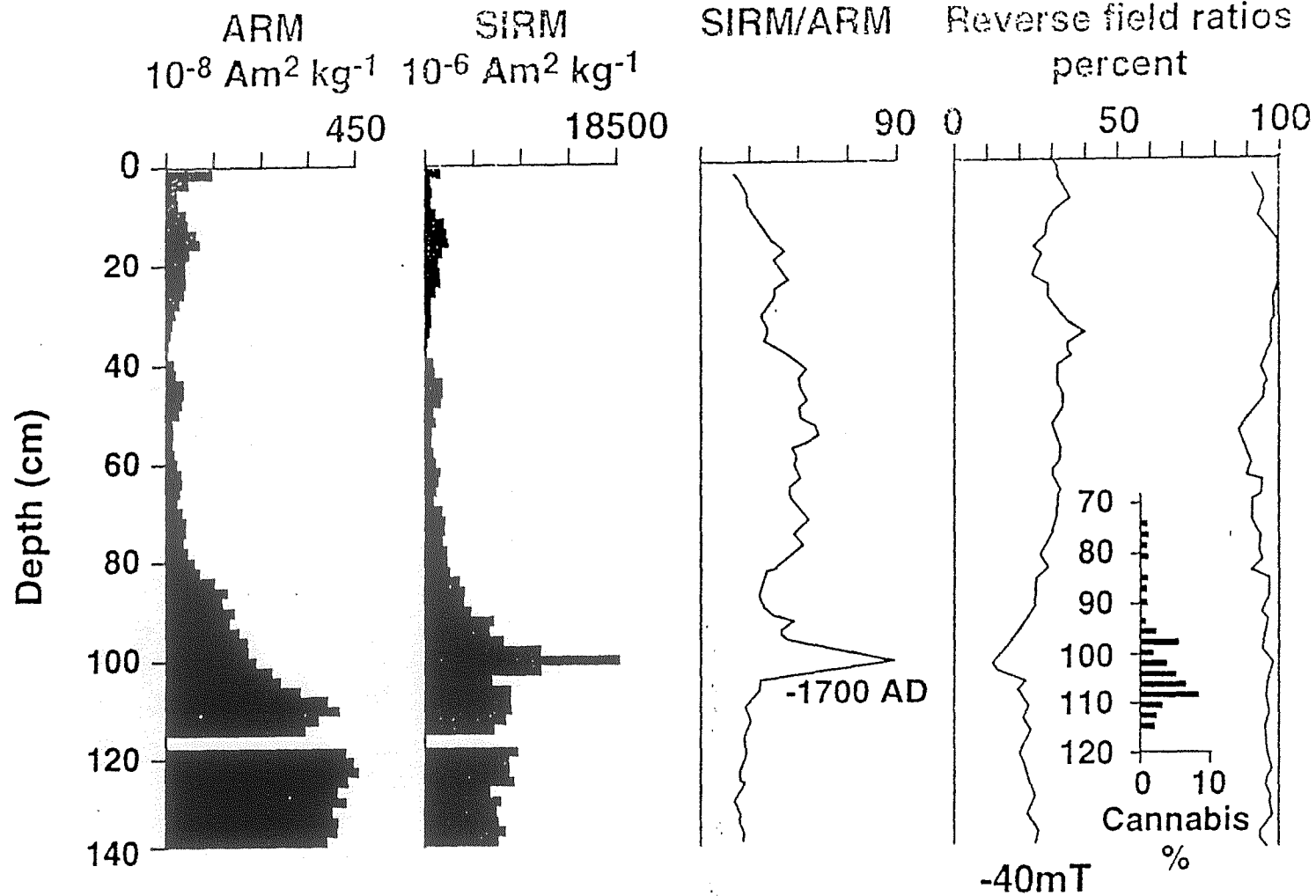
Precipitation Data

Figure 4





Lough-na-Shade (Core DW): magnetism and pollen

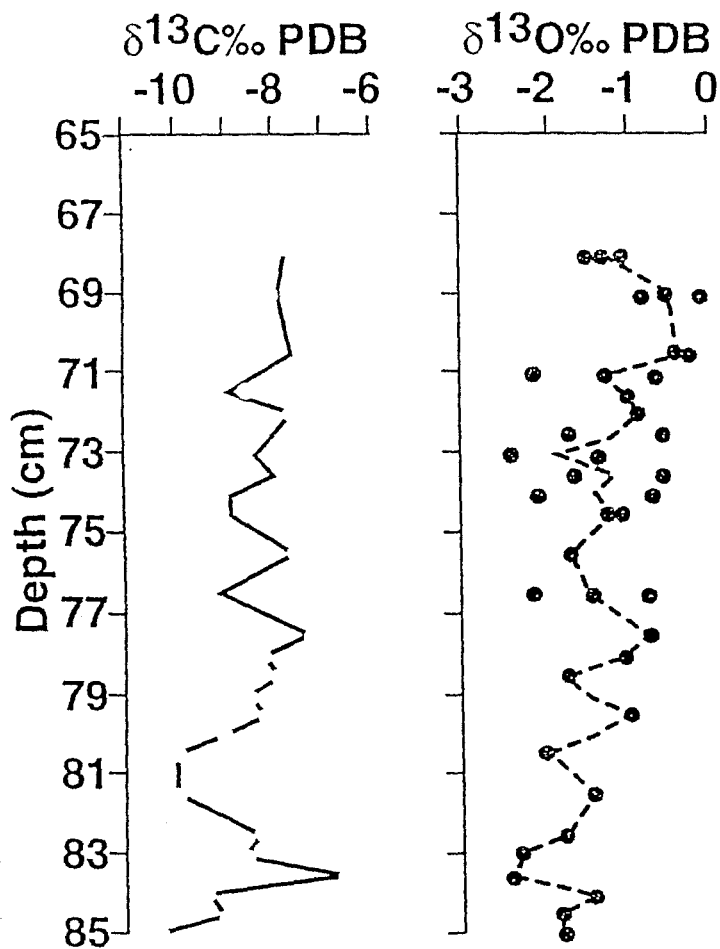


Frank Oldfield & David Weir

Figure 5

Lough-na-Shade.

Stable isotope determinations on Ostracod shells (*Candona* spp.)



Increasing rate of photosynthesis within the lake

Increasing air temperature

Increasing ppt/evap.

Increasing input of carbon from organic decay

Decreasing ppt/evap.

Increasing temperature of calcite formation

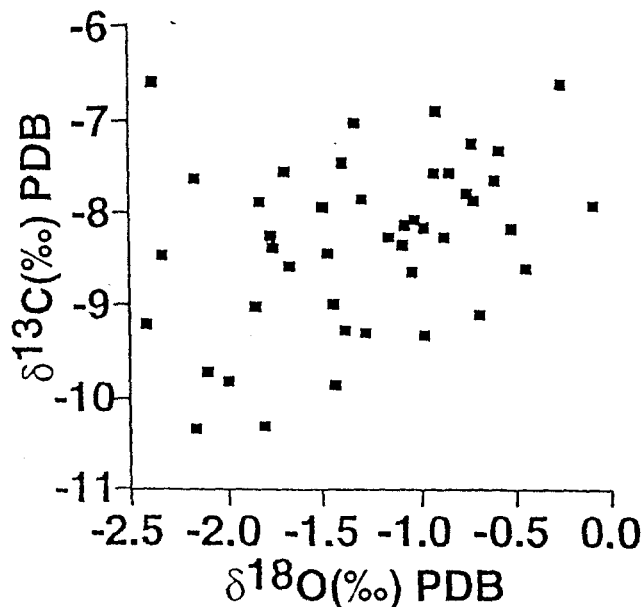
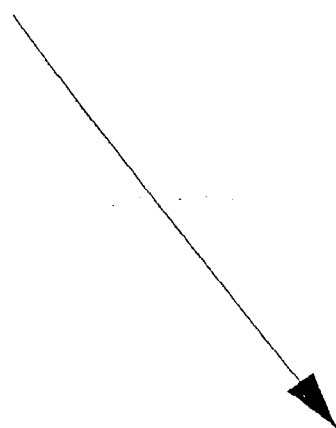
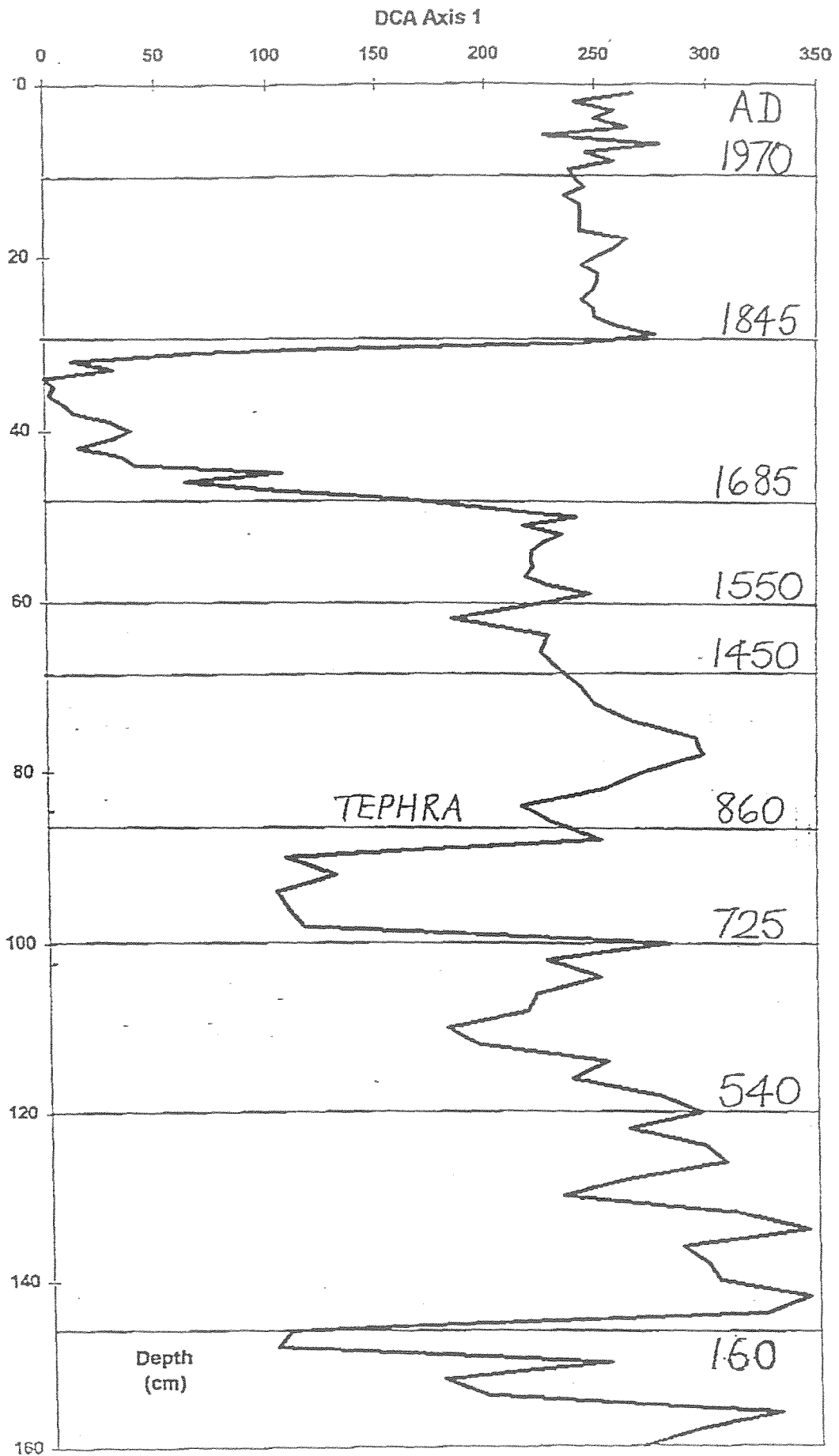


Figure 7



FALLAHOOGY BOG, NORTHERN IRELAND: PROFILE 1: DCA / DEPTH

Lochan Uaine Core UACT4

Depth versus Age

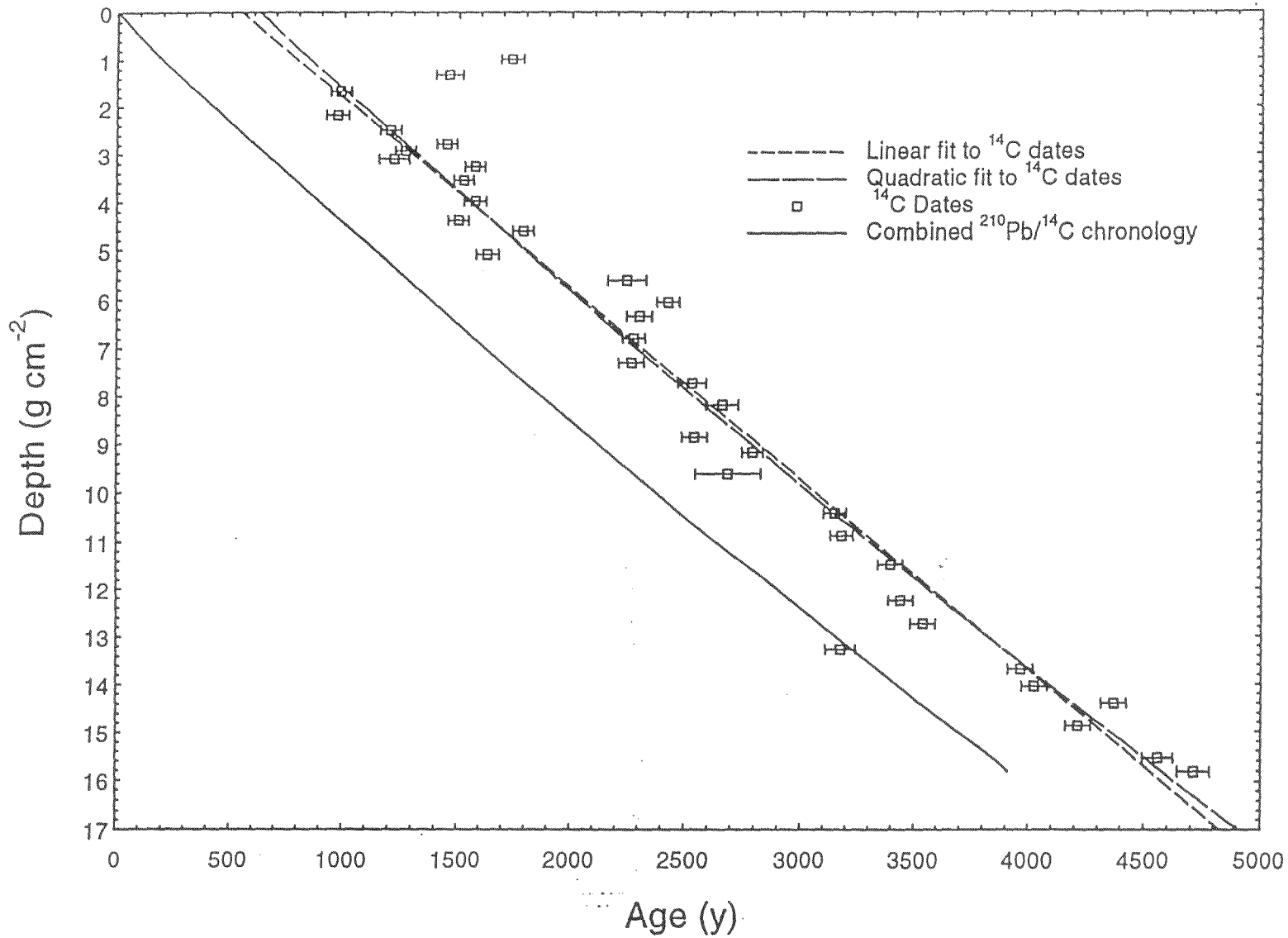


Figure 8

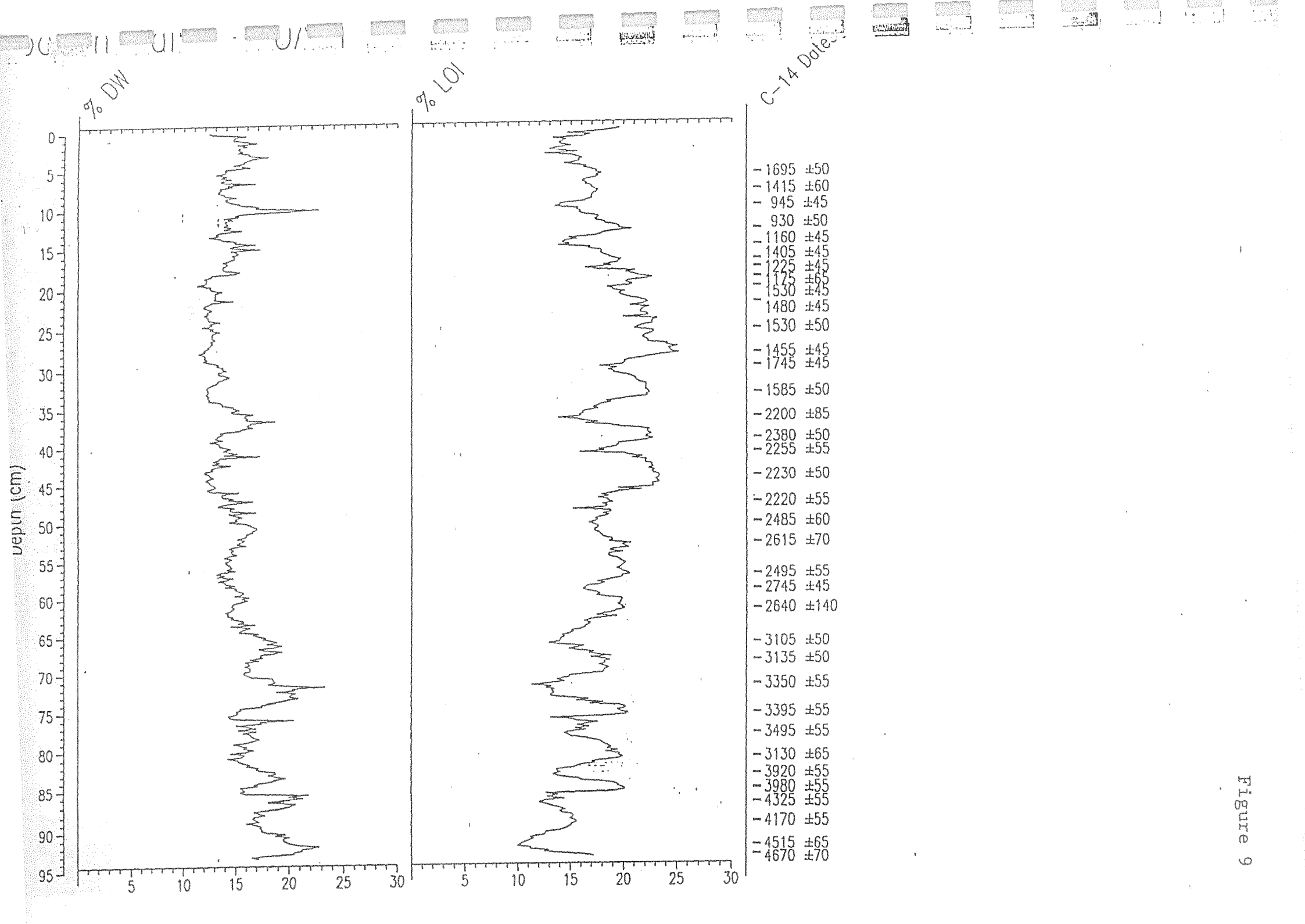
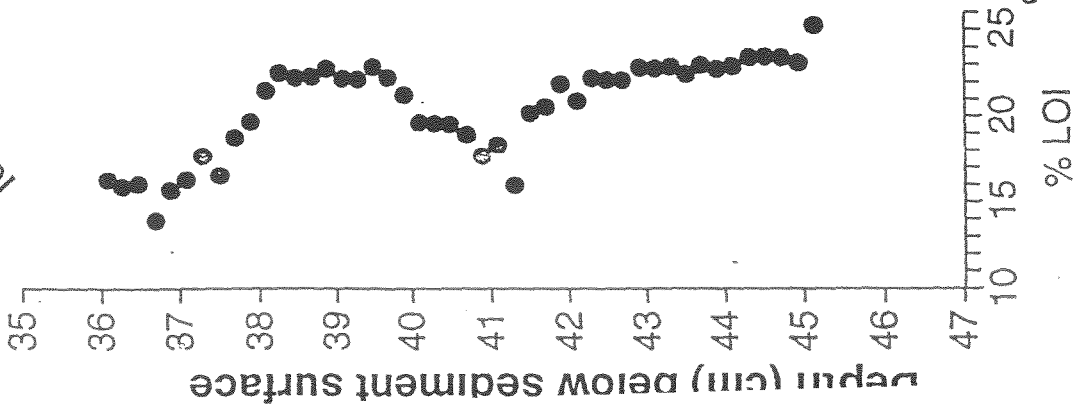
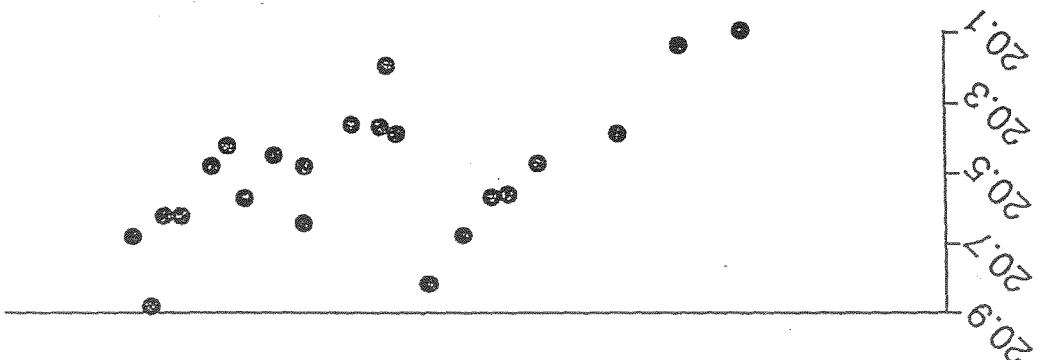


Figure 9

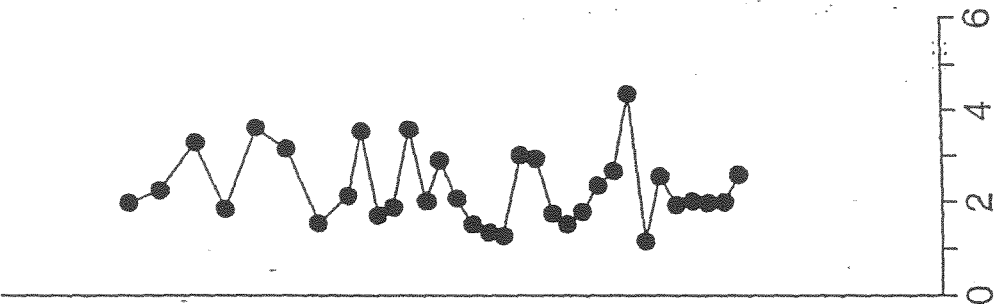
loss on ignition



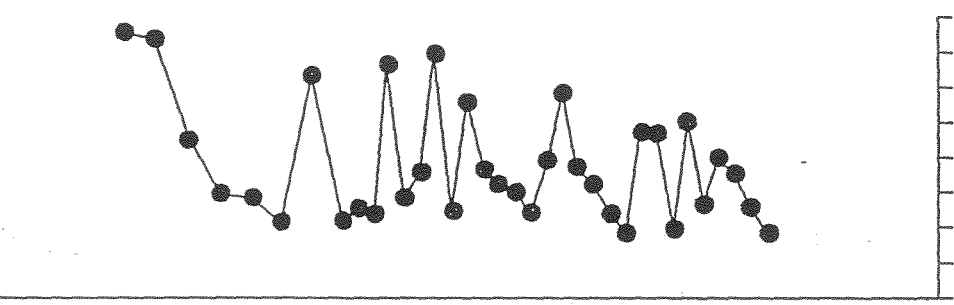
$\delta^{13}C$



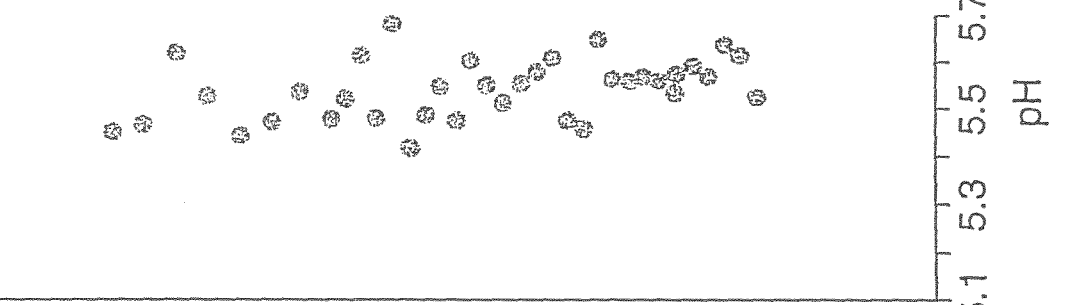
diatom concentration (x108)



chrysophyte cyst concentration (x108)



diatom based pH reconstruction



HIRM (X10-5 Am² kg⁻¹)
Date AD

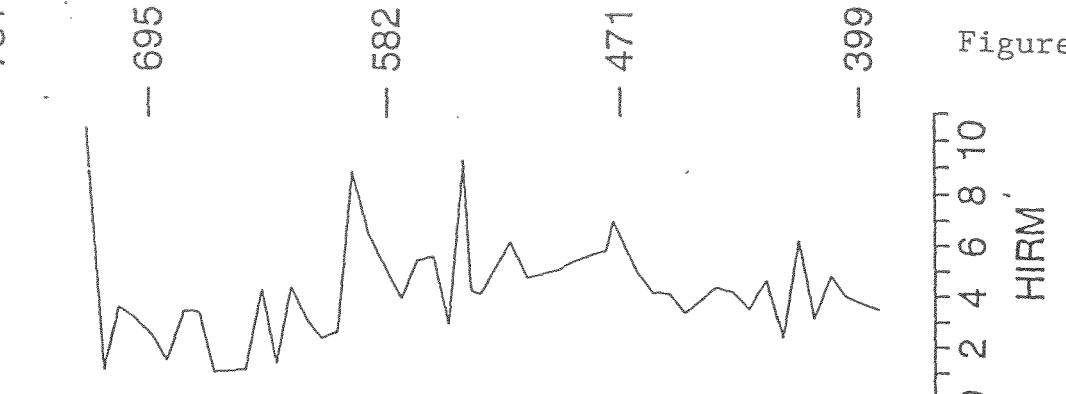


Figure 10

181
— 781
— 695
— 582
— 471
— 399

Depth (cm) below sediment surface



Lochan Uaine - Chironomidae

S.J. Brooks, 18 December 1995

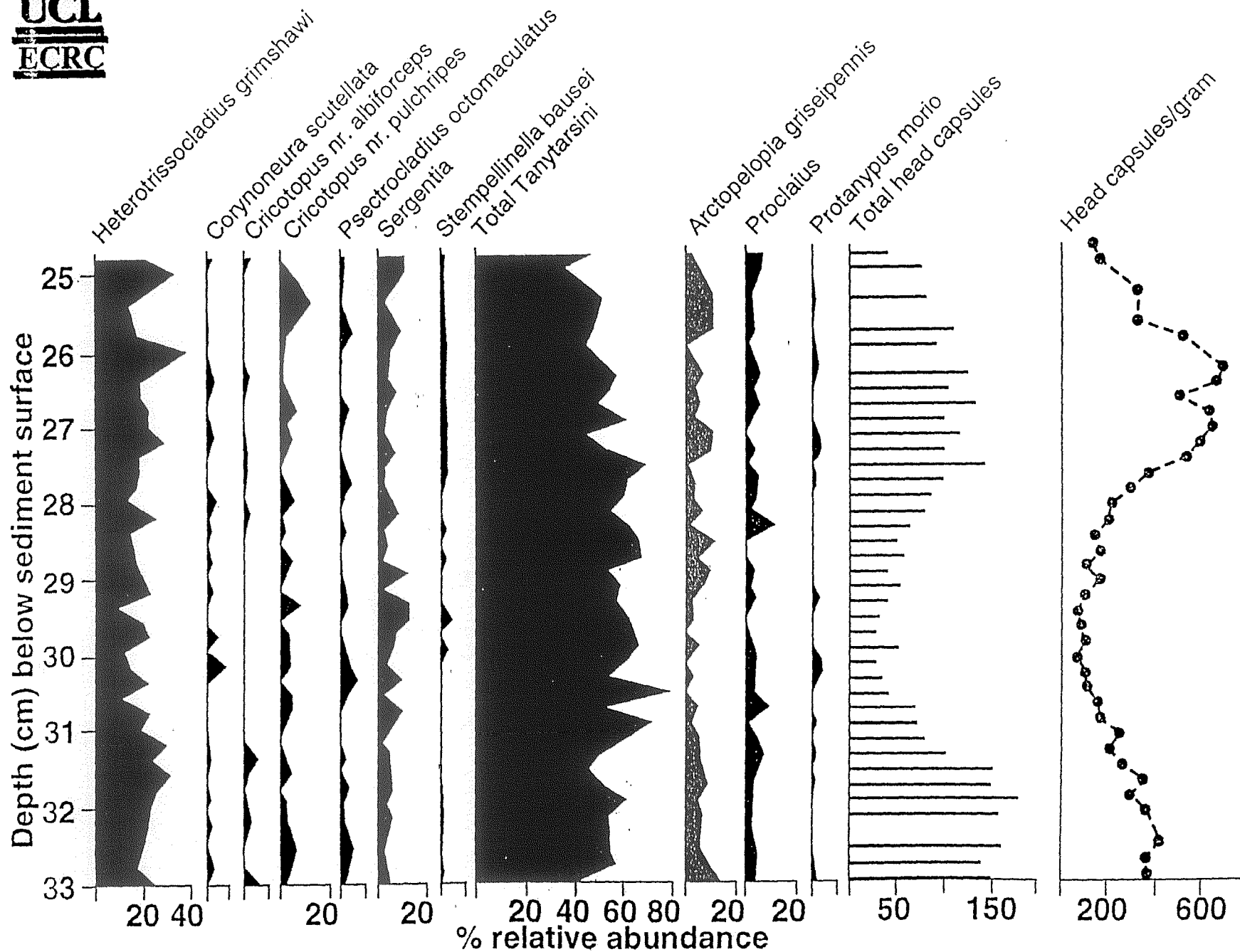
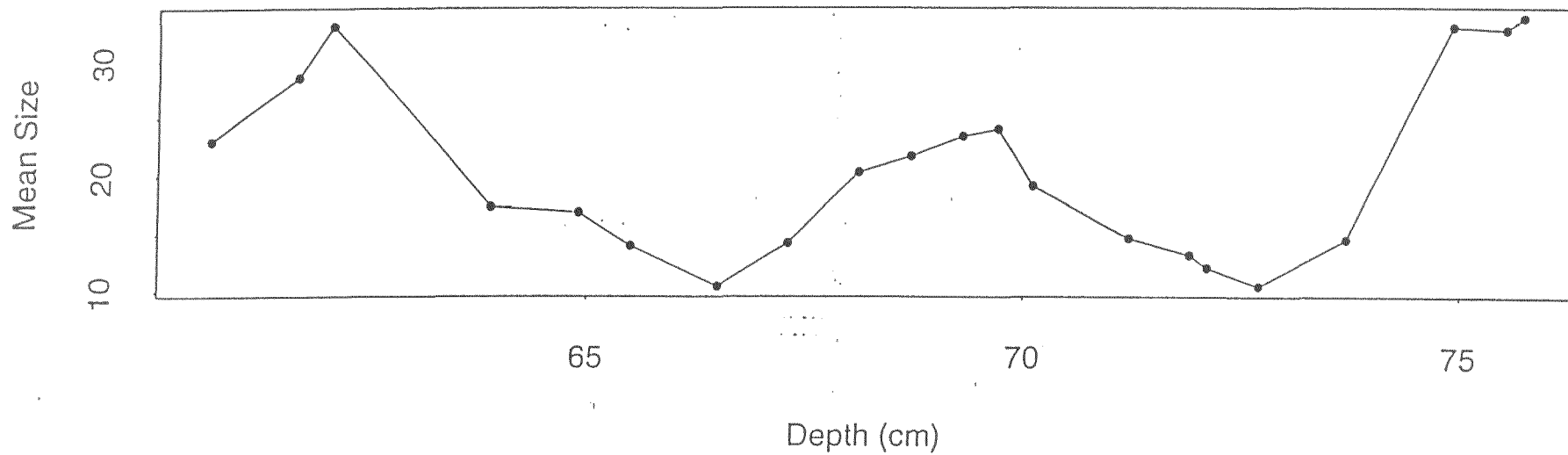
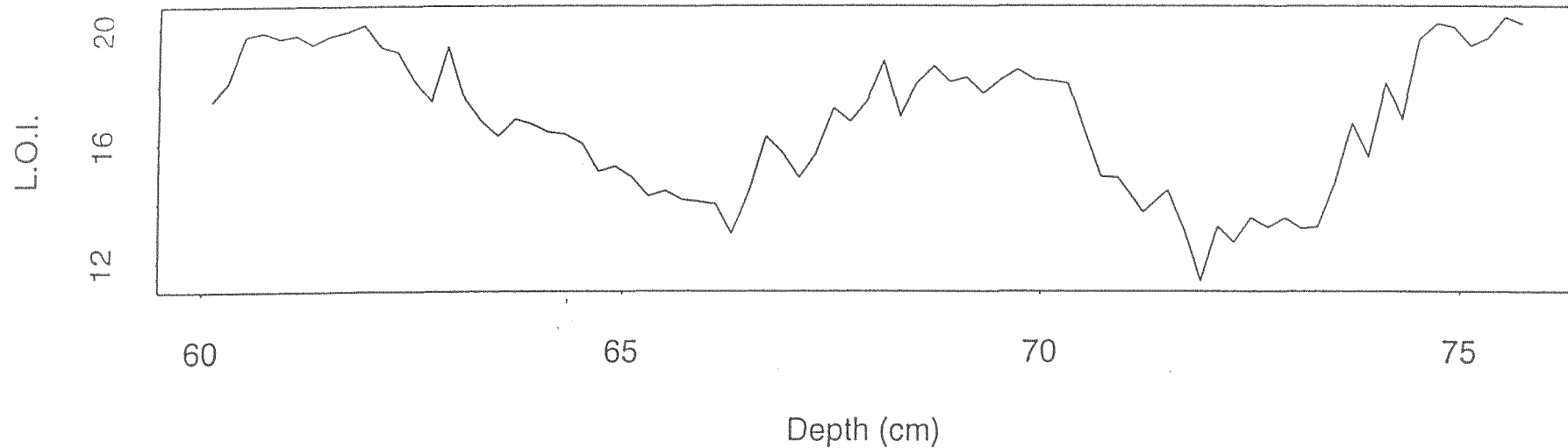


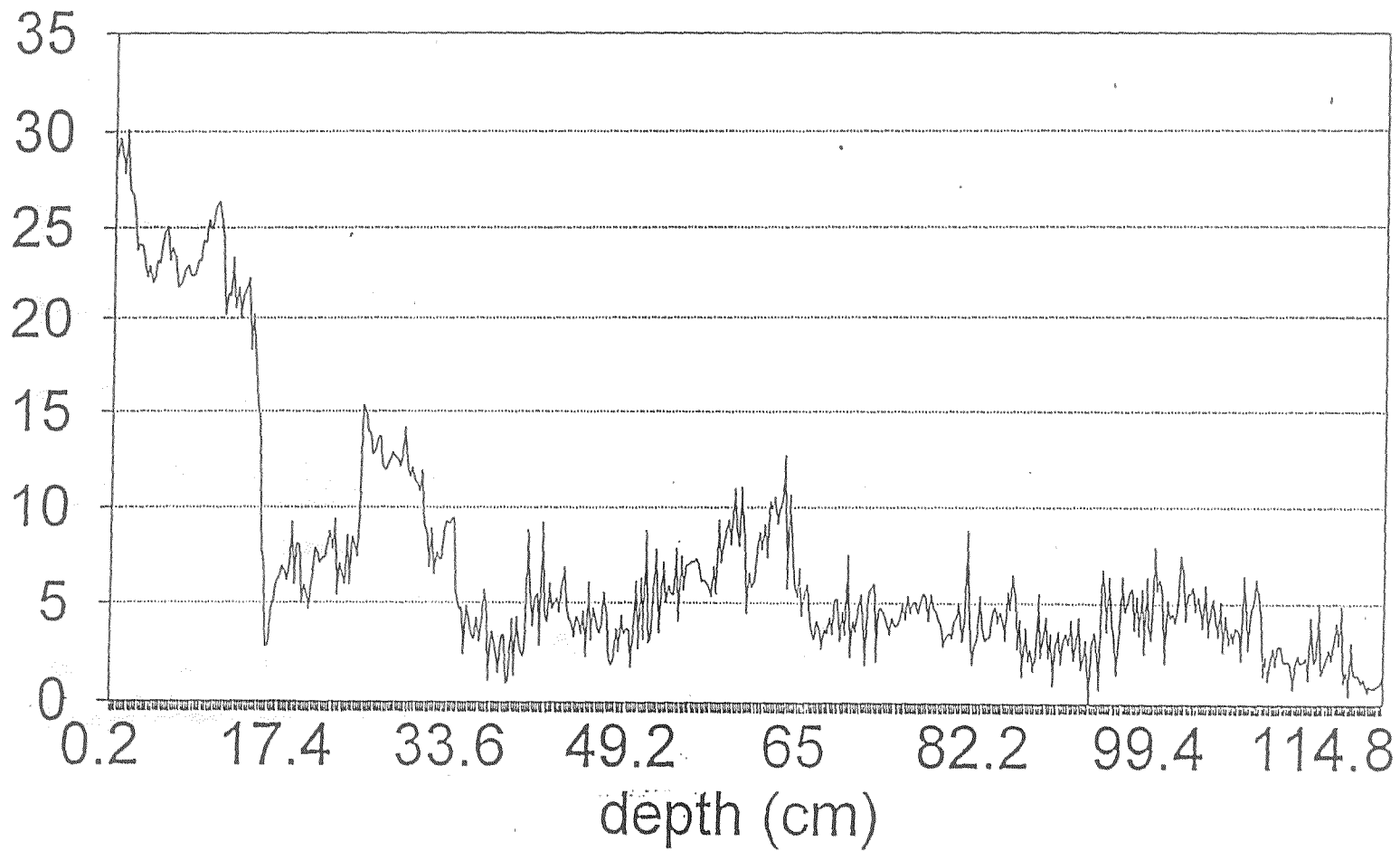
Figure 11

Comparison of LOI and Pre-treated Particle Sizes

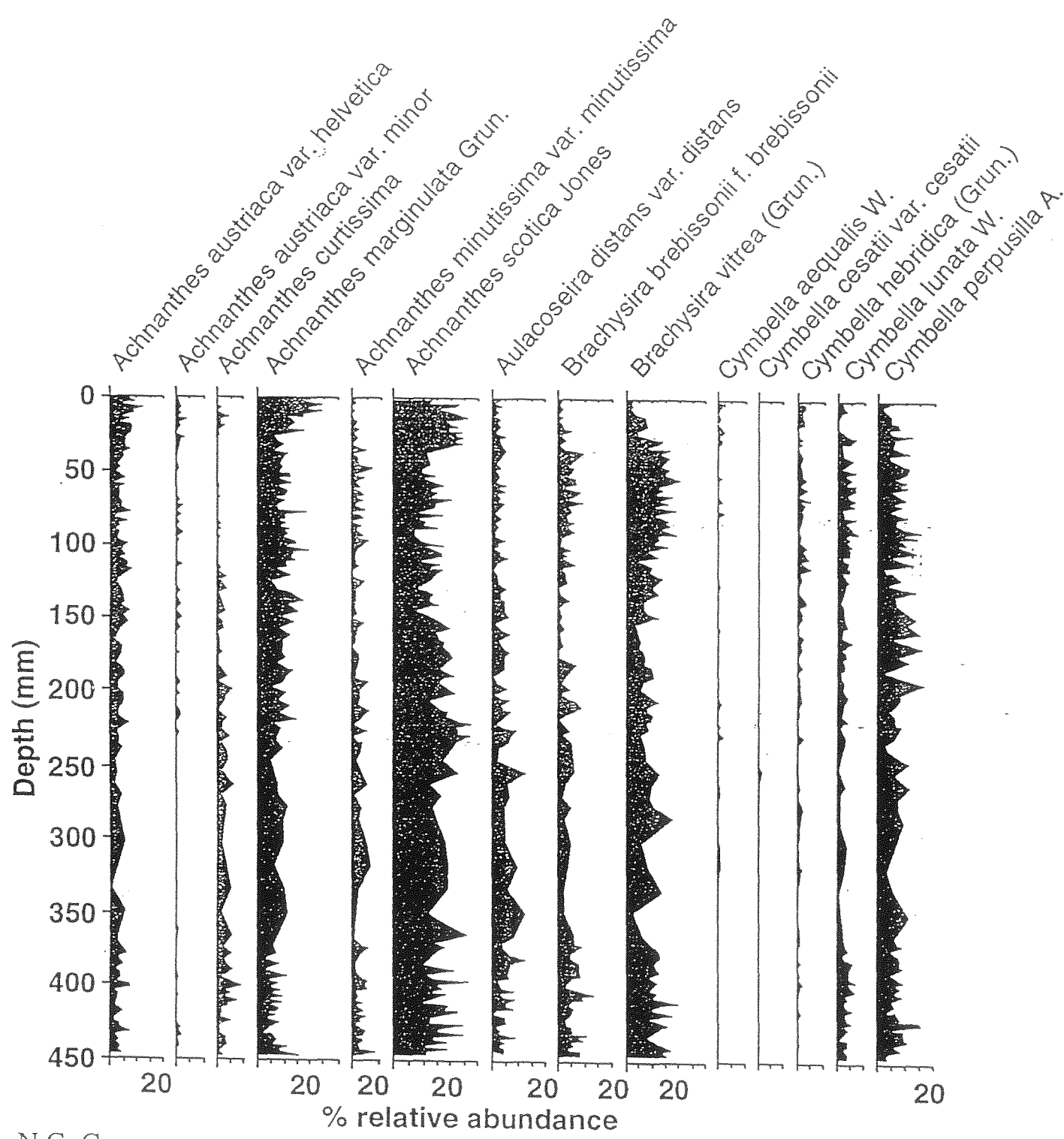


Lochan Uaine

HIRM



L. Uaine (UACT4) Scotland



N.G. Cameron



Lochan Game Chironomidae

S.J. Brooks, 18 December 1995

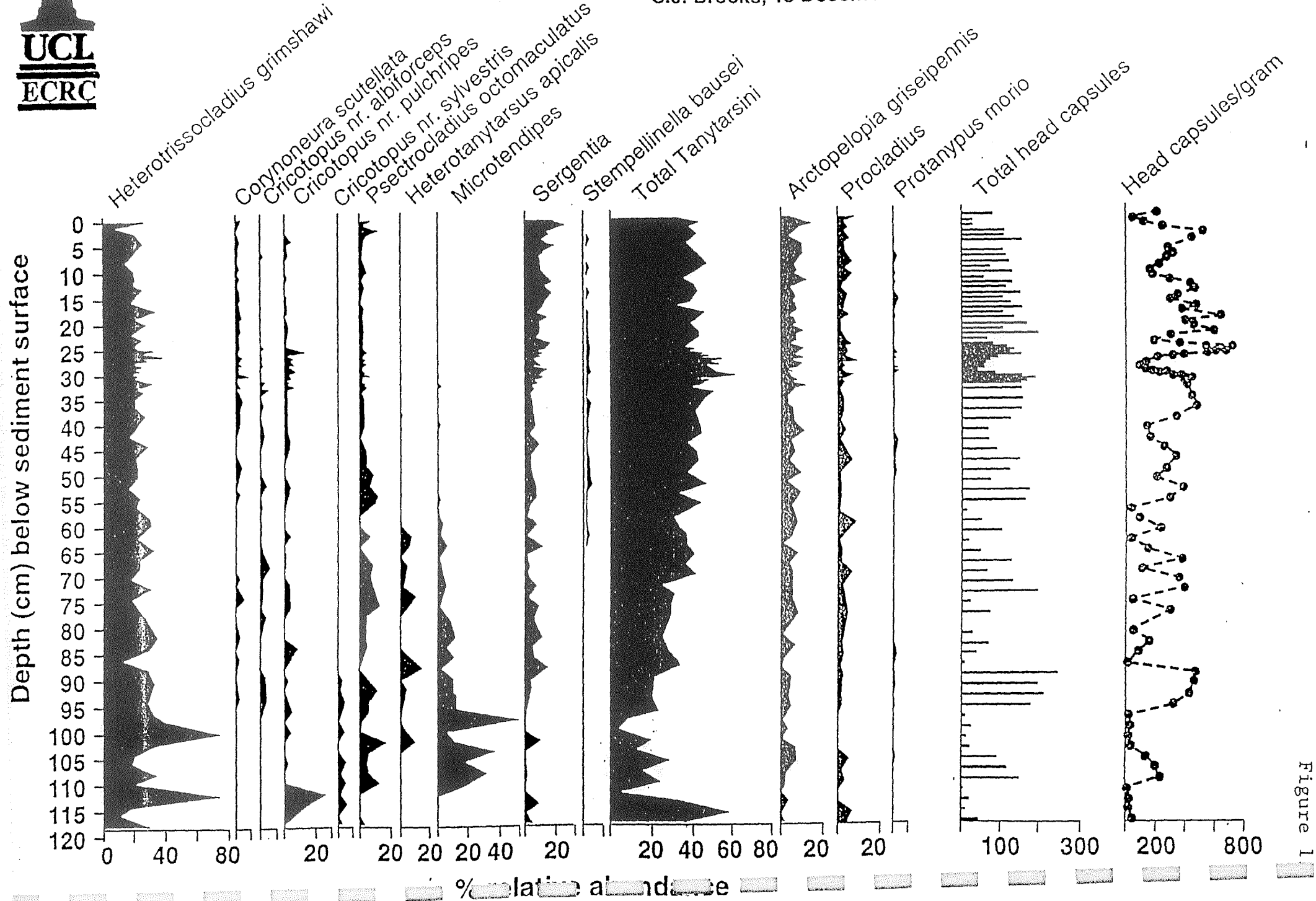


Figure 1

L. Uaine (UACT4) Scotland

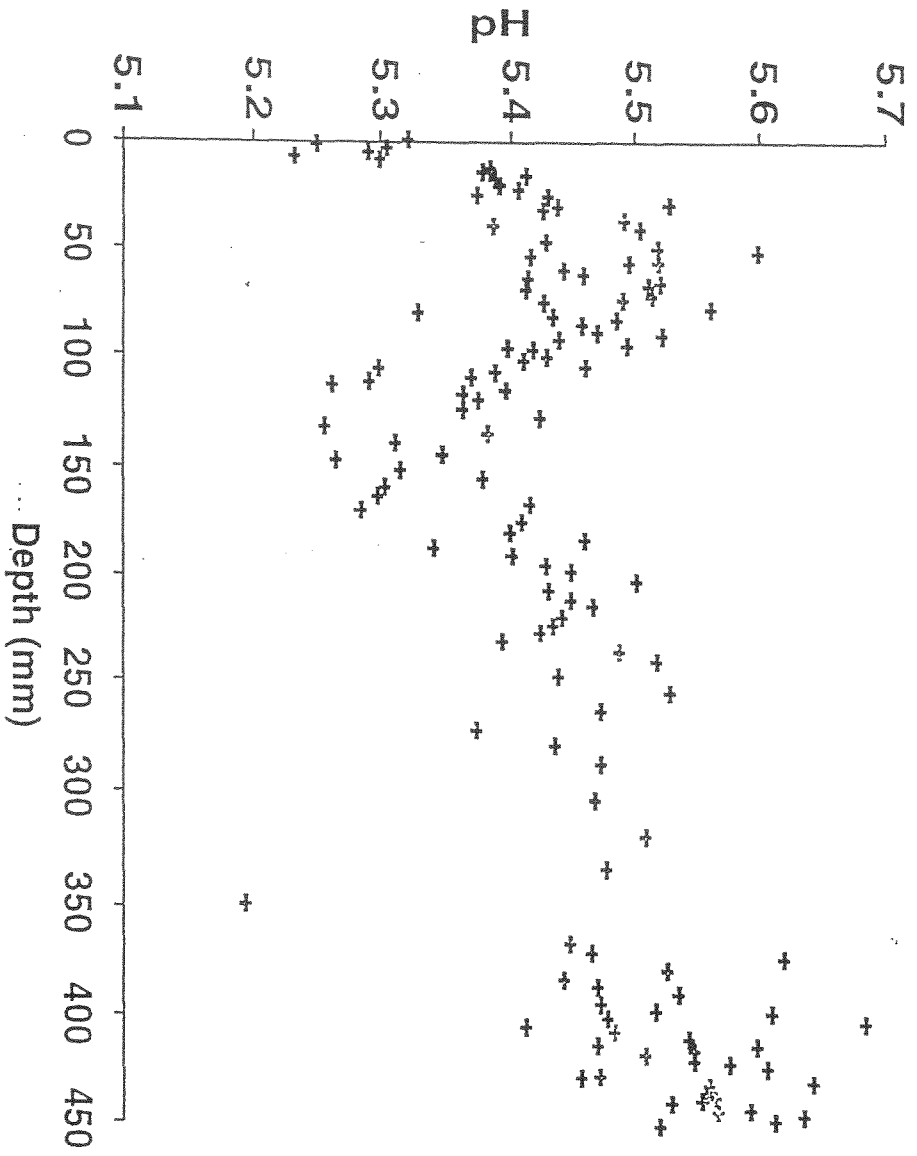
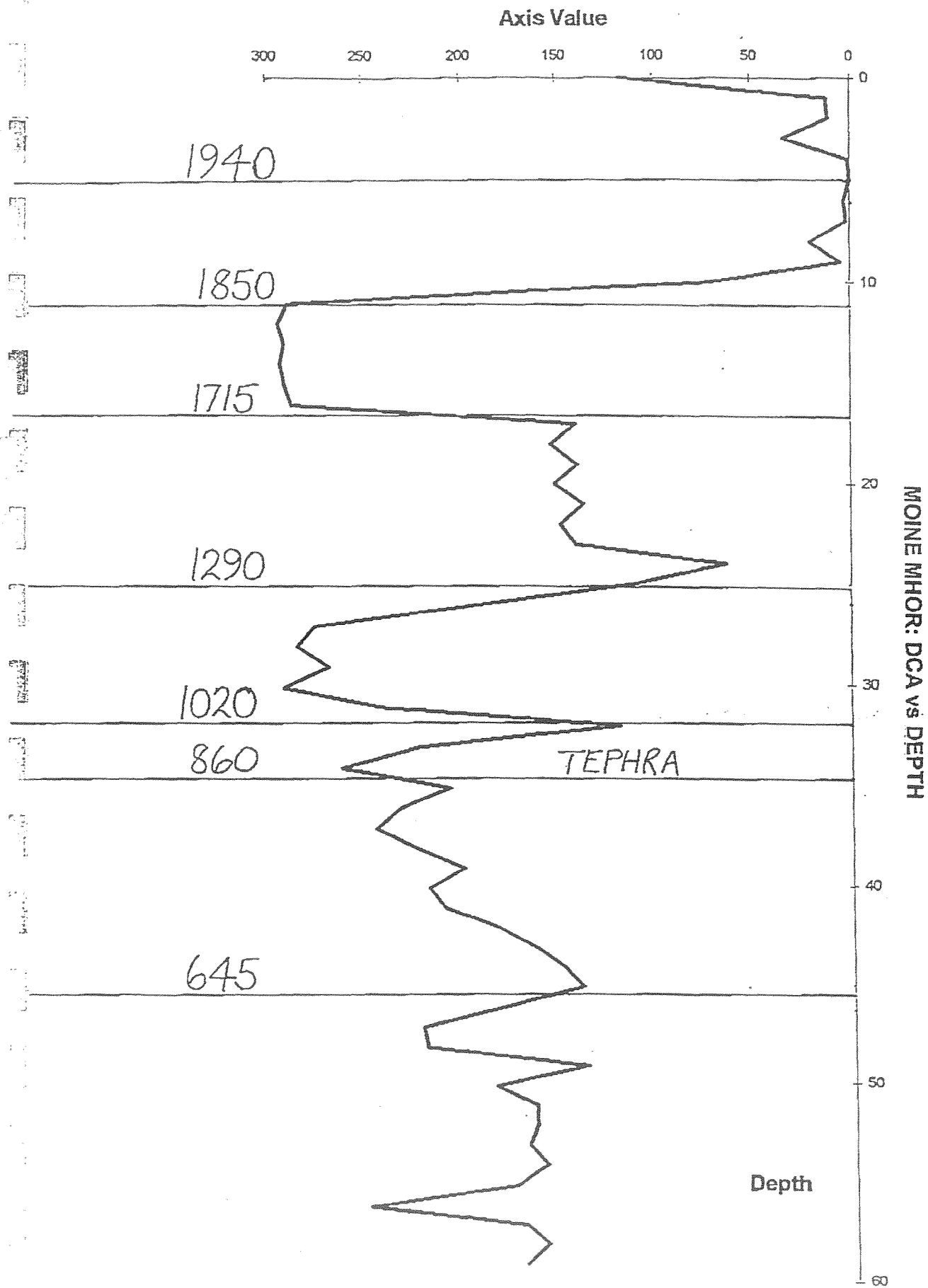


Figure 16

Figure 17



210-lead dates

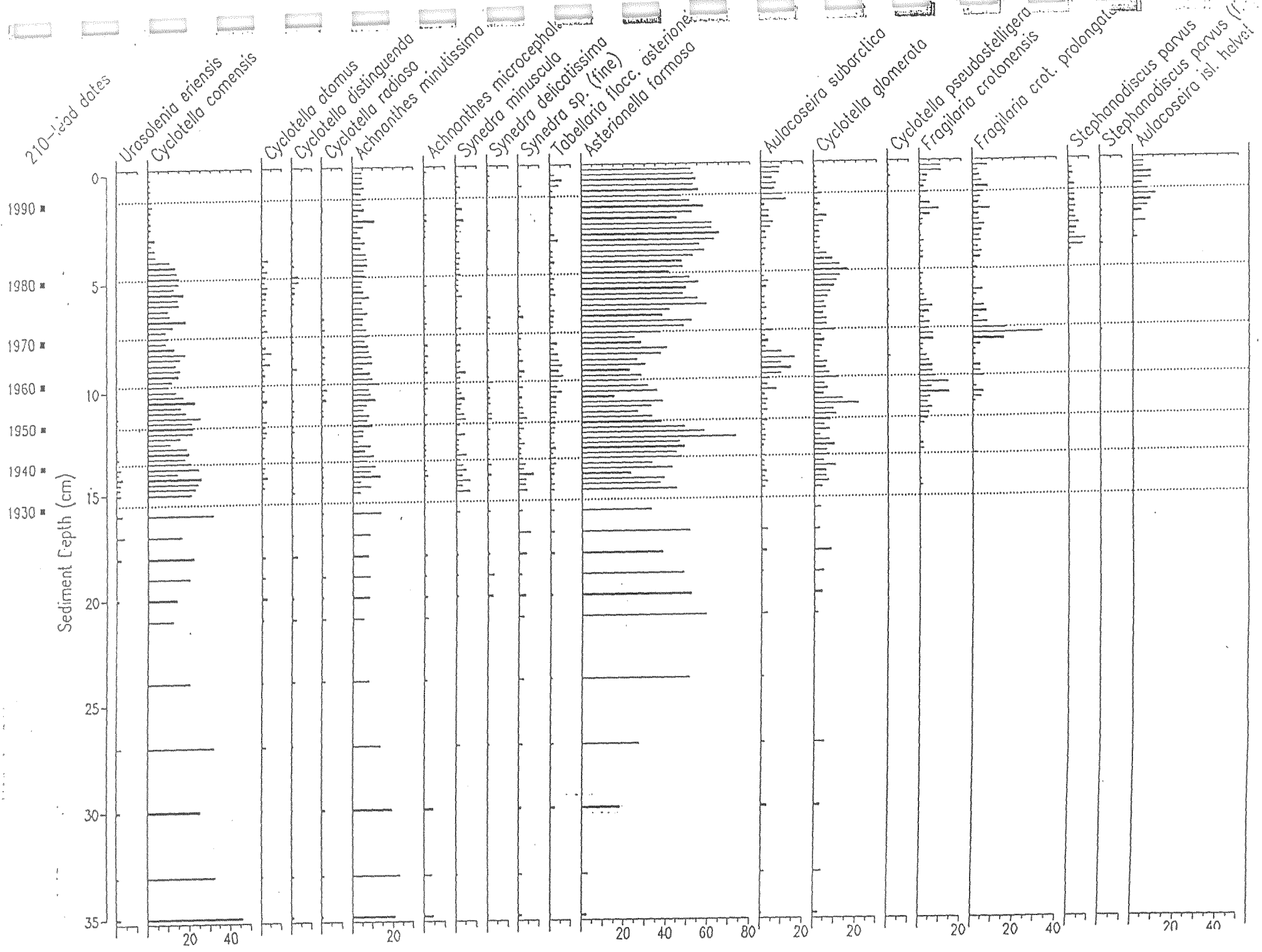
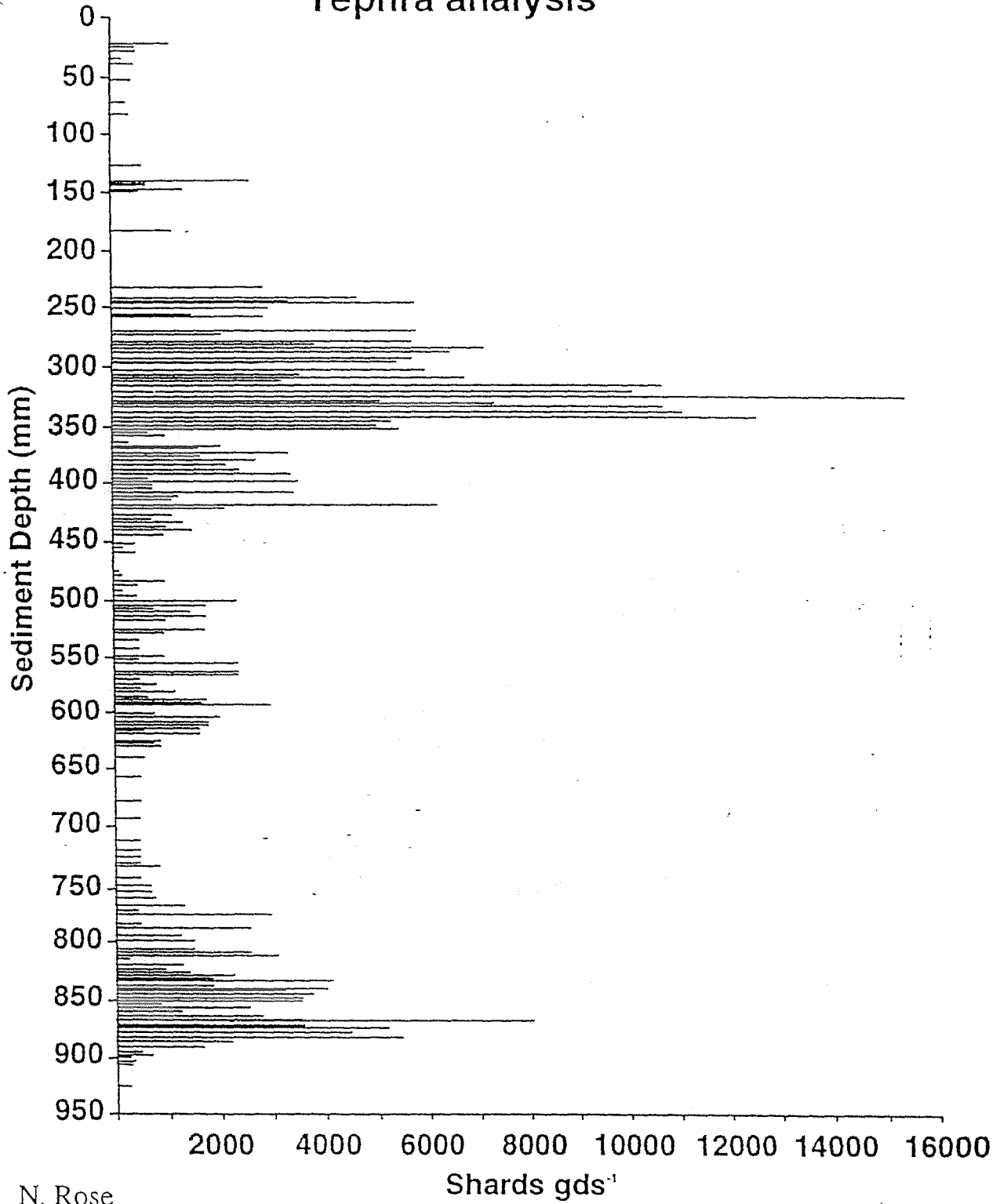


Figure 18

L. Uaine (UACT4) Scotland

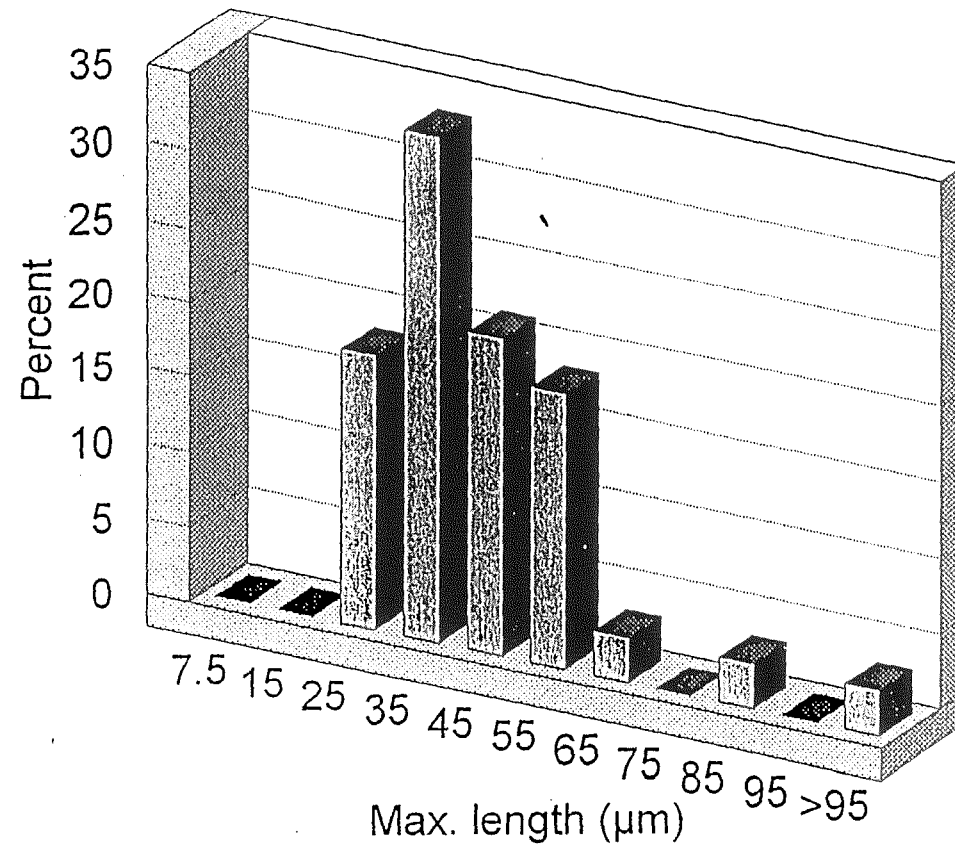
Tephra analysis



N. Rose

Lochan Uaine 32.4 - 32.6cm

Tephra size analysis



Fallahogy 86-87cm

Tephra size analysis

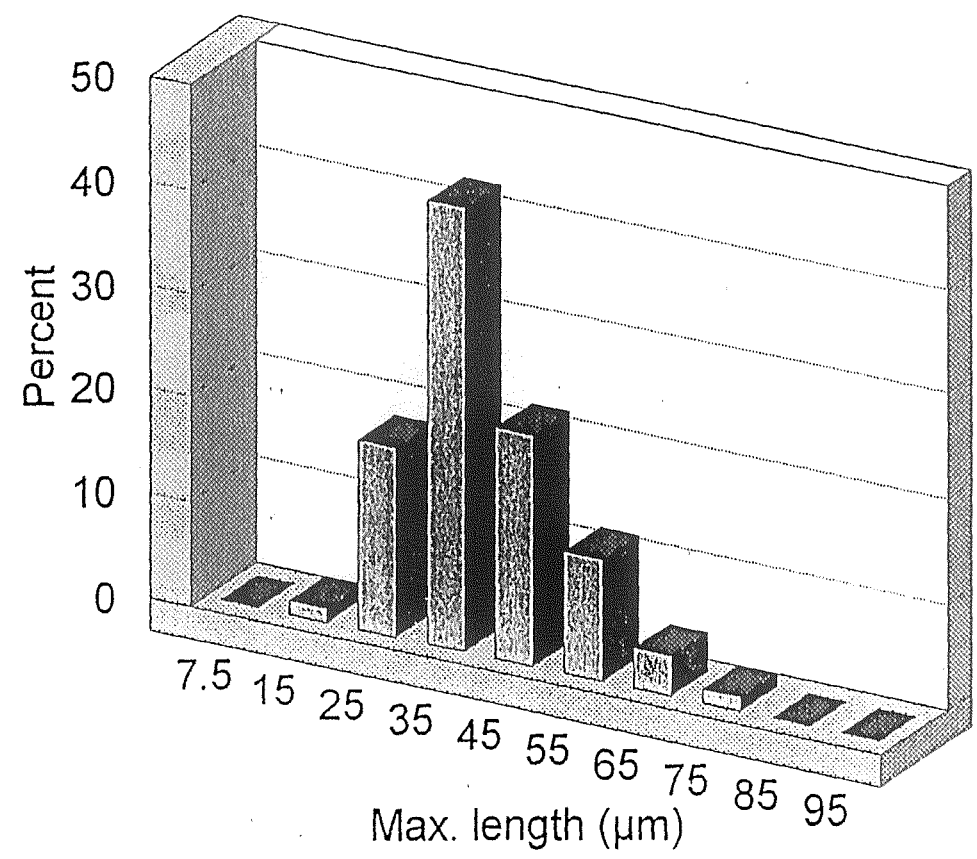


Figure 21

Moine Mhor 34-35cm

Tephra size analysis

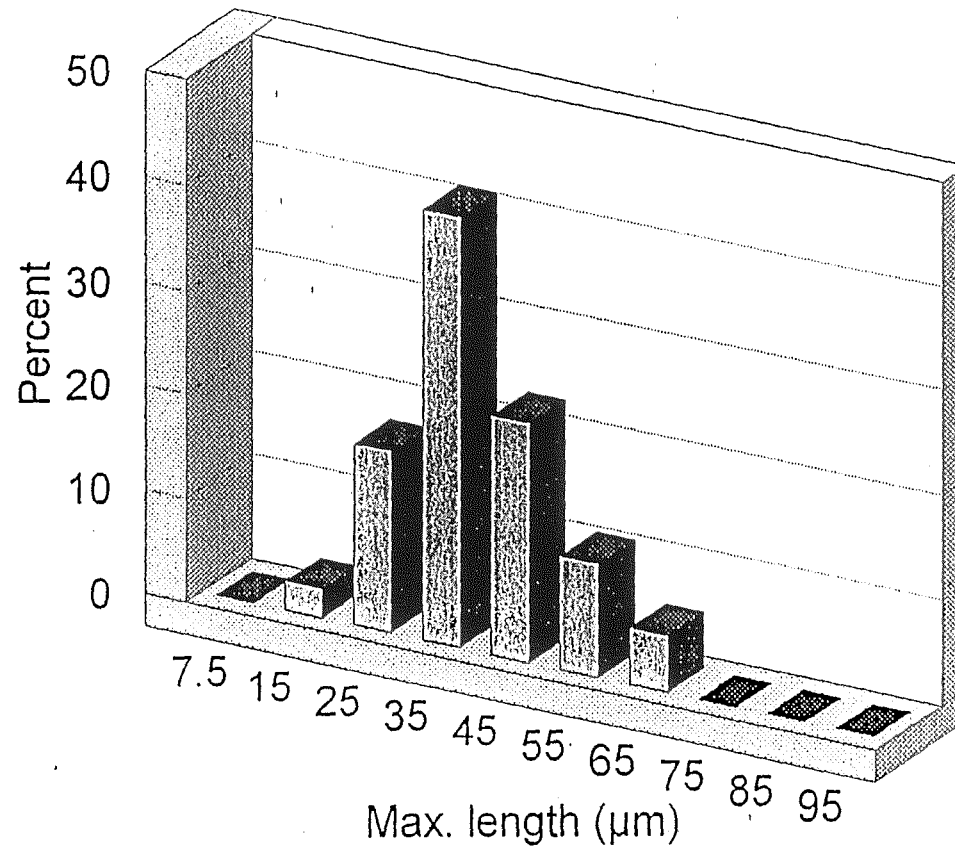


Figure 22

Lochan Uaine 86.6-86.8cm

Tephra size analysis

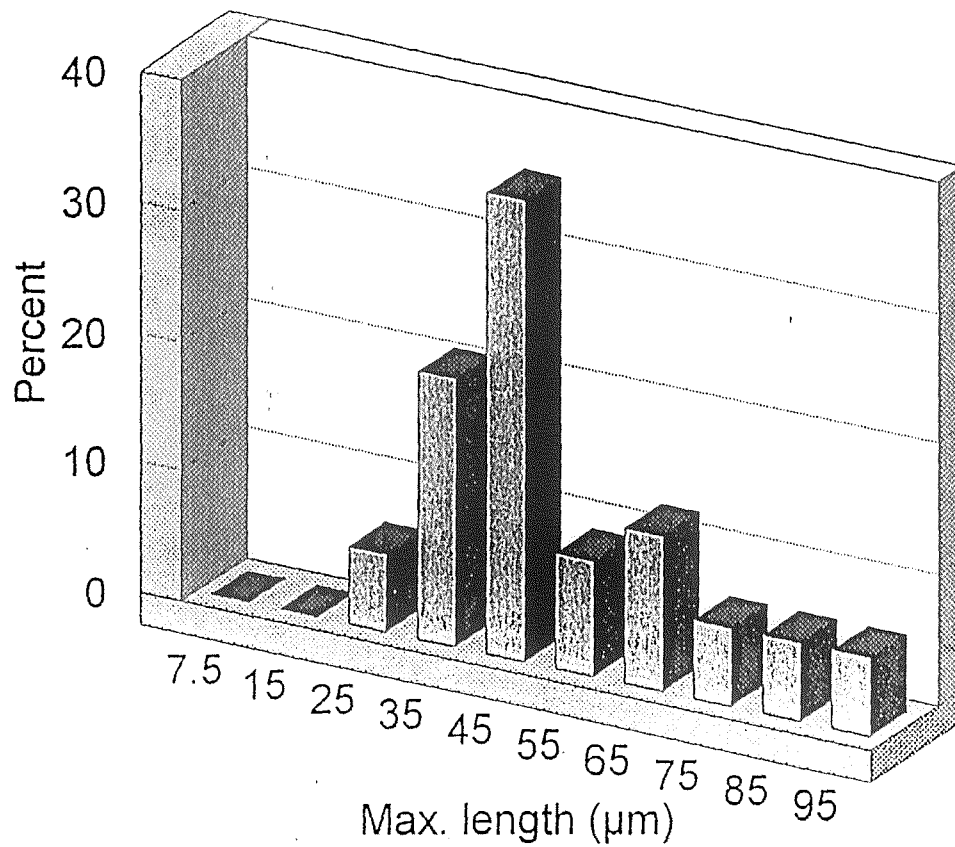


Figure 23

Appendix

Publications and publication policy

During the course of the project a series of Newsletters have been produced to aid communication within the consortium and between the consortium and members of the NERC steering group. Newsletter 4 is appended as an example.

So far there have been two papers published based entirely on TIGGER results. These are also appended.

A number of other papers are in preparation and an overview paper is being prepared for the final TIGGER meeting of March 1997.

TIGGER IIa NEWSLETTER 4

JULY 1995

PROXY RECORDS OF CLIMATE CHANGE IN THE UK OVER THE LAST TWO MILLENIA

A NERC SPECIAL TOPIC GRANT : GST /02/701

Principal Investigators:

1. Professor Rick Battarbee, UCL (joint co-ordinator)
2. Dr Keith Barber, Southampton (joint co-ordinator)
3. Professor Frank Oldfield, Liverpool
4. Dr Roy Thompson, Edinburgh
5. Dr Tony Stevenson, Newcastle
6. Professor Geoff Eglinton, Bristol
7. Dr Liz Haworth, IFE Windermere
8. Dr Steve Brooks, NHM London

The overall aim of TIGGER IIa is to evaluate the relative usefulness of lake and bog sediment records as proxy indicators of climate change over the last 2000 years in the UK.

The grant formally began on November 1st 1992 and ends on 31st October 1995. UCL is the main contractor, and sub-contracts have been issued to other collaborating PIs or their institutions.

The project is divided into eight inter-linked sub-projects. In particular there is a focus on lake and bog sequences in Ulster (sub-projects 3 and 4), and on instrumental records, lake, bog sequences in the Cairngorms (sub-projects 1,5, and 6). There is also a sub-project (7) on the recent sediments of Lake Windermere. Sub-project 2 on tree-rings in Ulster was not funded.

This is the fourth TIGGER 2A newsletter. To make complete sense of it probably requires a reading of the first three newsletters, copies of which can be obtained from Rick Battarbee.

In general almost all sub-projects are achieving, or have achieved their aims. Most analyses have been completed, and this Newsletter is designed to make data available both within the project and to interested external parties. Our hope is to complete all work on schedule, with a final workshop at UCL on Thursday October 5th, followed by a public meeting in spring 1996, in combination with groups from other TIGGER projects.

1. Historical climate records (Project leader: Roy Thompson)

Roy Thompson & Roger Hutchinson (University of Edinburgh)

1.1 Precipitation

An analysis of the available historical precipitation records has revealed the pronounced between sites variations in long term rainfall across the TIGGER 2a region anticipated in the last newsletter. A plot of the raw data (three left hand panels of Figure 1.1) and after smoothing using a ten year filter (three right hand panels of Figure 1.1) from three sites around Scotland is included to illustrate the clear differences between the sites. This variability makes it impossible to produce a long term homogenised precipitation record from the short local records available. The record from Eallabus, just off the west coast of Scotland, extends to 1800 AD and this represents the longest homogenous precipitation record available.

1.2 Temperature

Temperature records, on the other hand, show much more spatial coherence and a homogenised record has been produced for the Edinburgh area. This new record (Figures 1.2a and 1.3a) was produced by calculating the monthly offsets between two paired local series. By comparing overlapping years the older series could be adjusted to the baseline of the newer series. In this way a record has been built up back to AD 1764. The new Edinburgh series uses data from Turnhouse Airport, The Royal Observatory, Dalkeith and the Mossman Compilation. The Alexandersson method was used to check the resulting series for inhomogeneities by comparing it with the record from Central England homogenised by Manley.

Spectral analysis of the new Edinburgh series reveals peak indicating periods of 12 months and 6 months (Figure 1.3b & 1.3c). The 6 month periodicity is caused by a difference in the sharpness of the summer peak compared to the winter trough and an asymmetry in the spring rise and the autumn fall in temperature.

The next step in producing an extended Scottish temperature record is to retrodict the Edinburgh historical series using longer records from further away. Since the correlation between any two sites drops with distance, the accuracy of the resulting series will obviously fall below the 0.1 ± 0.1 C accuracy of the new historical record. Several possible sources of further data exist for the retrodiction study. These include (i) the Central England record (AD 1674 onwards), (ii) the series of monthly indices produced by Pfister for the Swiss Alps (AD 1525 onwards), (iii) the middle Rhine index series of White (AD 1300 onwards) and (iv) the long tree ring reconstructions from Scandinavia. The correlations between the overlapping parts of the first two series and the new Edinburgh series are:

Site	r	r^2
Central England 0.74 (1674-)	0.86	0.74
Pfister's indices (1500-)	0.54	0.30

These correlation values may seem low, with the Pfister series only accounting for 30% of the variation seen in the Edinburgh record, but in the absence of any more highly correlated data they represent the best chance to extend the Scottish temperature record. There are also tree ring data available from around Scotland and it is hoped that these, along with the Scandinavian series, will also prove useful in further extending the temperature record.

Figures

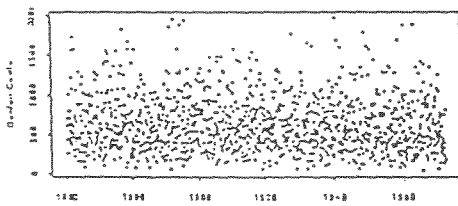
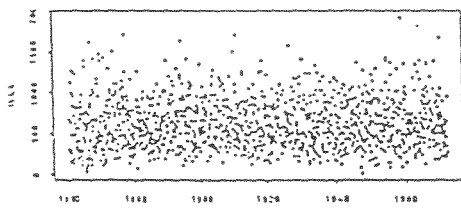
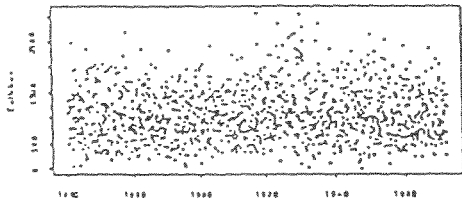
Figure 1.1 Precipitation data from three sites around Scotland (west, north and north-east coasts) illustrating the high degree of spatial variance

Figure 1.2 Temperature data from three sites in Western Europe illustrating the high level of coherence between sites. Note the same overall rise of about 0.5°C in the last 200 years and the lack of cold winters in the 1910s and 1920s

Figure 1.3 The new Edinburgh series shown as (i) the raw data; (ii) the raw periodogram and (iii) the smoothed frequency spectrum with a clear sharp peak corresponding to a period of 12 months and a second peak at a period of 6 months.

Figure 1. Precipitation data from three sites around Scotland (west, north and north east coasts) illustrating the high degree of spatial variance.

Raw Data:



Ten Year Filter:

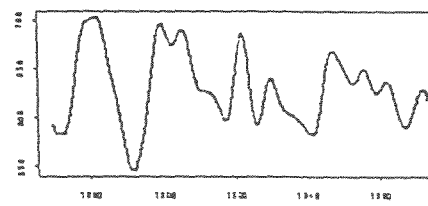
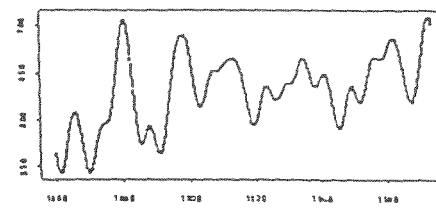
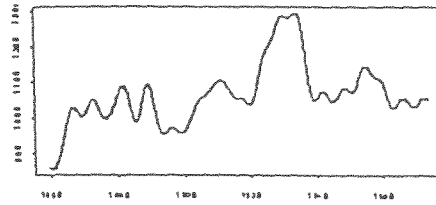
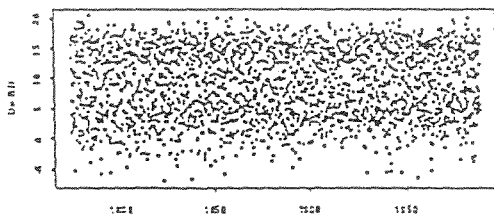
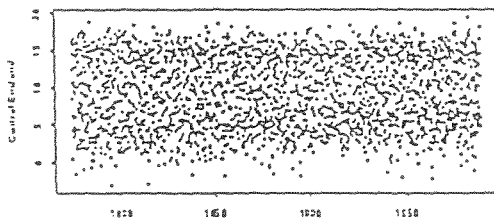
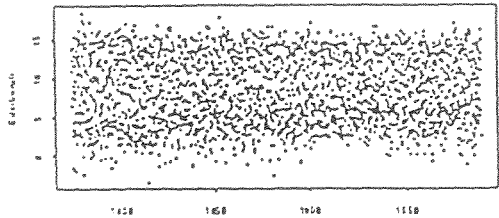


Figure 2. Temperature data from three sites in Western Europe illustrating the high level of coherence between sites. Note the same overall rise of about 0.5°C in the last 200 years and the lack of cold winters in the 1910's and 1920's.

Raw Data:



Ten Year Filter:

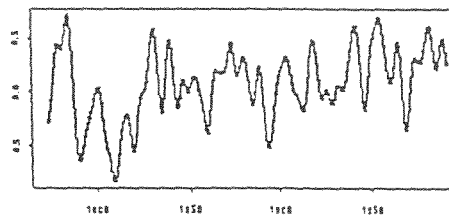
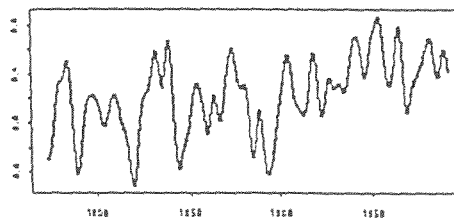
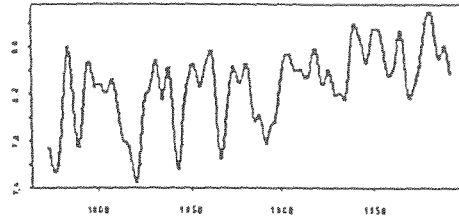
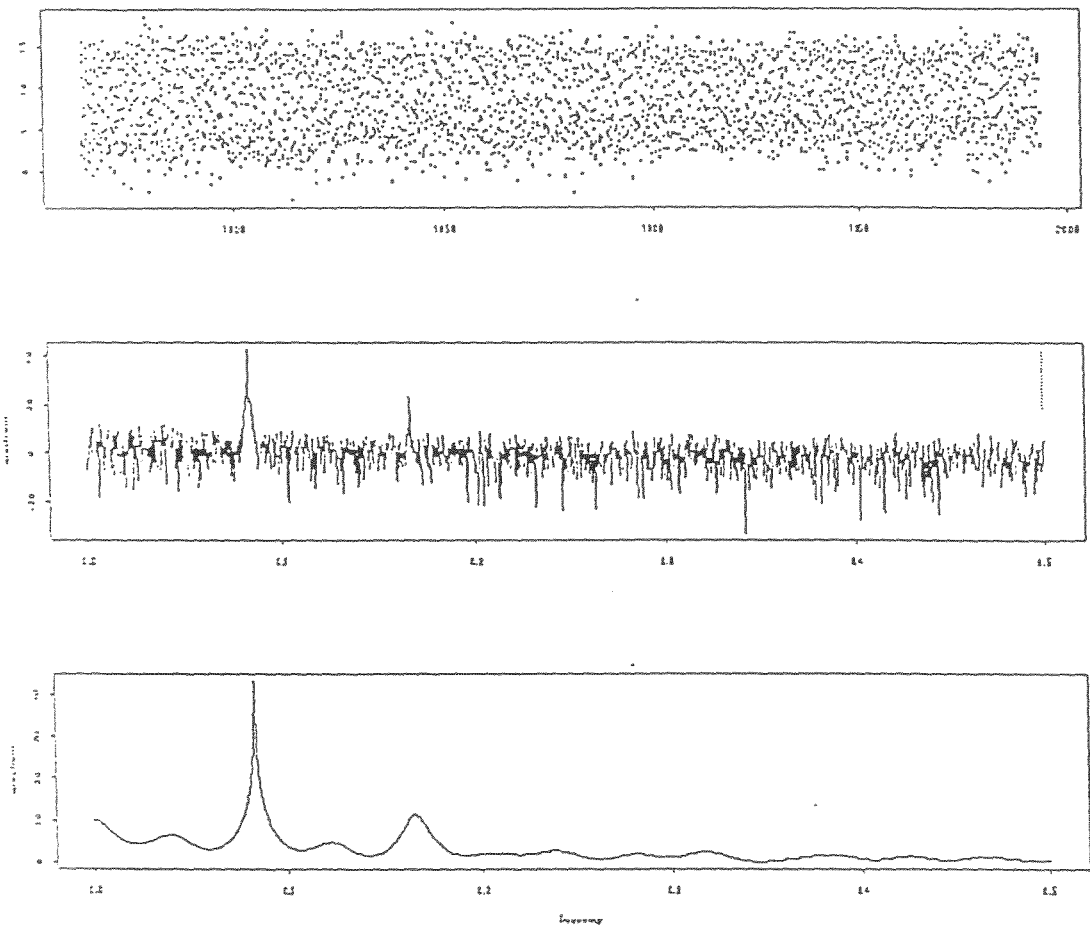


Figure 13. The new Edinburgh series shown as (i) the raw data (ii) the raw periodogram and (iii) the smoothed frequency spectrum with a clear sharp peak corresponding to a period of 12 months and a second peak at a period of 6 months.



2. Tree ring records and tephra in Ulster (Project leader: Mike Baillie)

This part of the project has not yet been funded.

3. Proxy-climate indicators in lowland lake sediments (Project leader: Frank Oldfield)

Jonathan Holmes (Kingston University), Bill Austin (University of Edinburgh), & Frank Oldfield (University of Liverpool).

3.1 Ostracods from Lough-na-Shade sediments

Work on ostracods from Lough-na-Shade has concentrated on stable oxygen and carbon isotope analysis in the section of the core from 68 to 85cm. Isotopic analyses have been undertaken at the SURRC (Scottish Universities Research and Reactor Centre) Stable-Isotope Facility at East Kilbride on 44 multiple-valve samples of *Candona* sp. using a VG-PRISM mass spectrometer. Results are presented in figure 3.1. Analytical precision was: $^{13}\text{C}=0.07$, $^{18}\text{O}=0.118$ (i.e. 1s for $n=9$ sm standards of 0.1mg or less). Values plotted in figure 3.1 are in the standard delta notation relative to the PDB standard.

The $^{18}\text{O}/^{16}\text{O}$ ratio of carbonates, such as ostracod shells, is predominantly controlled by the temperature and the $^{18}\text{O}/^{16}\text{O}$ ratio of the water in which the carbonate is formed. Previous work suggests that ostracod shells are precipitated in near isotopic equilibrium with the host water (e.g. Xia, J. *et al.*, 1993). The $^{18}\text{O}/^{16}\text{O}$ ratio of the host water may be controlled by the isotopic composition of regional rainfall (itself controlled by air temperature and air-mass source), the isotopic composition of runoff inputs and the ratio of precipitation to evaporation.

In the UK, especially at a more oceanic locality such as Lough-na-Shade, the most important factor governing the $^{18}\text{O}/^{16}\text{O}$ ratio of the lake water is likely to be the isotopic composition of regional rainfall. Andrews *et al.* (1994), in a study of tufa carbonate in Derbyshire, attribute variations in $\delta^{18}\text{O}$ of up to 1‰ during the Holocene mainly to changes in the $^{18}\text{O}/^{16}\text{O}$ of precipitation, which are in turn related to changes in air temperature. Changes in the ratio of precipitation to evaporation may also be important, especially in a small basin such as Lough-na-Shade. However, the effects of changes in the precipitation/evaporation balance tend to have been discounted by mid-latitude workers. For Lough-na-Shade, therefore, increases in $\delta^{18}\text{O}$ could reflect decreases in temperature of precipitation, or, more likely, increase in air temperature and, possibly, reduced precipitation/evaporation. A change in air mass source could also cause the changes, although at this stage it is difficult to assess the likely direction and magnitude of this effect.

The $^{13}\text{C}/^{12}\text{C}$ ratio of ostracod carbonate reflects the $^{13}\text{C}/^{12}\text{C}$ ratio of the lake water's dissolved inorganic carbon (DIC), which is largely a reflection of carbon source. More negative $\delta^{13}\text{C}$ values suggest greater influence of decayed organic carbon on the DIC of lake water, while less negative values reflect active photosynthesis dominating decay: hence, in lakes, $\delta^{13}\text{C}$ is often regarded as a palaeoproductivity proxy.

There is weak covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. Covariance, although poorly understood and probably of more than one origin, often occurs in closed lakes with long residence times (Talbot, 1990).

Although the trends within the Lough-na-Shade cores are quite clear, there is some considerable scatter at each level where replicate samples have been analysed. This reflects within-sample variability, and is especially marked where only a few valves per sample are analysed (e.g. Xia, J. *et al.*, 1993), as was the case in some of our earlier samples. This variability is largely a function of seasonal and interannual (if samples integrate >1 year) changes in the $d^{18}O$ and $d^{13}C$ of the water/DIC. It is especially marked for $d^{13}C$: this may be because $d^{13}C$ is controlled more strongly by micro-habitat variations in the carbon isotope ratio of the DIC within the lake, whereas $d^{18}O$ shows less spatial variation within a well mixed lake.

Ostracods from the remaining parts of the Lough-na-Shade sequence are currently being picked for stable isotope analyses. Where sufficient material remains, samples will also be run for trace element determinations in Kingston using ICP-AES. Mg/Ca and Sr/Ca ratios within the ostracod valves will provide additional palaeohydrological information. In particular, variations in Mg/Ca, which are controlled in part by water temperature changes, will place important constraints on the oxygen-isotope record.

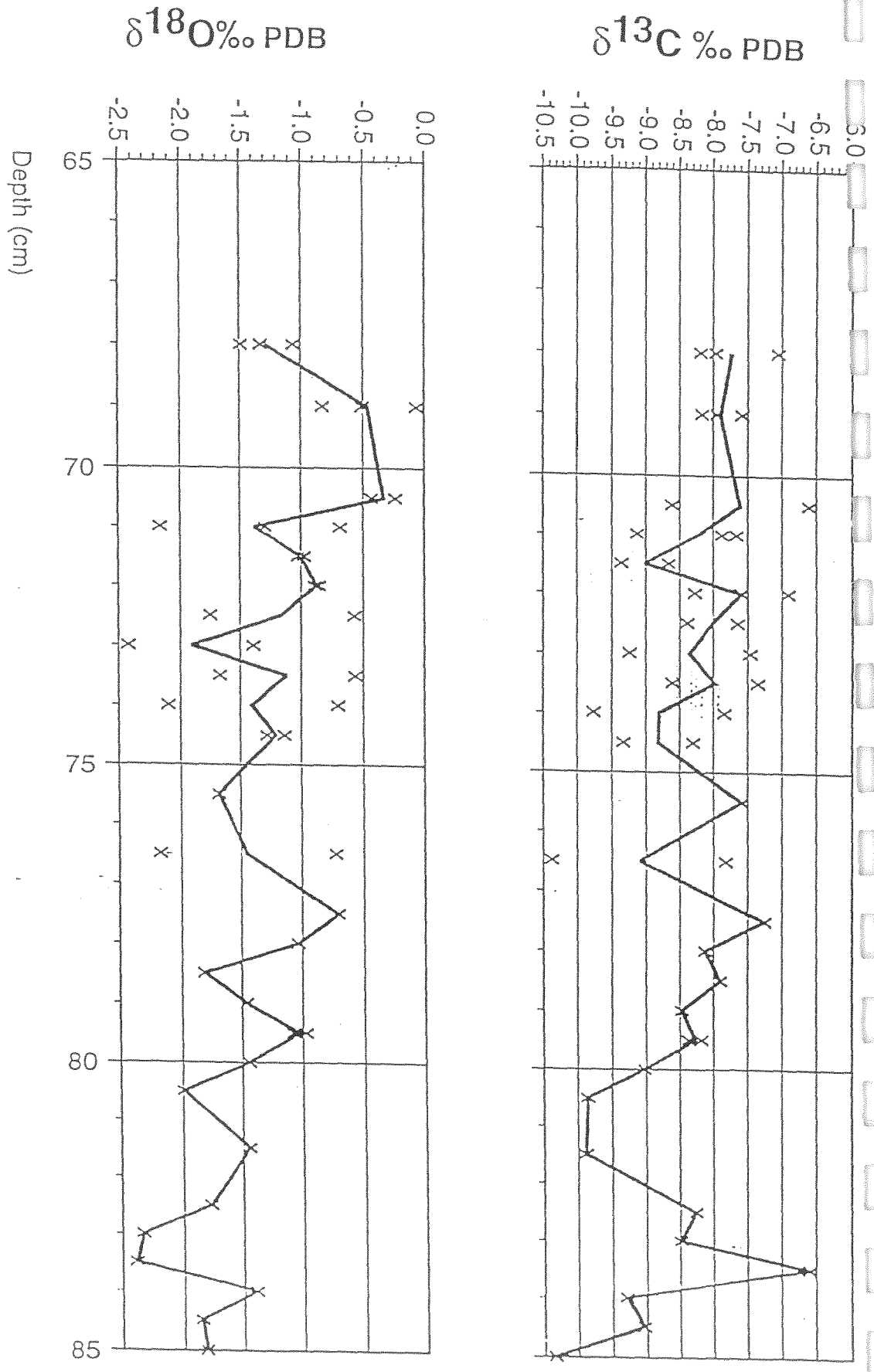
References

- Andrews *et al.* (1994) *The Holocene* 4, 349-355.
- Talbot, (1990) *Chemical Geology (Isotope Geosciences Section)* 80, 261-279.
- Xia, J. *et al.*, (1993). *EOS Trans. am. geophys. Union* 74, 365.

Figures

Figure 3.1 Stable isotope data for Lough-na-Shade

Lough-na-Shade



4. Proxy-climate indicators in raised bogs (Project leader: Keith Barber)

Keith Barber & Rob Stoneman (Southampton University), Tony Stevenson (Newcastle University), Neil Rose, & Paul Golding (UCL), Kath Ficken (Bristol).

4.1 Macrofossils

The lowland raised bog of Fallahogy in Northern Ireland, analysed by Rob Stoneman, produced a striking macrofossil diagram (Figure 4.1), with climate-driven changes between peat components and different *Sphagnum* species. The two wettest periods are pre-Medieval and between AD1630-1815. There have been problems with the dating of the upper 40 cm due to the penetration of bomb ^{14}C , perhaps via root channels following a fire in the 1960s, but due to the pollen analyses we are confident of the integrity of this profile. The complete profile of 160 cm certainly covers the last 2,000 years - the radiocarbon date from 145 cm is 1865 +/- 40 uncal. BP. A further 10 radiocarbon assays are in progress to give a detailed geochronology below 50 cm, after which a full palaeoecological interpretation will be made with the benefit of multivariate statistics.

4.2 Humification

The humification profile (Figure 4.2) is a similarly strong signal, with a very significant decline from values touching 50% in the early part of the last 2,000 years down to lows in the 20 -30% range after about AD600. The least humified part of the profile (apart from the fresh surface material) around 35 cm is coincident with the wet period in the macrofossils, as one would expect. Together with the macrofossils these diagrams present a detailed sequential picture of climate change in Northern Ireland over the last two millennia.

4.3 Tephra

The tephra profile for Fallahogy is shown in Figure 4.3. It shows a major peak at 86-87 cm, although tephra is present at many other levels. The pattern is consistent with earlier work at this site (Pilcher & Hall 1992).

4.4 Pollen

Figure 4.4 shows the pollen diagram from Fallahogy.

4.5 Organic geochemistry

4.5.1 Molecular characterisation of lipids

Following the macrofossil analysis of the Fallahogy core four samples, one from each zone, were selected and are presently being analysed. The lipids extracted from these sediments will be split into three fractions:

1. hydrocarbon fraction
2. alcohol fraction
3. acid fraction

Each of these fractions will be characterised on a molecular scale by gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). Molecular fingerprints of the fractions will be compared.

4.5.2 $\delta^{13}\text{C}$ characterisation of the hydrocarbon fraction

The stable carbon isotopes of the hydrocarbon fraction will be characterised. Downhole plots of $\delta^{13}\text{C}$ for the individual alkanes for each layer will be plotted and compared. A comparison with other records, such as ice cores and European lake temperature, pollen records etc. will be made.

4.5.3 PY-GC of sediments

Extracted sediment residues of two samples will be analysed by pyrolysis-gas chromatography (py-GC) in order to obtain information on the resistant organic matter such as lignins, cuticles etc. If this information proves useful, pyrolysis-GC-MS will be performed to characterise fully the chromatograms, and additional samples may be analysed.

4.6 Remaining work

1. 10 ^{14}C assays remain in the allocation for this site and will be used to tie down the chronology of the changes below 50 cm;
2. DCA and time-series analyses will then be performed;
3. The tephra analyses need geochemical typing at Edinburgh - this will prove problematic due to the small shard size;
4. Carbonaceous particles will be counted in the uppermost peat (by Neil Rose).

References

Pilcher, J.R. & Hall, V.A. (1992) Towards a tephrochronology for the Holocene of the north of Ireland. *Holocene* 2: 255-259

Figures

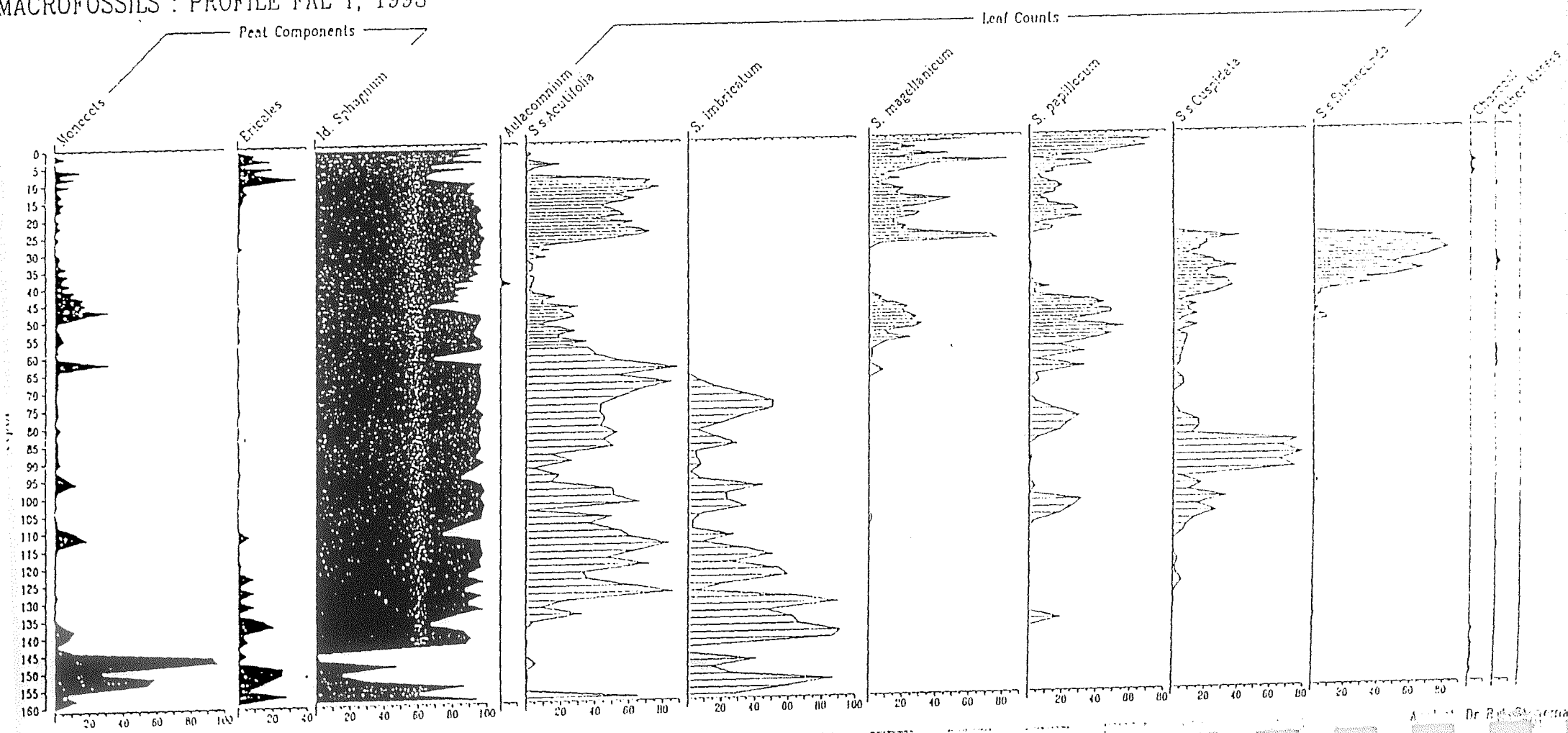
Figure 4.1 Macrofossil diagram for Fallahogy Bog

Figure 4.2 Humification profile for Fallahogy Bog

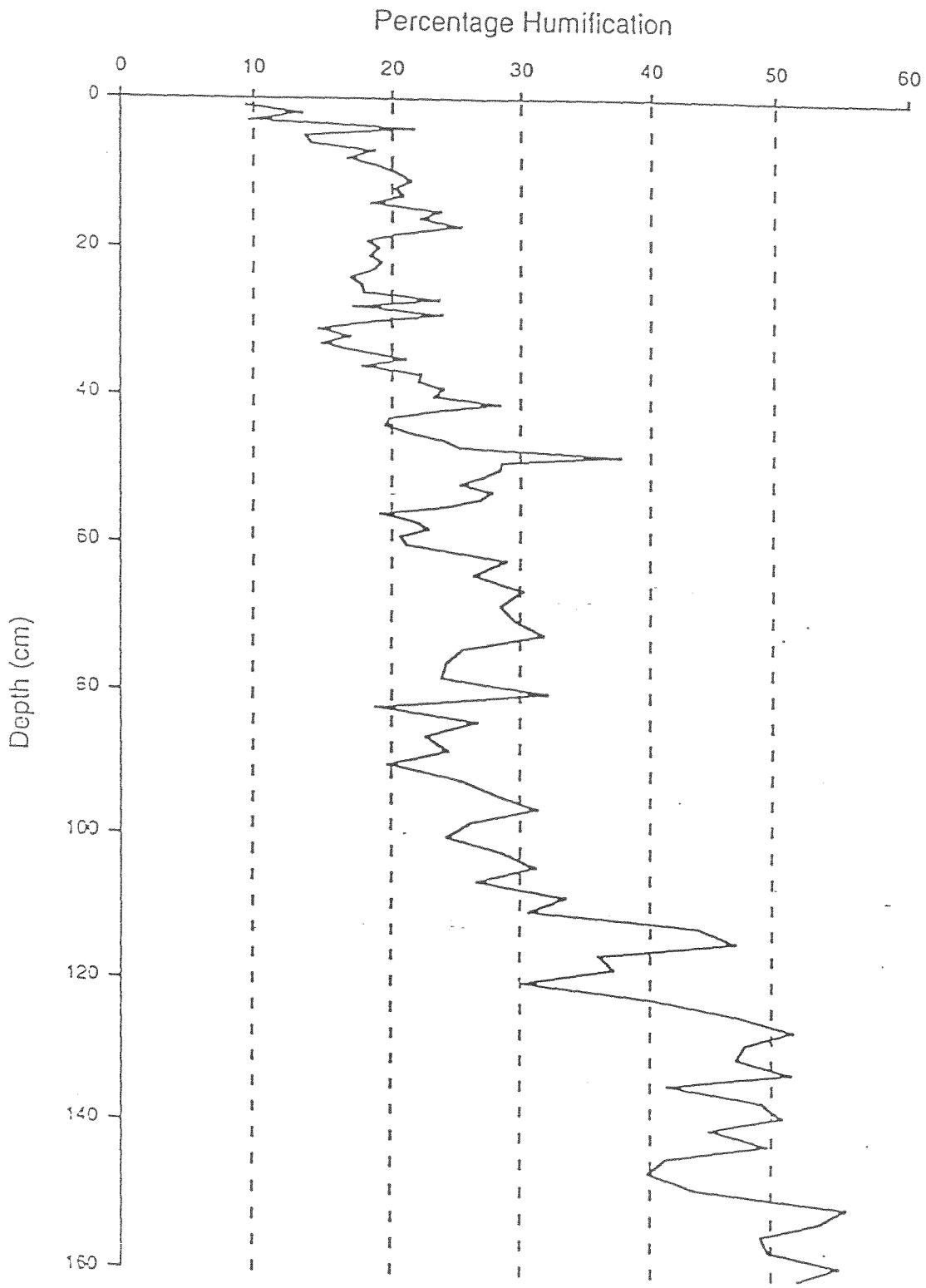
Figure 4.3 Tephra diagram for Fallahogy Bog

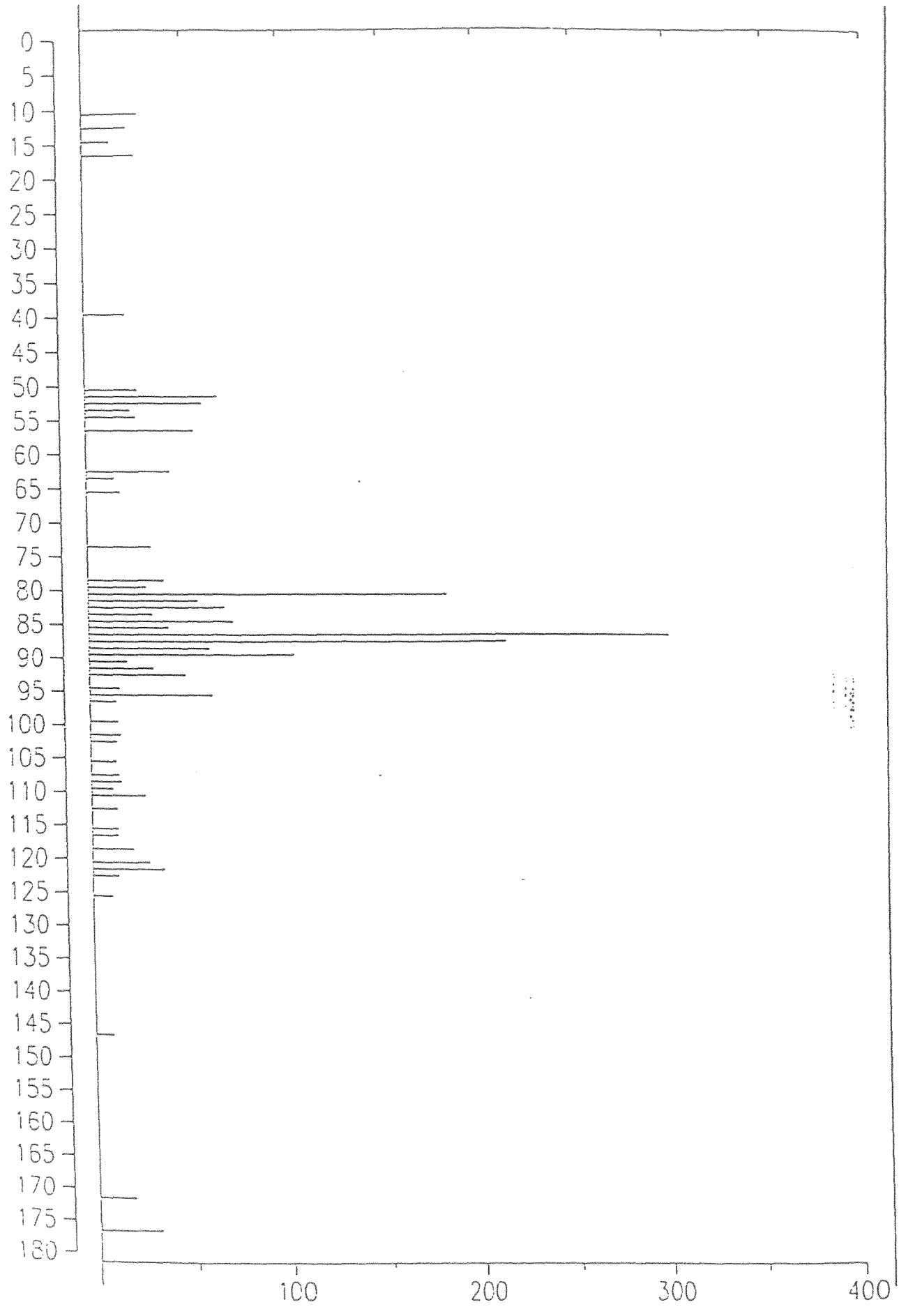
Figure 4.4 Pollen diagram for Fallahogy Bog

FALLAHOGY BOG, NORTHERN IRELAND
MACROFOSSILS : PROFILE FAL 1, 1993



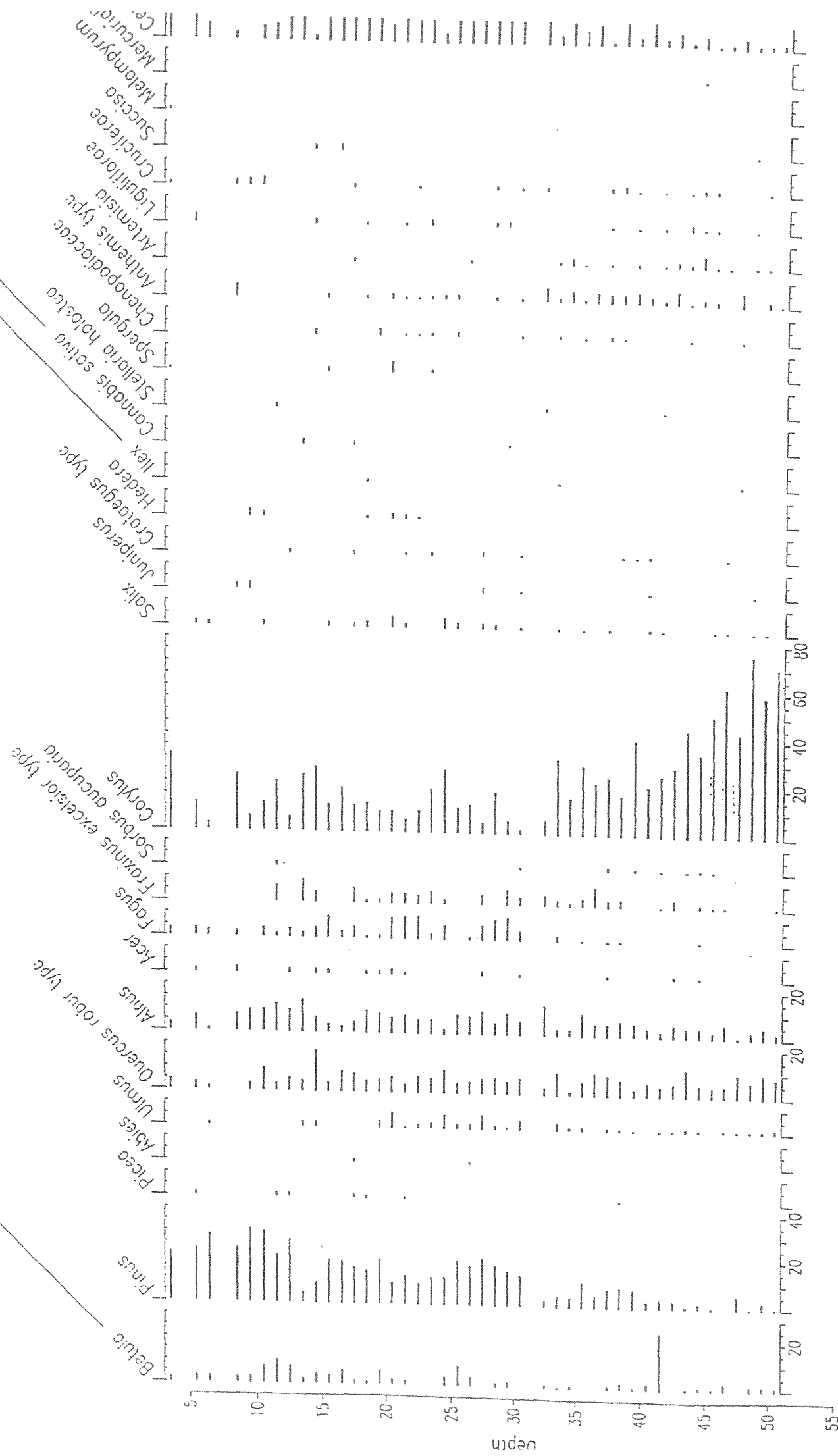
Fallahogy Bog (FAL/1/93) - Humification Profile





No. spores cm⁻³

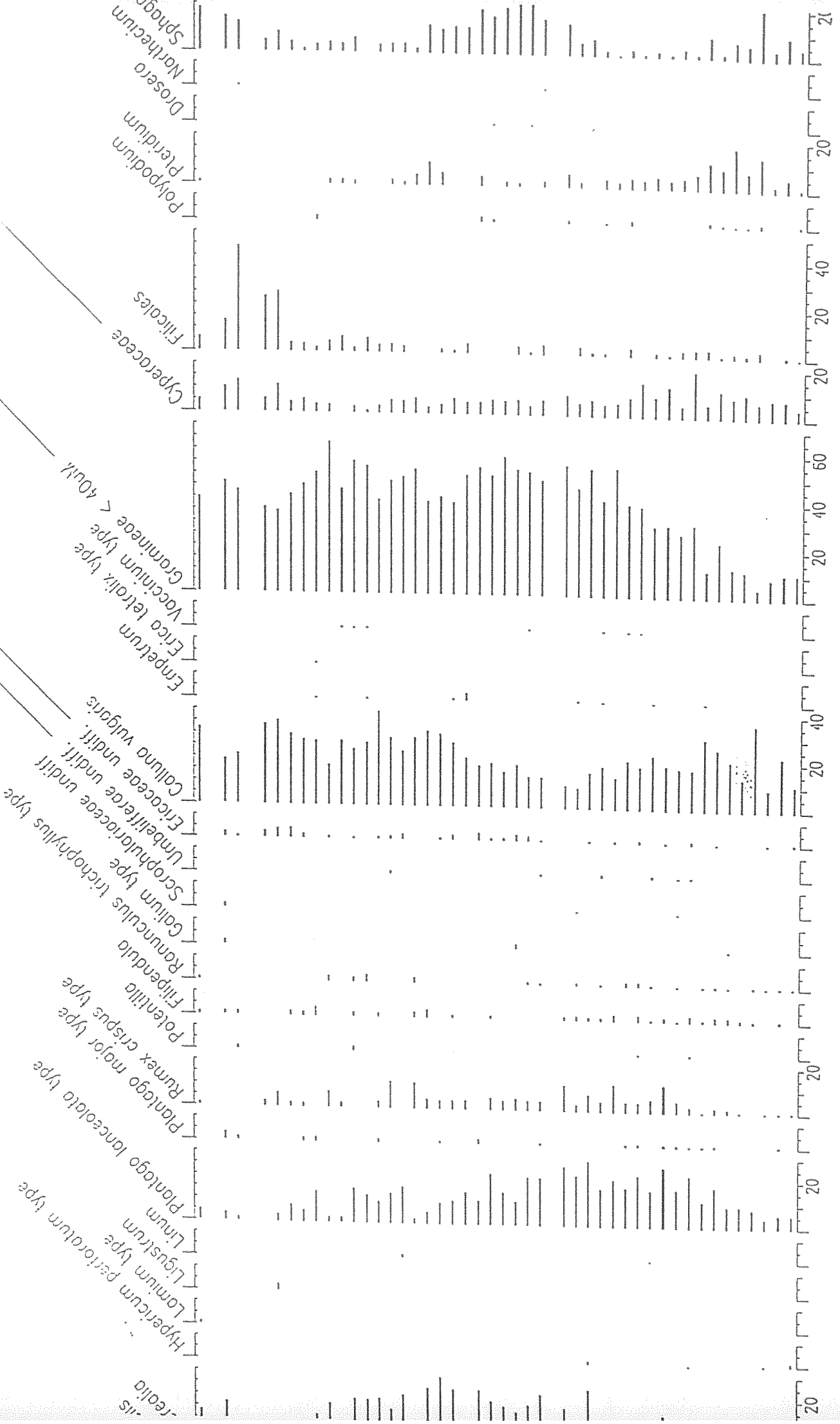
Trees and shrubs



Ferns

Dwarf shrubs and grass

Herbs



3000

Menyanthes

1

5. Proxy climate indicators in montane lake sediments (Project leader: Nigel Cameron)

5.1 Chronology

5.1.1 Radiocarbon dating (Doug Harkness, East Kilbride; Nigel Cameron, UCL)

We now have the full set of 36 AMS radiocarbon dates from the NERC laboratory in East Kilbride. They are shown alongside the lithostratigraphic loss on ignition profile (Fig. 5.1). Figure 5.2 shows the ages of samples selected from peak organic values as opposed to those selected from trough organic values. There is a suggestion that relatively older dates are associated with LOI troughs, this would be consistent with inwash events increasing the amount of older carbon supplied to the lake sediment. Dates can now be transferred directly from the "mastercore" UACT4 to the other cores by Roy Thompson using his sequence slotting program for stratigraphic correlation. Frank Oldfield has made some useful suggestions re. the use of dates and the most appropriate dates based on his work at Kassjön

5.1.2 Time series analysis of ^{14}C dates (Roy Thompson, University of Edinburgh)

The detailed sequence of ^{14}C dates measured for the L. Uaine core provide an excellent basis for carrying out time series analysis on down core measurements. First the ^{14}C ages need some interpretation (as above). Three main schemes can then be used (Figure 5.3) to derive a time-scale:

1. Constant accumulation - by discarding the three upper measurements that are likely to be contaminated by old carbon a constant linear accumulation rate of 0.018 mm/year is found.
2. Convex hull analysis - by using the envelope of points least affected by any old carbon, a maximum accumulation rate relationship can be produced. This scheme (not favoured here) would produce a recent accumulation rate of 0.023 mm/year.
3. Polynomial or spline fitting - a time-varying accumulation rate can be derived by smoothing the data judged not to have been affected by old carbon contamination. Spline fitting leads to a recent accumulation rate of 0.013 mm/year.

The ^{210}Pb results can be used as a test of these schemes (see below).

For the time series analysis the ^{14}C dates were calibrated and both a linear and a spline fit to the data were used to calculate depths at equally spaced ages. The LOI and dry weight data were then interpolated at these equally spaced ages. Both the Fourier transform and the smoothed periodogram were obtained from this equally spaced data. No periodicity was found in either data set using either dating scheme. A separate study was made of the section of the core below 28cm as this section appeared, from initial inspection, to contain periodic variations. Again the time series failed to reveal any true periodicity in the data.

5.1.3 ^{210}Pb and ^{137}Cs dating (Peter Appleby, University of Liverpool)

Sediment samples from core UACT4 were analysed for ^{210}Pb , ^{226}Ra , and ^{137}Cs by gamma spectrometry using a well-type coaxial low background intrinsic germanium detector fitted with a NaI (Tl) escape suppression shield (Appleby *et al.* 1986). The results are given in Table 5.1, and shown graphically in Figures 5.4 and 5.5.

^{210}Pb chronologies have been calculated using both the CRS and CIC ^{210}Pb dating models (Appleby & Oldfield 1978) and the results are shown in Figure 5.6. Unsupported ^{210}Pb activity (Figure 5.4b) declines more or less exponentially with depth and there is negligible difference between the two sets of dates. Both indicate a very slow but uniform sediment accumulation during the past 100 years. Equilibrium of ^{210}Pb with the supporting ^{226}Ra (ca. 1876) occurs at a depth of just 3.5 cm. The mean sediment accumulation rate during this period is calculated to be $0.0051 \pm 0.0006 \text{ g cm}^{-2} \text{ yr}^{-1}$ (or $0.030 \pm 0.004 \text{ cm yr}^{-1}$). ^{210}Pb dates calculated using this value are given in Table 5.2.

Validation of the ^{210}Pb by ^{137}Cs was precluded by the slow accumulation rate and evident ^{137}Cs mobility. Maximum ^{137}Cs activity occurred in the topmost sample, and significant values were recorded down to below 3 cm, well before the 1954 onset of nuclear weapons testing. One unusual aspect of the result is the abnormally low ^{137}Cs inventory of the core (Table 5.1). In contrast the ^{210}Pb inventory is comparable to that supported by the atmospheric flux. Traces of ^{241}Am , also a product of the atmospheric testing of nuclear weapons were recorded in the 0.4-0.6 cm sample, suggesting a date of ca. 1963 for this level (Appleby *et al.* 1991). Figure 5.6 shows that this is in reasonable agreement with the ^{210}Pb chronology.

Figure 5.7 compares the ^{210}Pb dates with the ^{14}C dates for the core. Excluding two anomalous results in the top 10 cm, the dates suggest a mean accumulation rate for the past 5000 years of 0.024 cm yr^{-1} . This is in relatively good agreement with the ^{210}Pb value (0.030 cm yr^{-1}), particularly since the ^{14}C is likely to be reduced by greater compaction of the deeper sediments. The absolute ^{14}C dates appear, however, to be too old by ca. 450 yr, presumably due to old carbon in the samples.

5.1.4 Tephra (Neil Rose & Paul Golding, UCL)

Tephra analysis for Lochan Uaine (UACT 4) has now been completed down to 50cm (^{14}C date approximately $2400 \pm 60 \text{ BP}$) and the profile is shown in Figure 5.8. The method used was one of selective chemical attack and is outlined below (Sub-project 7) Three 'groups' of shards have been found as in the two peat cores (see sub-projects 4 and 6), but again the shards are small and have not been analysed geochemically. The peak occurs at 32cm (^{14}C date approximately $1450 \pm 45 \text{ BP}$) putting it too early for the previously suspected Hekla 1104 AD eruption. However, the peak is not as clearly defined as in the peat cores and so the dating is doubtful.

The UACT 4 core is 95cm long and although strictly speaking outside the TIGGER 'last 2000 years' it is hoped to continue the analysis to the base of the core in a search for Hekla 4 shards (approximately 4000 BP or 85-90cm in UACT 4). These should be large enough to analyse geochemically.

Table 5.1 Lochan Uaine (Cairn Toul): Radiometric Data Core UACT4

Depth cm	Dry Mass gcm ⁻²	²¹⁰ Pb Concentration				²²⁶ Ra Conc		¹³⁷ Cs Conc	
		Total		Unsupp					
		Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±	Bq kg ⁻¹	±
0.10	0.01	2836.4	87.0	2477.3	87.9	359.1	12.9	117.1	8.8
0.50	0.07	1915.6	49.4	1496.0	50.5	419.6	10.4	104.3	7.6
0.90	0.14	1459.8	66.4	1001.5	68.0	458.3	14.8	96.2	10.8
1.30	0.20	1272.0	64.5	775.5	66.2	496.5	15.1	66.9	10.1
1.70	0.28	1097.7	84.2	507.6	86.7	590.1	21.1	61.9	13.9
2.10	0.35	871.7	33.9	299.3	35.4	572.4	10.0	36.0	5.5
2.50	0.41	832.0	56.1	242.1	58.6	589.9	17.2	41.5	11.9
2.90	0.48	761.2	58.0	215.2	59.7	546.0	14.3	31.2	7.2
3.30	0.56	691.7	44.9	63.0	47.0	628.7	13.9	25.4	7.2
3.70	0.63	455.0	27.3	-62.7	28.9	517.7	9.4	11.1	4.4
4.10	0.70	568.0	40.4	-23.2	42.2	591.2	12.1	13.7	5.6
6.10	1.02	729.3	50.7	101.1	52.7	628.2	14.3	0.0	0.0
8.10	1.33	661.4	79.3	102.3	81.7	559.1	20.0	0.0	0.0
12.10	2.01	669.0	43.9	67.9	46.0	601.1	13.8	0.0	0.0

Unsupported ²¹⁰Pb inventory 4050 ± 146 Bq m⁻²
²¹⁰Pb flux 126 ± 5 Bq m⁻²y⁻¹
¹³⁷Cs inventory 398 ± 23 Bq m⁻²

Table 5.2 Lochan Uaine (Cairn Toul): ^{210}Pb chronology Core UACT4

Depth cm	Dry Mass gcm^{-2}	Chronology			Sedimentation Rate		
		Date AD	Age yr	\pm	$\text{gcm}^{-2}\text{yr}^{-1}$	cmyr^{-1}	\pm (%)
0.00	0.00	1993	0				
0.10	0.01	1990	3	2			
0.20	0.03	1988	5	2			
0.30	0.04	1985	8	2			
0.40	0.06	1982	11	2			
0.50	0.07	1979	14	2			
0.60	0.09	1976	17	2			
0.70	0.11	1972	21	2			
0.80	0.12	1969	24	2			
0.90	0.14	1966	27	2			
1.00	0.16	1963	30	2			
1.10	0.17	1960	33	3			
1.20	0.19	1956	37	3			
1.30	0.20	1953	40	3			
1.40	0.22	1950	43	3			
1.50	0.24	1946	47	4			
1.60	0.26	1943	50	4			
1.70	0.28	1939	54	4	0.0051	0.030	12%
1.80	0.29	1936	57	5			
1.90	0.31	1932	61	5			
2.00	0.33	1929	64	6			
2.10	0.35	1926	67	6			
2.20	0.36	1922	71	7			
2.30	0.38	1919	74	7			
2.40	0.40	1916	77	8			
2.50	0.41	1912	81	9			
2.60	0.43	1909	84	10			
2.70	0.45	1906	87	11			
2.80	0.47	1902	91	12			
2.90	0.48	1899	94	13			
3.00	0.50	1895	98	15			
3.10	0.52	1892	101	16			
3.20	0.54	1888	105	17			
3.30	0.56	1884	109	19			

5.2 Particle size analysis (Roy Thompson, University of Edinburgh)

5.2.1 Methodology and relationship to dry weight and LOI data

Particle sizing has been conducted on Lochan Uaine core 4 down to a depth of 38 cm (corresponding to the last 2000 years). Measurements were made at 2mm intervals using a Coulter LS1000 particle sizer. A total of 189 samples have been measured. The results have been analysed to produce a measure of the mean and variance of the particle size distribution. The particle sizer measures the intensity of the light diffracted at each of an array of 132 detectors. This intensity depends on the curvature of the particles encountered by the light beam and is converted to give a percentage of the total sample volume present in a total of 73 bins. These correspond to regular sizes on a logarithmic scale ranging from 0-1000 microns (Figure 5.9). The mean and variance were calculated using a simple algorithm taking the % volume and the particle size as input. The resulting data are plotted against the dry weight and loss on ignition data for core 4 (Figure 5.10) in order to identify the degree of agreement between the data. As can be seen from the plots, the data are not highly correlated. The variations in the LOI data are not strongly reflected in the particle size data. This result is unexpected. Catchment erosion processes would, for example, be anticipated to produce coherent variations in minerogenic content and hence in both LOI and particle size. There is some indication in the lower left panel of Figure 5.10 that the coarser grained sediments have lower dry weights. This is the normal relationship expected between particle size and density. Following discussion at the TIGGER 2a meeting held at UCL in MARCH we are awaiting samples from the ECRC which have had the organics removed to check that our particle size data have not been adversely affected by the sample preparation method used in Edinburgh. We will report our findings as soon as data are available.

5.2.2 Particle size distribution decomposition

Figure 5.11 shows the results of a decomposition procedure which has been devised to isolate log normal components in the particle size data. In this example the top 159 horizons have been analysed separately and decomposed into two separate components. The main component of the sediment is seen in Figure 5.11a to consist of a log normal distribution with a mean size of 40 μm . This main component dominates the particle size distribution at almost all levels in the top 38cm of the core. A smaller component (Figure 5.11b) has a mean size of about 250 μm . The size distributions again do not coincide with the expectation of diatoms (~10-20 μm) making up a significant proportion of these high Cairngorm sites. Further work is planned to investigate these unexpected results.

5.3 Magnetic measurements (Frank Oldfield, University of Liverpool).

5.3.1 Methods

Magnetic measurements have been carried out on Lochan Uaine core UACT 3. Subsamples from all 2mm slices have been subjected to the following sequence of measurements:-

- Lowfield, low frequency susceptibility ($\chi_{LF} = \chi$)
- Anhysteretic Remanent Magnetization (ARM)
- 'Saturation' (= 1 Tesla) Isothermal Remanent Magnetization (SIRM)
- Stepwise DC demagnetization of SIRM at -20mT, -30mT, -40mT, -50mT, -100mT and -300mT.

Susceptibilities were measured using a Bartington MS2 Meter and dual frequency sensor. ARM's were grown in a Molspin AF- demagnetizer with ARM attachment, using a peak AF field of 0.1T and a DC bias of 0.04mT. Isothermal remanences were grown and demagnetized using a Molspin Pulse Magnetizer. All remanences were measured on a Minispin slow speed spinner Fluxgate Magnetometer. Susceptibility values have all been adjusted for the diamagnetic effect of the plastic sample holders and cling-film packing. Around 5% of the samples have been omitted from the data set because of inconsistent measurements. The measurements allow a wide range of mass specific, quotient and percentage calculations of which six are shown here. All the measurements made are close to the noise level of the instruments used and/or the contamination levels of the sample pots. Consequently the results as a whole are marked by a high level of variability. Despite this, coherent trends and fluctuations can be recognized.

5.3.2 Results and discussion

Figures 5.12-5.17 show a selection of the results: χ , χ_{arm} , 'Soft' IRM (SIRM-IRM_{-20mT}), 'Hard' IRM (SIRM + IRM_{-300mT}), 'Hard' IRM as a percentage of SIRM and χ_{arm} /'soft' IRM.

The reverse field ratios confirm that an imperfect antiferromagnetic mineral, presumably haematite derived from the granite catchment bedrock is a major contributor to the rock magnetic properties and their variations throughout the core. Where this is the case, it can be safely inferred that 'haematite' is the dominant magnetic mineral in terms of concentration.

The χ_{arm} /SIRM χ_{arm} /'Soft' IRM' and χ_{arm}/χ quotients strongly suggest that multidomain magnetite/titano-magnetite is the dominant ferrimagnetic phase in the sediments, though finer grained components may also be present in smaller quantities.

The SIRM/ χ quotients and reverse field ratios indicate that greigite, a ferrimagnetic iron sulphide now known to be present in a wide range of sediments, does not appear to have contributed significantly to the magnetic properties of any of the samples.

From the above observations, it may be concluded that the magnetic properties of the sediments from Lochan Uaine are dominated by catchment-derived, dominantly primary, lithogenic magnetic minerals and that the fluctuations recorded in these components may reflect changes in particle size, in the balance between different catchment source types and/or shifts in the importance of lithogenic inputs as a whole relative to other sediment components.

The strongest fluctuations are in the 'hard' IRM (= 'haematite') component whether expressed

on a mass specific (Figure 5.15) or a 'percentage of SIRM' (Figure 5.16) basis. The high values above 16cm may reflect atmospheric deposition in part, but the provisional ^{14}C chronology, interpreted conservatively, points to a pre - AD 1800 date for the onset of the rise and an increase in catchment erosion related to 'Little Ice Age' conditions is a possibility.

The fluctuations in 'hard' IRM below this are more modest in mass specific terms, though the percentage values show strong oscillations, with three maxima dating to around 1400, 2500 and 4500 BP (uncalibrated) if a provisional and very approximate chronology is derived from the 'youngest' of the dates in the suite of measurements now available.

Fluctuations in the ferrimagnetic 'magnetite' component of the record are superimposed on an overall decline in concentrations that may reflect some mineral dissolution. The steep decline in 'hard' IRM above 16cm strongly suggests that declines in ARM (Figure 5.13) and 'soft' IRM (Figure 5.14) components in this upper part of the profile are more likely to reflect catchment processes than dissolution. Below this, the strongest signs of down-core reductions in concentration are in the ARM and intermediate coercivity of IRM components. This could be interpreted as some progressive dissolution of bacterial magnetosomes. Failure of the χ (Figure 5.12) and 'soft' IRM (Figure 5.13) profiles to show a significant down-core decline below 16cm suggests that the catchment derived components were little affected by any dissolution that may have occurred. This being the case, it is interesting to note that the variations in 'soft' and 'hard' IRM components are not strongly coupled, suggesting that they may be responding to different catchment processes.

Several additional lines of research are envisaged with a view to exploring the possible environmental inferences to be drawn from the variations observed:-

1. Magnetic measurements on particle-size separates from aggregated undried samples
2. More detailed magnetic measurements on aggregated, dried subsamples, including:
 - (a) high field remanence acquisition
 - (b) low temperature remanence and susceptibility
 - (c) analysis of IRM acquisition spectra
 - (d) Curie temperature experiments
 - (e) hysteresis loop plots
 - (f) frequency-dependent susceptibility measurements.

5.4 Diatoms and a preliminary pH reconstruction (Nigel Cameron & Paul Golding)

Diatoms have been counted in several sections of UACT4 between 0 to 45 cm which covers the 2000 year remit of the TIGGER IIa project.

Diatom (& chrysophyte cyst in the lower part) concentrations for 2 sections of the UACT4 are plotted with lithostratigraphy (Figure 5.18-5.20). No correlation between lithostratigraphic changes and valve or cyst concentrations is apparent although diatom concentrations are generally higher in the lower part of the core where the sediment organic content is higher (Figure 5.20). Valve & cyst concentrations are positively correlated (Figures 5.21, 5.22).

The composition of diatom assemblages in the sections of the core counted so far are relatively stable (e.g. Figure 5.23). Using the SWAP 167 lake diatom surface sediment/water chemistry calibration set we have reconstructed the pH over the section of the UACT4 core 36.5-45.0 cm. Values were in the range 5.2-5.5, but there is as yet no evidence for systematic pH variation, for example, linked to the %DW/%LOI cycles observed (Figure 5.24). The present day measured lakewater pH of Lochan Uaine is in the range 5.8-5.9 (n=4), but surface sediment pH has not yet been reconstructed for comparison. Work is in progress to complete the analysis of contiguous samples throughout this section. The next stage will be to use a new diatom surface sediment calibration set based on our pan-European alpine-arctic 118 lake surface sediment/diatom training set (Birks *et al.* in prep.) to reconstruct pH over this part of the core.

There is a growing interest in the possibilities of using freshwater lake diatom assemblages from appropriate arctic & alpine lakes to reconstruct palaeotemperatures directly (Pienitz *et al.* 1995, Vyverman & Sabbe 1995). As yet these methods lack the ecophysiological basis that underpins diatom-based pH, salinity & nutrient reconstructions. However, the coupling of pH and temperature remains an indirect link between diatom assemblages and climate (see earlier Tigger News).

5.5 Chironomidae analysis (Steve Brooks, Natural History Museum)

Samples from the Lochan Uaine sediment core (UACT 3) were received via Liverpool University in November 1994. So far chironomid head capsules have been sorted and slide mounted from 36 samples. Head capsules have been identified from 29 of these samples at roughly 5 cm intervals from the surface sample down to 120 cm. Eventually it is planned to complete analysis of the core at 2 mm intervals from selected levels.

5.5.1 Preservation of head capsules

The concentration of head capsules in the samples has been variable. Relatively high numbers have been present in the top 60 cm of the core. Below this, numbers have been generally low with sporadic samples having a high concentration. The quality of the head capsules has been poor. In many cases the head capsules have lost their mandibles, premandibles and antennae. When present, the mandibles and mental teeth are often badly worn. Many capsules are fragmented and have the appearance of being partially dissolved. The chitinised head capsules preserve best in anaerobic sediments and it may be that conditions were too aerobic for good preservation.

The poor state of preservation has meant that the head capsules have been difficult to identify and taxonomic resolution has not been as good as might have been hoped. The greatest difficulty has been experienced with the Tanytarsini. It has been possible to identify only relatively few specimens of this tribe to genus or species level.

5.5.2 Results

Although the sampling resolution of the core has so far been relatively coarse, a distinct change in the chironomid fauna is evident from the data. Figure 5.25 shows the results of the preliminary chironomid analysis. The chironomid diagram can be divided into three zones.

ZONE 3 (120-110 cm)

The chironomid fauna is dominated by Orthoclaadiinae, especially *Heterotrissocladius grimshawi*.

ZONE 2 (110-59 cm)

This zone is characterised by the presence of *Microtendipes* nr *pedellus* and *Heterotanytarsus apicalis*. Throughout the zone there is a gradual increase in the relative abundance of Tanytarsini. At the beginning of the zone there is a brief peak in abundance of *Microtendipes* coinciding with a decline in *H. grimshawi*. After the *Microtendipes* peak there is an increase in abundance of *H. grimshawi*, *Sergentia coracina* and *Heterotanytarsus apicalis*.

ZONE 1 (59-0 cm)

Microtendipes and *Heterotanytarsus* are absent in zone 1. The zone is characterised by high abundance of *H. grimshawi*, *S. coracina*, Tanytarsini and the continued presence of *Corynoneura scutellata* and *Protanypus morio* which were infrequent in the preceding zones.

A sample of pupal exuviae from the lake in July 1993 revealed the presence of six species (Table 5.3). This sample has helped to clarify the identity of some of the taxa present as head capsules in the lake sediment.

Table 5.3 Species of Chironomidae collected as pupal exuviae from Lochan Uaine, 23 July 1993.

Arctopelopia griseipennis (van der Wulp)
Corynoneura scutellata Winnertz
Heterotrissocladius grimshawi (Edwards)
Psectrocladius octomaculatus Wülker
Micropsectra atrofasciata Kieffer
M. junci (Meigen)

5.5.3 Ecological interpretation.

During Zone 3, with the high relative abundance of *Heterotrissocladius grimshawi* and the low abundance of Chironomini the lake must have been cool and oligotrophic. The appearance of *Microtendipes* at the start of zone 2 indicates that the lake probably became more productive. The genus typically inhabits mesotrophic to eutrophic lakes. In addition, it is possible that the lake also became warmer at this time since *Microtendipes* also occurs

in temperate lakes. Both factors would also account for the decline in relative abundance of *Heterotrissocladius* which is typical of cold, oligotrophic lakes.

Heterotanytarsus apicalis occurs in relatively warm, oligotrophic, humic lakes. The presence of this species therefore suggests a build up of humic material in the lake. This may have been brought about by the development of a bog round the lake following an increase in precipitation. If rainfall was high at the onset of zone 2 this may have resulted in an in-wash of nutrients from the surrounding soils producing an increase in lake productivity and promoting conditions likely to favour *Microtendipes*. Once nutrients had largely been exhausted from the soil, conditions have become favourable for bog formation and lake productivity may have fallen. This would account for the decrease in abundance of *Microtendipes* and the subsequent establishment of *Heterotanytarsus* in the lake. *Psectrocladius* is tolerant of acidic conditions and its relatively high abundance in Zone 2 appears to corroborate the evidence suggested from the presence of *Heterotanytarsus* of a decrease in pH.

Following the putative rise in temperature at the beginning of zone 2, changes in the chironomid assemblage suggest that conditions gradually became cooler. The cold stenotherm *Sergentia coracina* becomes more abundant after the *Microtendipes* peak and the gradual increase in Tanytarsini is also indicative of cooling.

The disappearance of *Microtendipes* and *Heterotanytarsus apicalis*, which marks the beginning of zone 3, might indicate that temperatures eventually fell to a level that became suboptimum for these two taxa. However, the continued presence of *Sergentia* indicates that the trophic level of the lake may have been higher in zone 3 than zone 1. In addition, the presence of *Corynoneura* and *Zavremylia* suggest conditions may have been a little warmer in zone 3 than zone 1. The small peak of *Psectrocladius* in the surface sediments may be as a result of present-day acidification.

In general, head capsule concentration is higher during zone 1 than in zone 2. This may be because the chironomid biomass was greater in zone 1 than zone 2. However, this would seem unlikely considering the hypothesis that lake productivity was actually greater in zone 2 than zone 1. An alternative explanation is that sedimentation rate was greater in zone 2 than in zone 1. This may have been brought about by high precipitation as discussed above.

5.5.4 Summary

During zone 3 the lake was probably cold and oligotrophic. Zone 2 is marked by a possible increase in precipitation and a rise temperature. This may have resulted in an initial rise in lake productivity and a subsequent formation of bog around the lake and decrease in pH. The brief rise in temperature was followed by a gradual fall. By the start of zone 1 the lake seems to have been oligotrophic once more with cooler and drier conditions. Nevertheless, the present day lake is apparently somewhat warmer and more productive than the zone 3 lake.

5.5.5 Chironomid work ahead

Samples will be taken at 2 mm intervals from selected levels down to 120 cm. By sampling at fine resolution, changes in the chironomid fauna that coincide with the fluctuations in LOI previously observed may become apparent. Possible changes in the chironomid fauna as a result of recent acidification may also be revealed.

In some of the samples in the lower half of the core very few head capsules were found. It may therefore be necessary to amalgamate some samples to produce significant numbers of head capsules.

No progress has been made on the analysis of ^{13}C from chironomid chitin. Surface samples from Lochan Uaine and the Lake District are available but a protocol to prepare the head capsules for analysis has yet to be formulated.

5.6 Pollen analysis

The pollen diagram for Lochan Uaine has now been completed (Figure 5.26).

5.7 Further work

There is growing interest in the nature of the LOI oscillations in the Lochan Uaine cores. Consequently Kath Ficken will carry out organic geochemical analysis of a series of samples across two of the oscillations, and Roy Switsur (Cambridge) has agreed to analyse samples from the same levels for variations in $\delta^{13}\text{C}$.

References

- Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J. & Battarbee, R.W. 1986 ^{210}Pb dating by low background gamma counting. *Hydrobiologia* 141, 21-27.
- Appleby, P.G. & Oldfield, F. 1978 The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena* 5, 1-8.
- Appleby, P.G., Richardson, N. & Nolan, P.J. 1991 ^{241}Am dating of lake sediments *Hydrobiologia* 214, 35-42.
- Pienitz, R., J.P. Smol & H.J.B. Birks 1995. Assessment of freshwater diatoms as quantitative indicators of past climatic change in the Yukon & Northwest Territories, Canada. *Journal of Paleolimnology* 13: 21-49
- Vyverman, W. & K. Sabbe 1995. Diatom temperature transfer functions based on the altitudinal zonation of diatom assemblages in Papua New Guinea: a possible tool in the reconstruction of regional climatic changes. *Journal of Paleolimnology* 13: 65-77

Figure captions

Figure 5.1 Percentage dry weight, loss on ignition and radiocarbon dates for Lochan Uaine, UACT 4.

Figure 5.2 Comparison of radiocarbon dates according to loss on ignition values for Lochan Uaine, UACT 4.

Figure 5.3 The gradients of the lines represent the accumulation rates of the most recent sediments for comparison with ^{210}Pb accumulation rates, as obtained from the three possible dating schemes: (i) constant accumulation; (ii) convex hull analysis; and (iii) polynomial or spline fitting.

Figure 5.4 Lochan Uaine dating of core UACT 4, (a) total ^{210}Pb activity versus depth; (b) unsupported ^{210}Pb activity versus depth.

Figure 5.5 Lochan Uaine dating of core UACT 4: ^{137}Cs activity versus depth

Figure 5.6 Lochan Uaine dating of core UACT 4: depth versus age

Figure 5.7 Lochan Uaine dating of core UACT 4: depth versus age for both ^{210}Pb and ^{14}C dates

Figure 5.8 Tephra concentrations for Lochan Uaine core UACT4.

Figure 5.9 Particle size data for Lochan Uaine down to 38 cm corresponding to the last 2000 years

Figure 5.10 Pairs plots of the mean and variance obtained from the particle size data and the LOI and dry weight data measured at the ECRC

Figure 5.11 Decomposition of particle size data for the top 159 samples from Lochan Uaine core 4 into two separate log normal components with means of $\sim 40\mu\text{m}$ and $\sim 250\mu\text{m}$.

Figure 5.12 Lochan Uaine, Core 3. Low field, low frequency susceptibility ($10^{-8}\text{m}^3\text{kg}^{-1}$). Strong inter-sample variation reflects the low sample masses available. Despite adjustment of the values for the diamagnetic effect of the sample holder and packing, a few samples still give negative values.

Figure 5.13 Lochan Uaine, Core 3. Anhysteretic Remanent Magnetization (ARM) plotted as the susceptibility of ARM, i.e. normalized by the strength of the DC field ($10^{-8}\text{m}^3\text{kg}^{-1}$). Many measurements are close to the noise level of the instrumentation.

Figure 5.14 Lochan Uaine, Core 3. 'Soft' IRM, i.e. $\text{SIRM}-\text{IRM}_{.20\text{mT}}$ ($10^{-5}\text{Am}^2\text{kg}^{-1}$).

Figure 5.15 Lochan Uaine, Core 3. 'Hard' IRM, i.e. $\text{SIRM} + \text{IRM}_{.300\text{mT}}$. ($10^{-5}\text{Am}^2\text{kg}^{-1}$)

Figure 5.16 Lochan Uaine, Core 3. 'Hard' IRM expressed as a percentage of SIRM.

Figure 5.17 Lochan Uaine, Core 3. $\chi_{rm}/$ 'Soft' IRM (10^{-3}mA^{-1}).

Figure 5.18 Diatom valve concentration compared to dry weight and loss on ignition measurements for Lochan Uaine UACT4, 3.7-12 cm

Figure 5.19 Diatom and chrysophyte concentration compared to dry weight and loss on ignition measurements for Lochan Uaine UACT4, 36-45 cm

Figure 5.20 Comparison of upper and lower core segments showing higher diatom valve concentration and higher loss on ignition values in the lower segment

Figure 5.21 Relationship between diatom valve and chrysophyte concentrations in Lochan Uaine UACT4 core segments

Figure 5.22 Ratio of diatom valve to chrysophyte concentration against depth for Lochan Uaine UACT4, 36-45 cm.

Figure 5.23 Diatom diagram for Lochan Uaine UACT4, 36-45 cm.

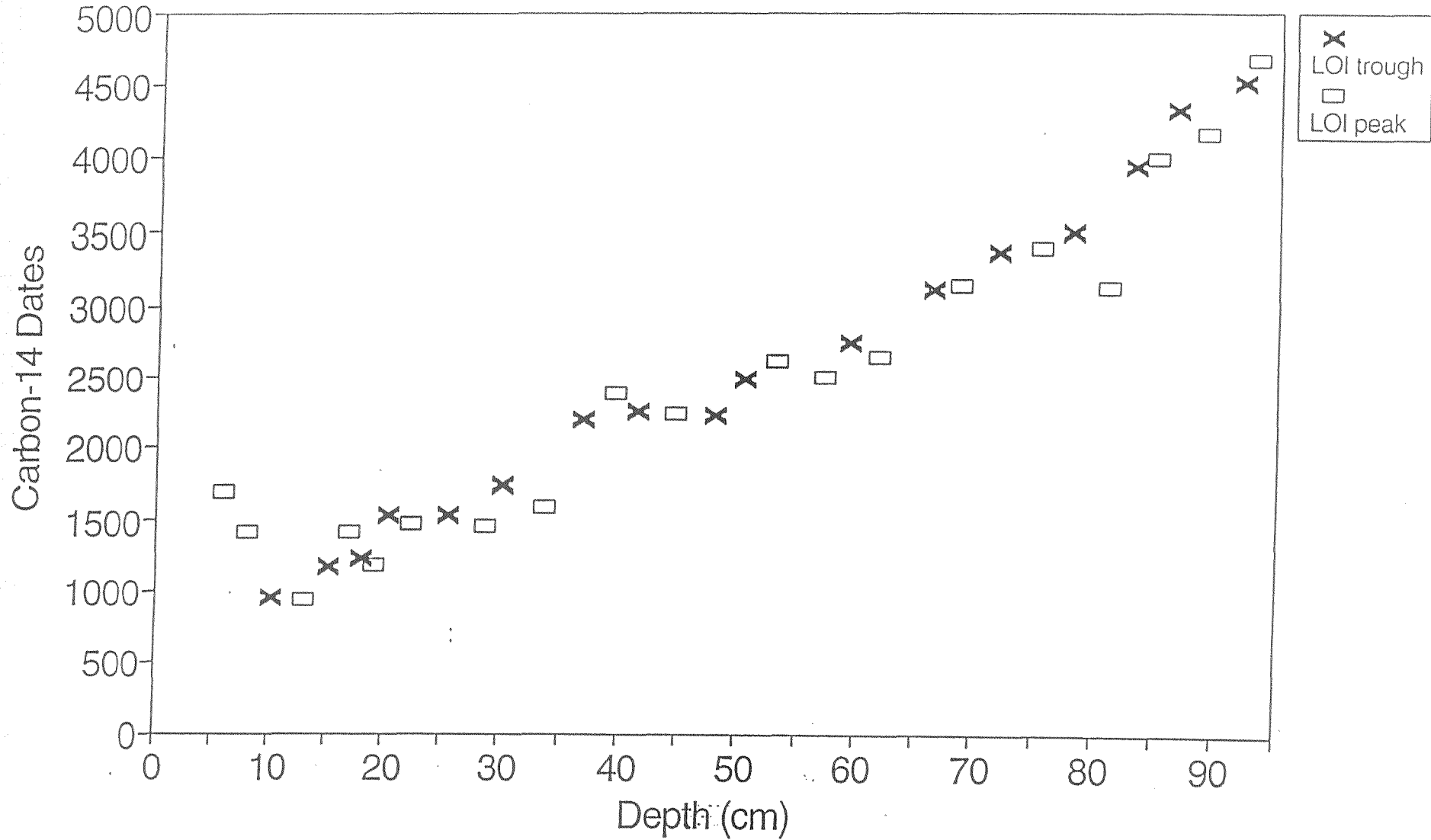
Figure 5.24 pH reconstruction (using SWAP training set) compared to dry weight and loss on ignition for Lochan Uaine UACT4, 36-45 cm.

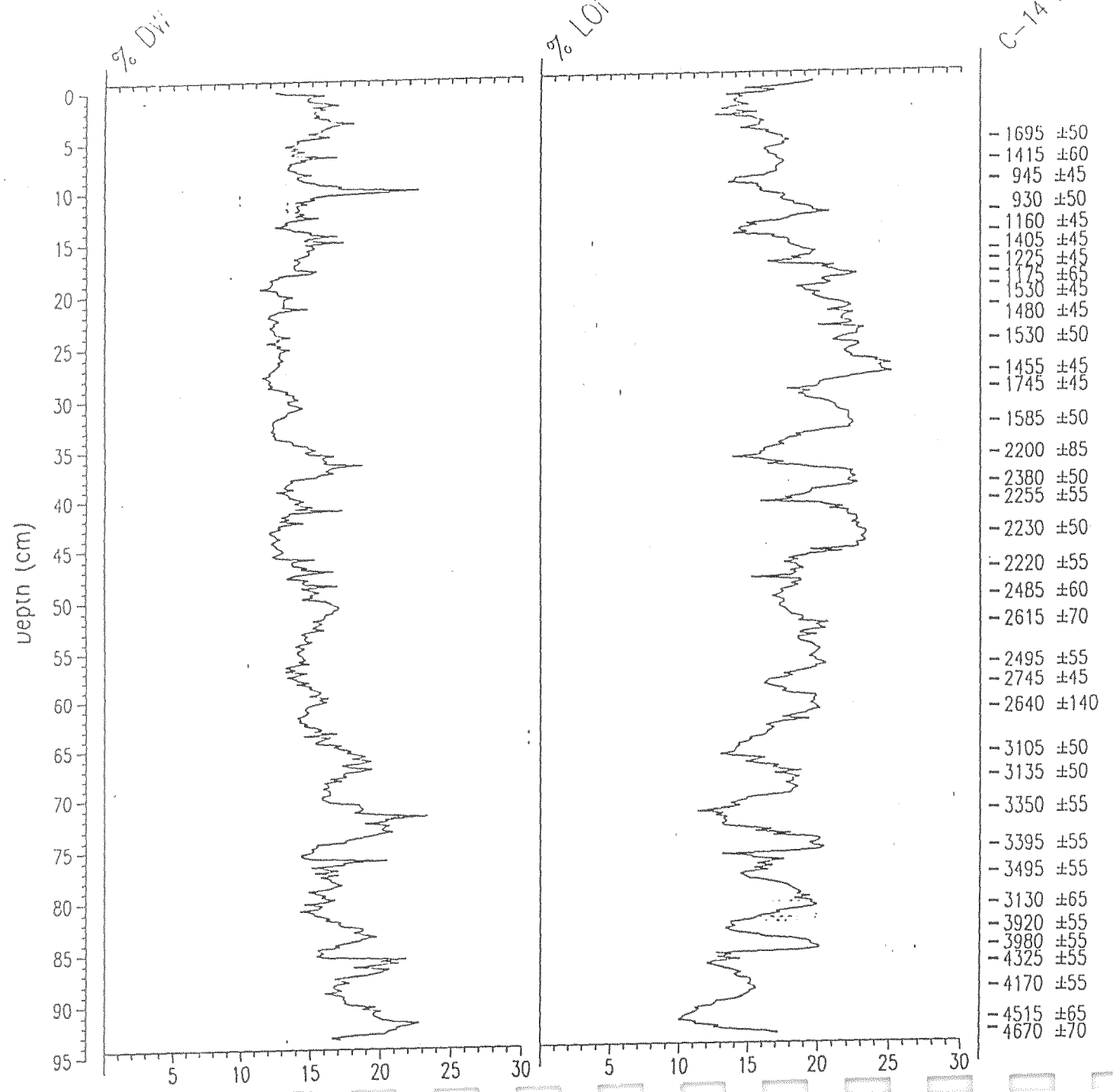
Figure 5.25 Chironomid diagram for Lochan Uaine

Figure 5.26 Pollen diagram for Lochan Uaine

Lochan Uaine - UACT 4

Date comparison of LOI peaks to troughs





- 1695 ±50
- 1415 ±60
- 945 ±45
- 930 ±50
- 1160 ±45
- 1405 ±45
- 1225 ±45
- 1175 ±65
- 1530 ±45
- 1480 ±45
- 1530 ±50
- 1455 ±45
- 1745 ±45
- 1585 ±50
- 2200 ±85
- 2380 ±50
- 2255 ±55
- 2230 ±50
- 2220 ±55
- 2485 ±60
- 2615 ±70
- 2495 ±55
- 2745 ±45
- 2640 ±140
- 3105 ±50
- 3135 ±50
- 3350 ±55
- 3395 ±55
- 3495 ±55
- 3130 ±65
- 3920 ±55
- 3980 ±55
- 4325 ±55
- 4170 ±55
- 4515 ±65
- 4670 ±70

Figure 5. The gradients of these lines represent the accumulation rates of the most recent sediments for comparison with Pb-210 accumulation rates, as obtained from the three possible dating schemes: i) Constant accumulation, ii) Convex hull analysis and iii) Polynomial or spline fitting.

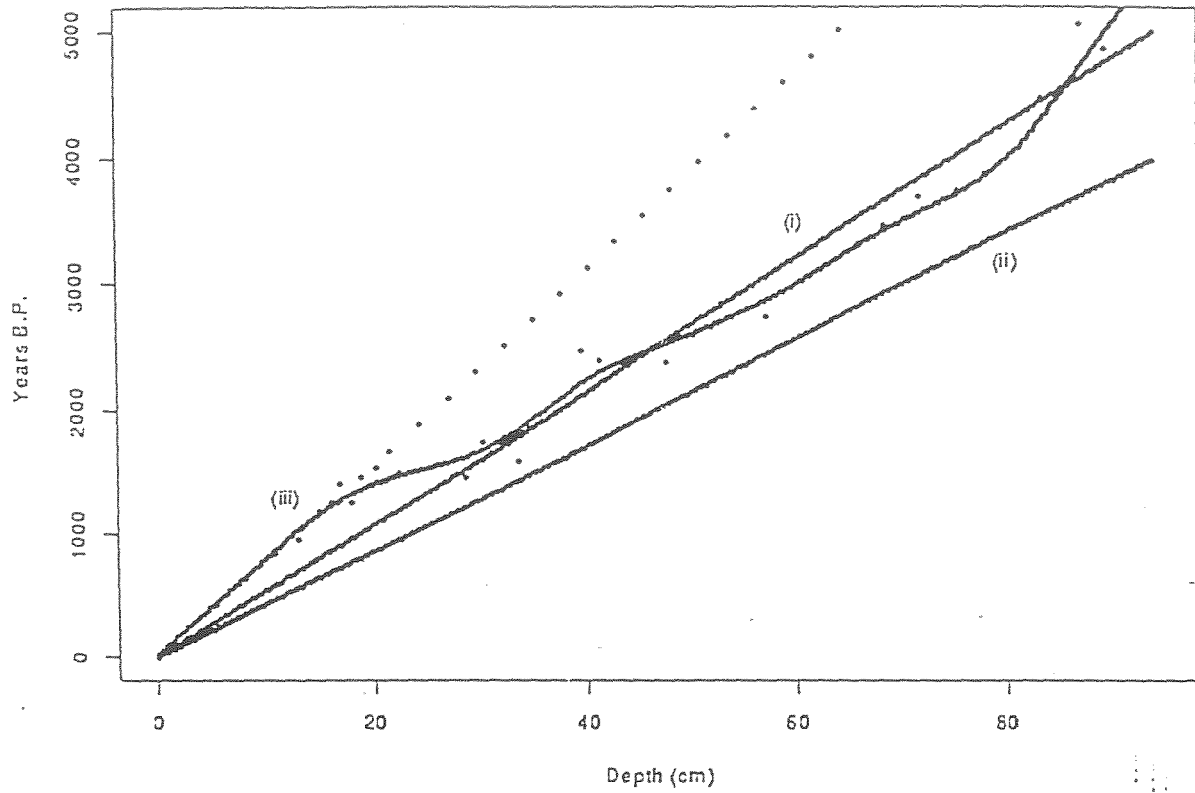


Fig 5.4a:

Lochan Uaine (Cairn Toul) Total ^{210}Pb Activity versus Depth

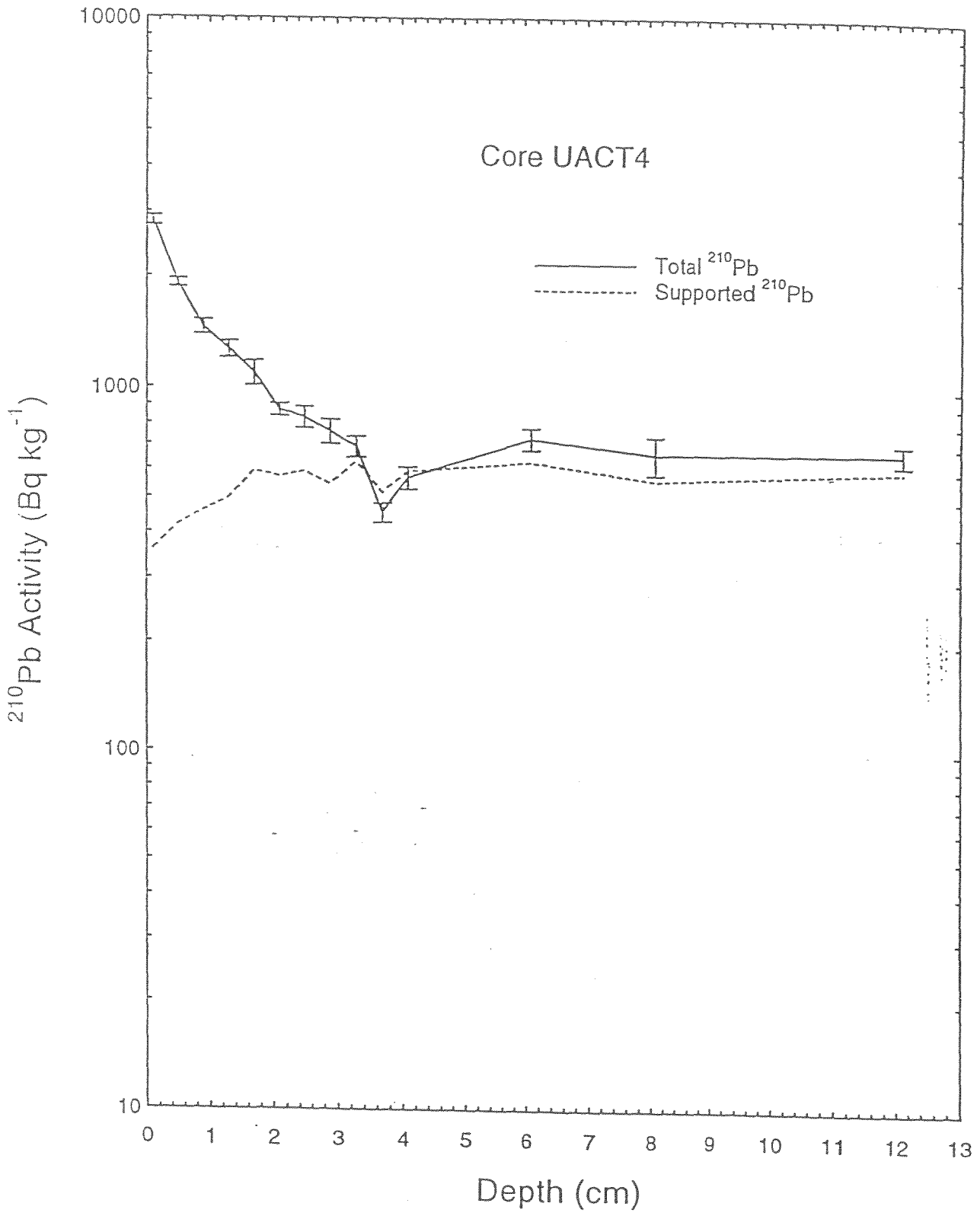


Fig 5.4b:

Lochan Uaine (Cairn Toul) Unsupported ^{210}Pb Activity versus Depth

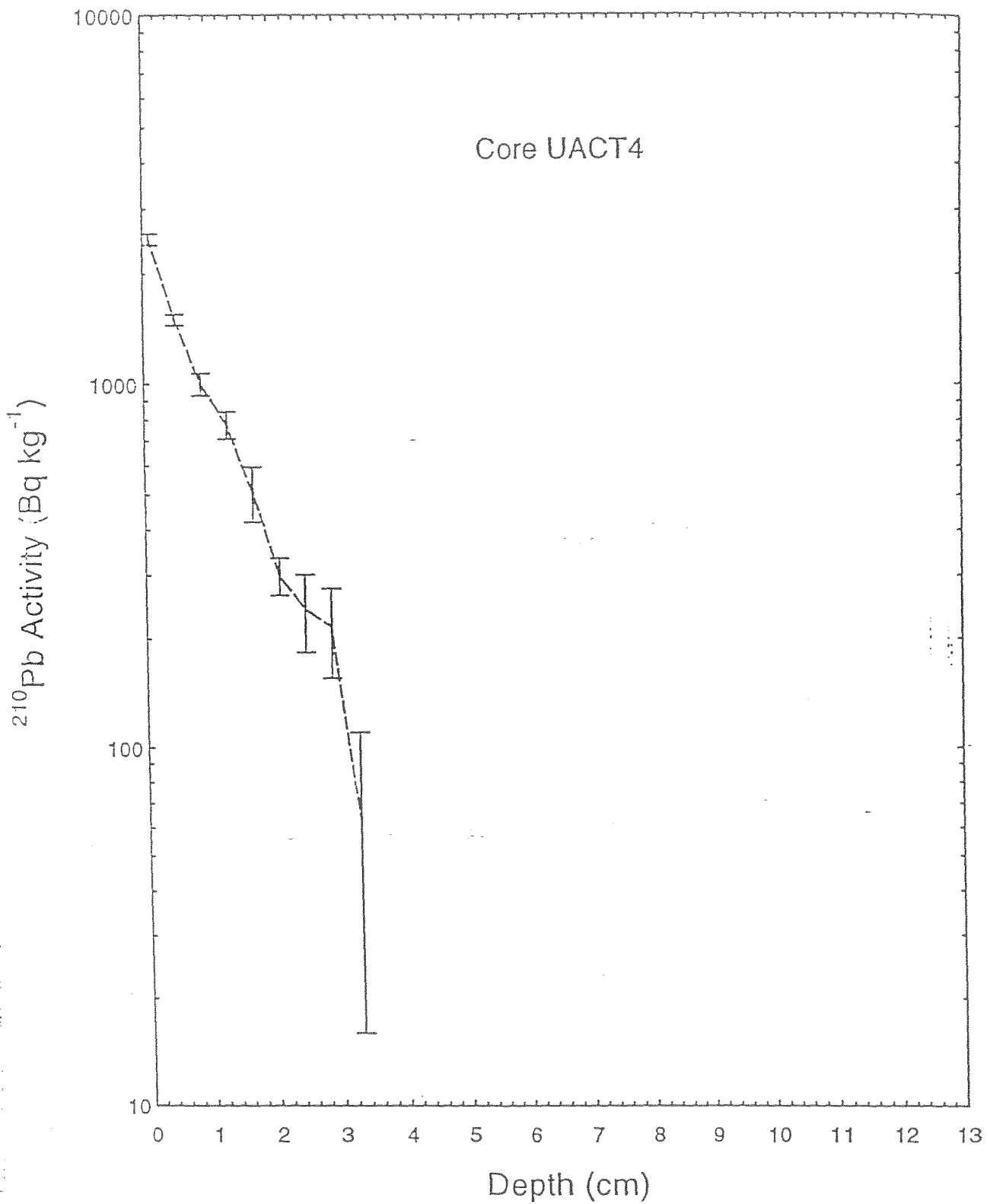


Fig. 5.5

Lochan Uaine (Cairn Toul)

^{137}Cs Activity versus Depth

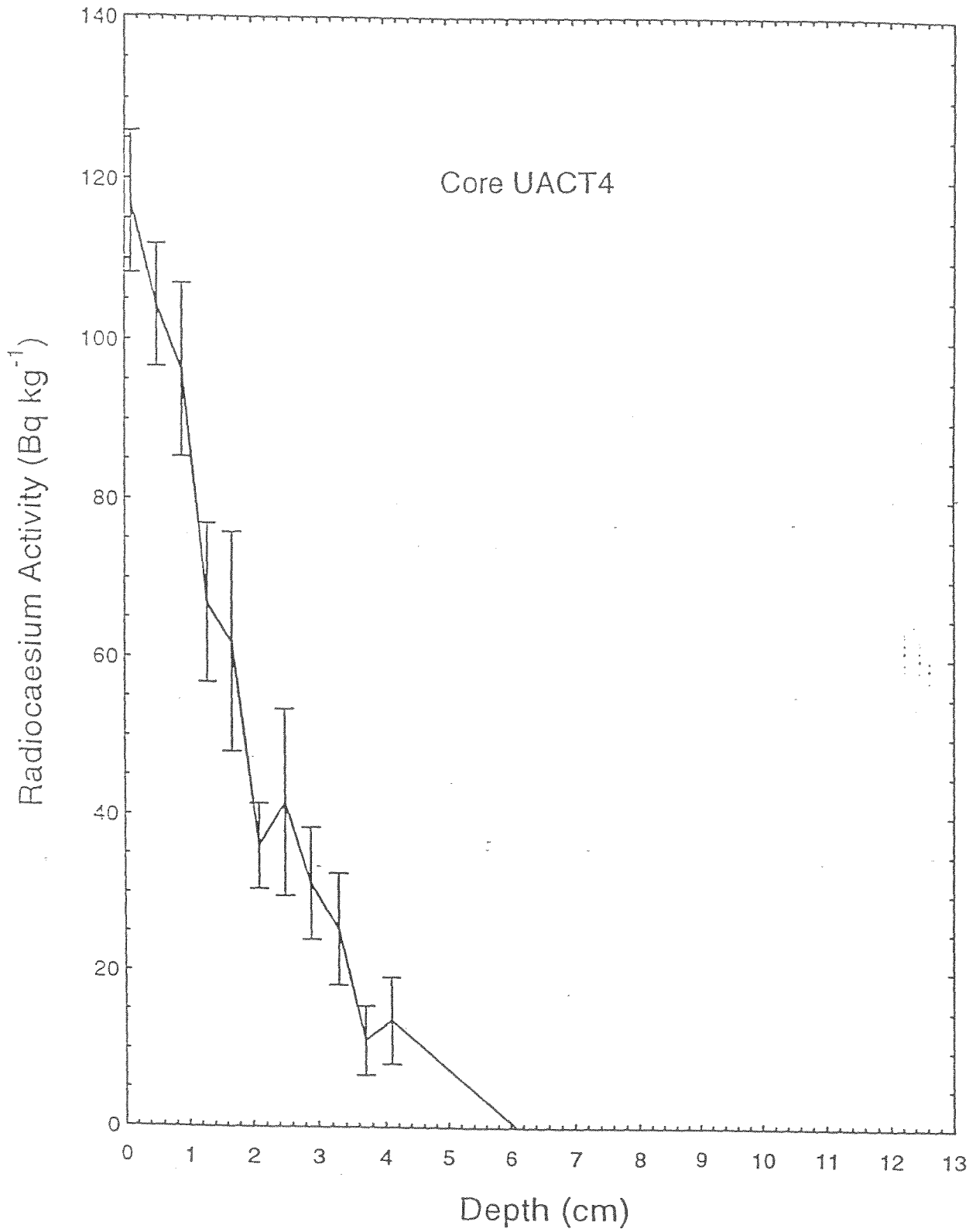
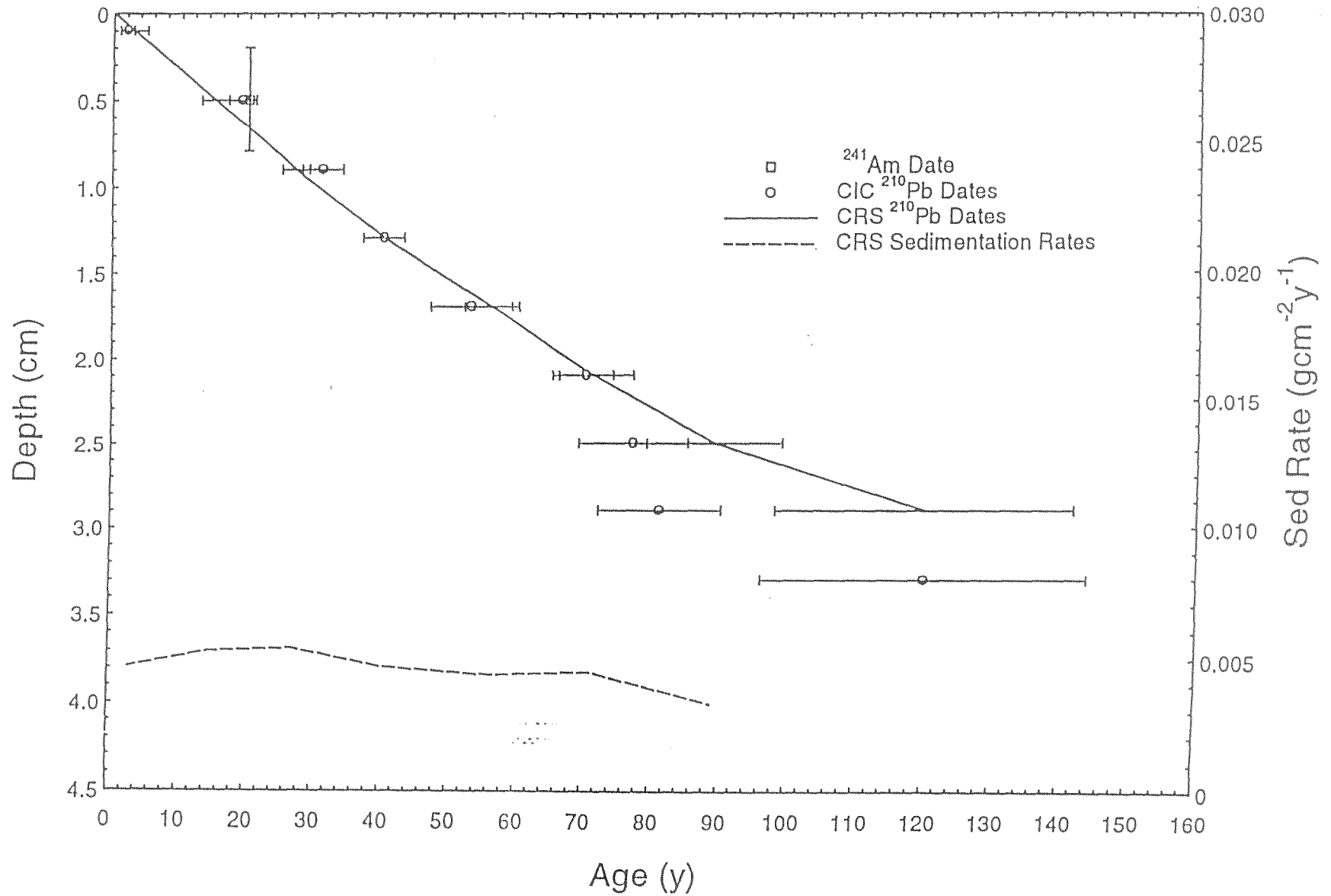


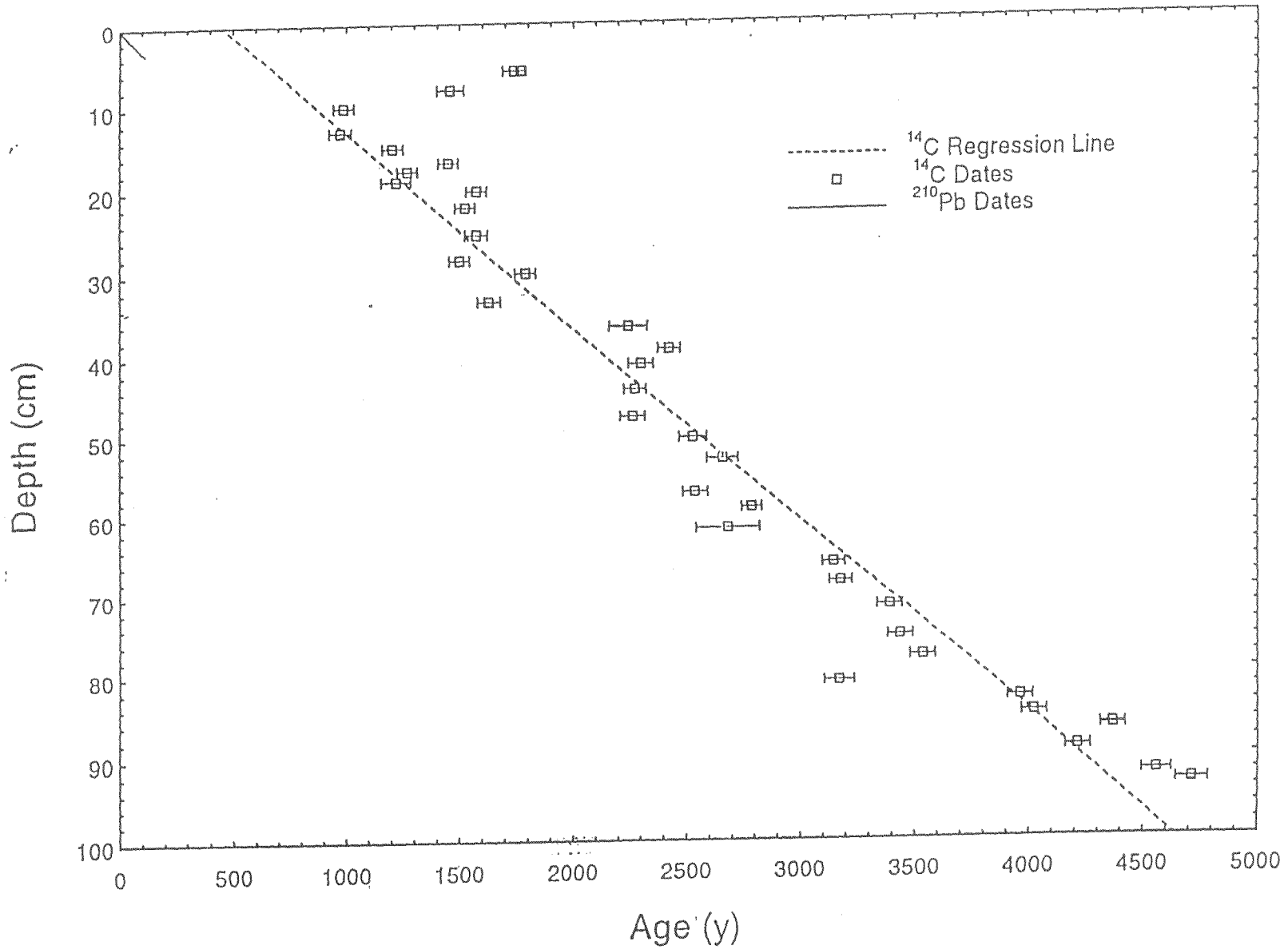
Fig. 5.6

Lochan Uaine Core UACT4 Depth versus Age



Lochan Uaine Core UACT4 Depth versus Age

Fig 5.7



Lochan Uaine (UACT 4)
Tephra concentration profile

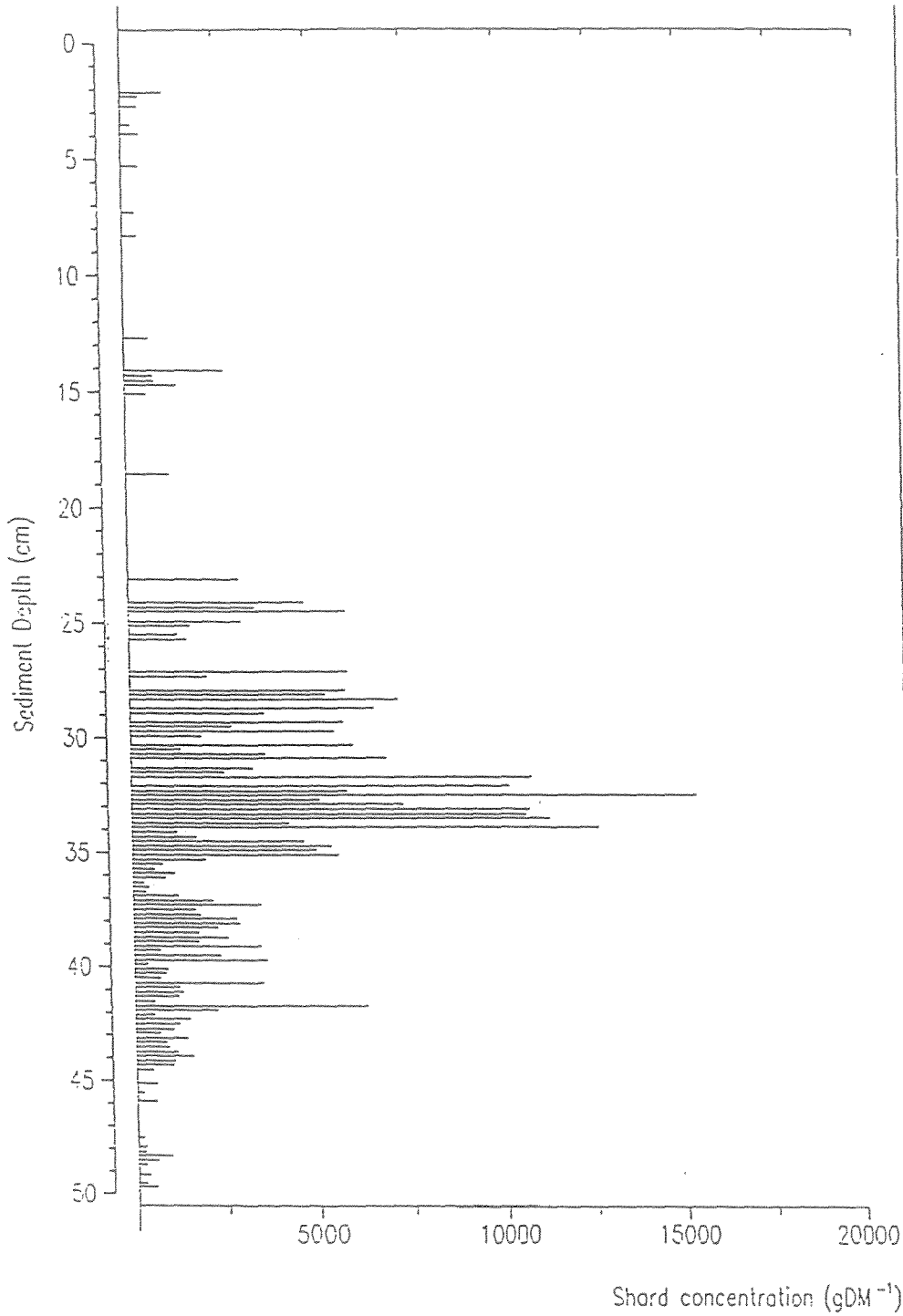


Fig 5.9 Particle size data for Lochan Uaine down to 38cm corresponding to the last 2000 years.

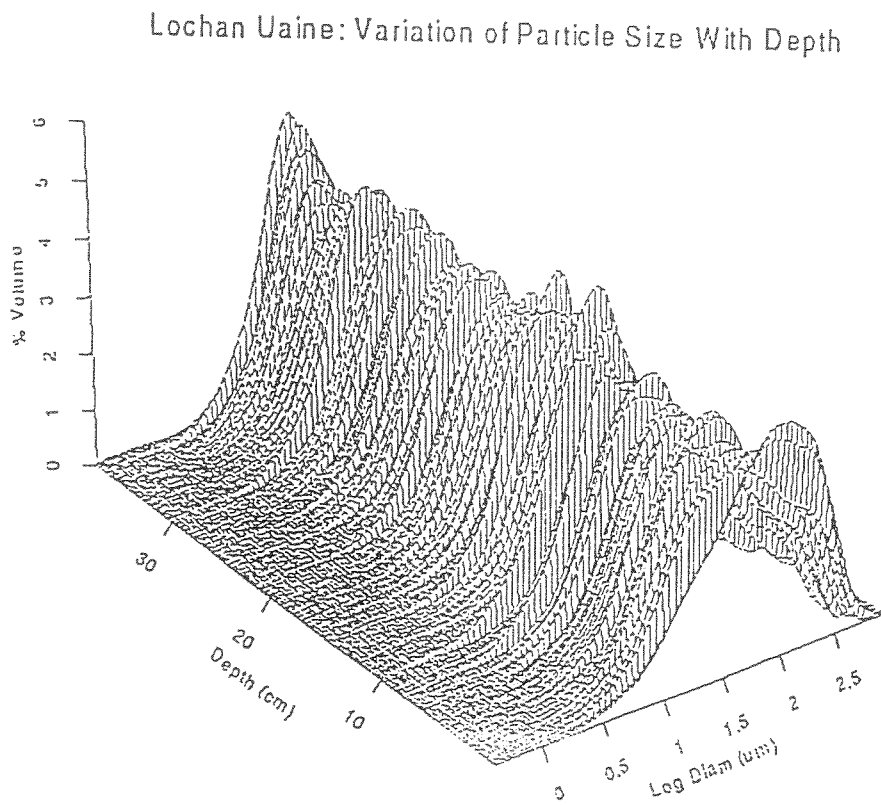


Fig 5. 10 Pairs plots of the mean and variance obtained from the particle size data and the L.O.I. and Dry Weight data measured at E.C.R.C.

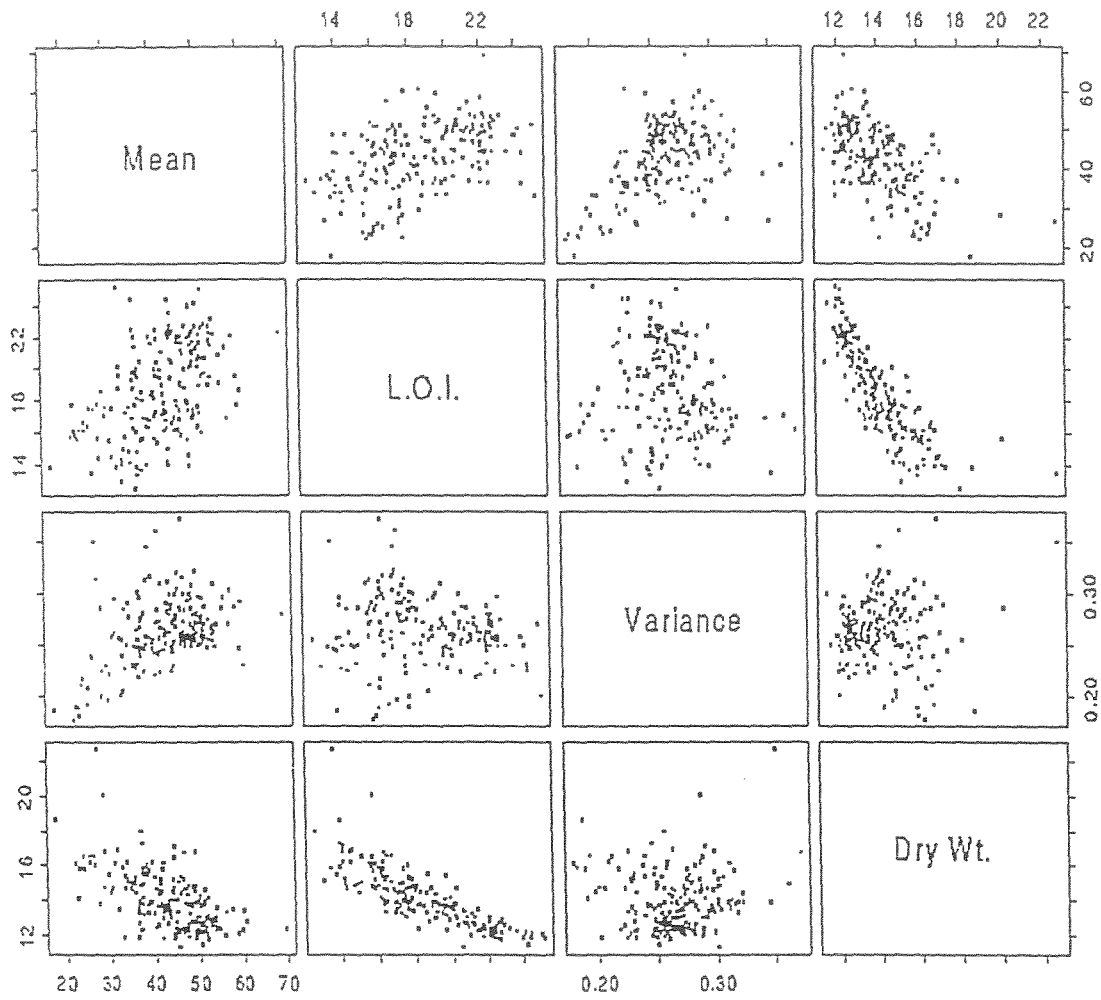
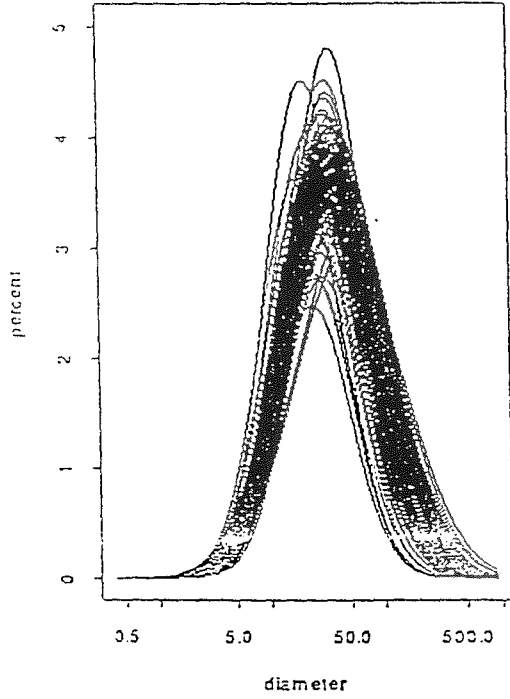


Fig 5.11 Decomposition of particle size data for the top 159 samples from L. Uaine core 4 into two separate log normal components with means of $\sim 40\mu\text{m}$ and $\sim 250\mu\text{m}$.

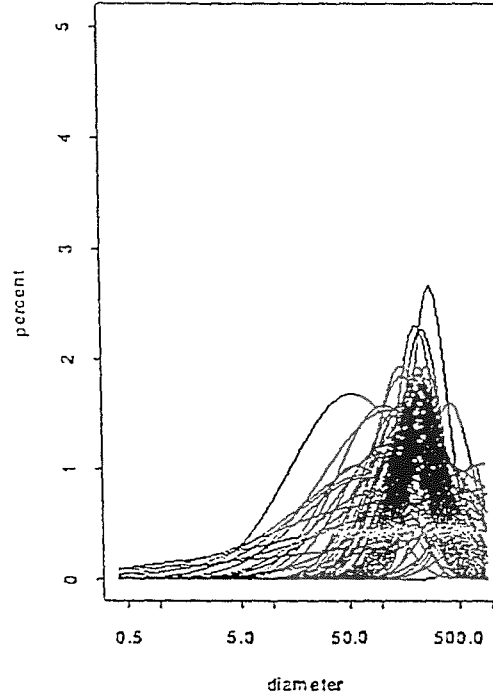
a)

L. Uaine Main component



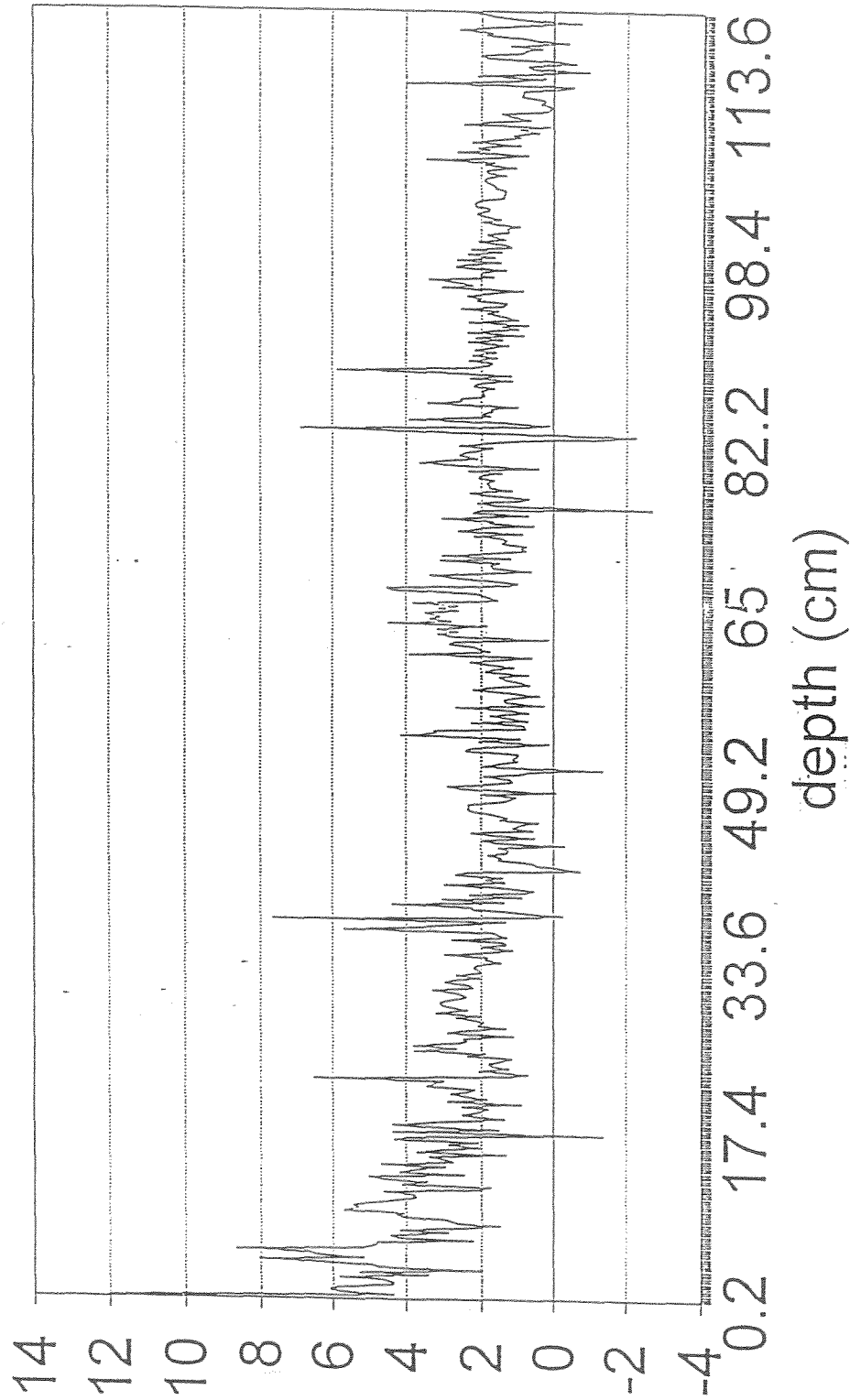
b)

L. Uaine Second component



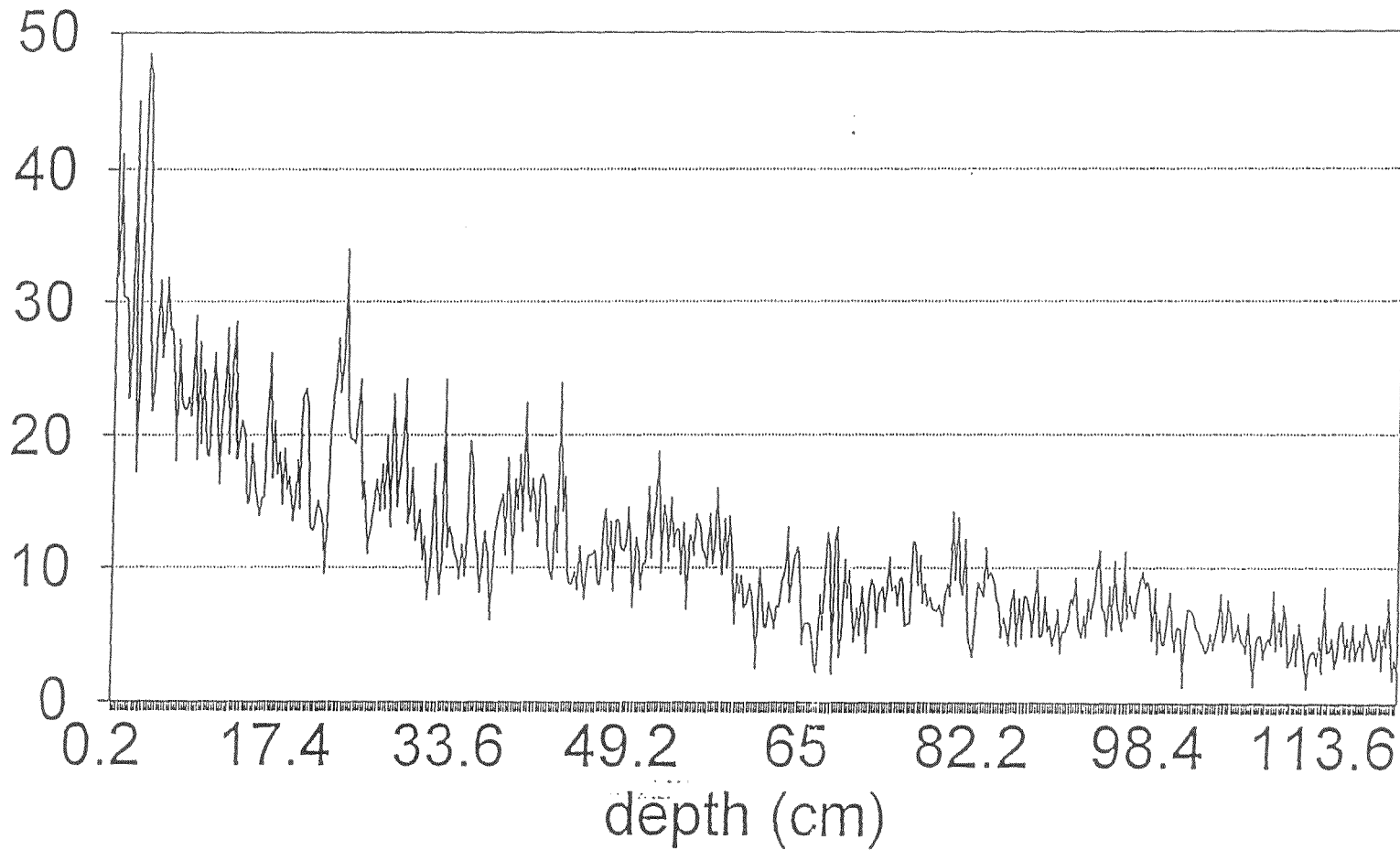
Lochan Uaine

Xlf



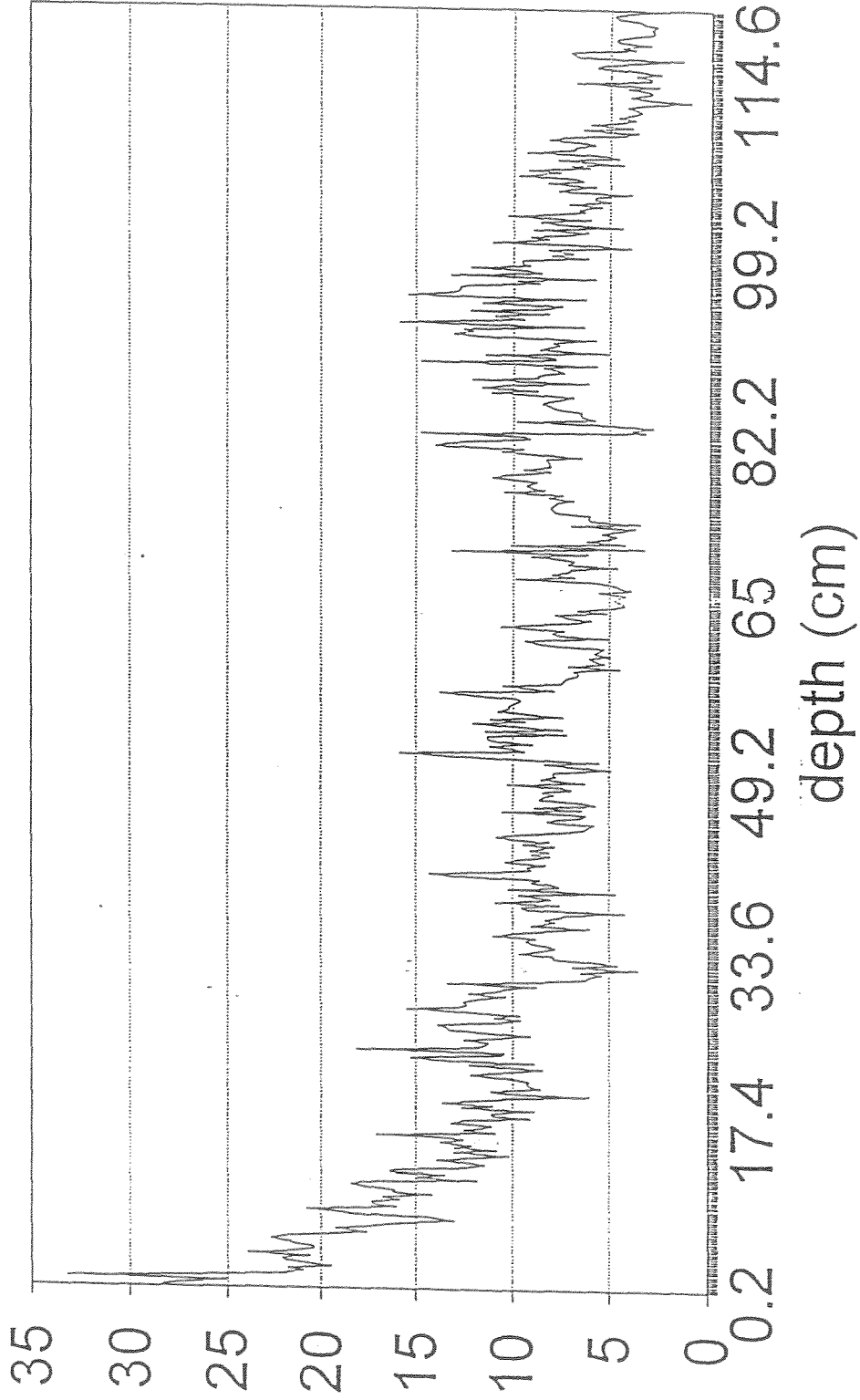
Lochan Uaine

Xarm



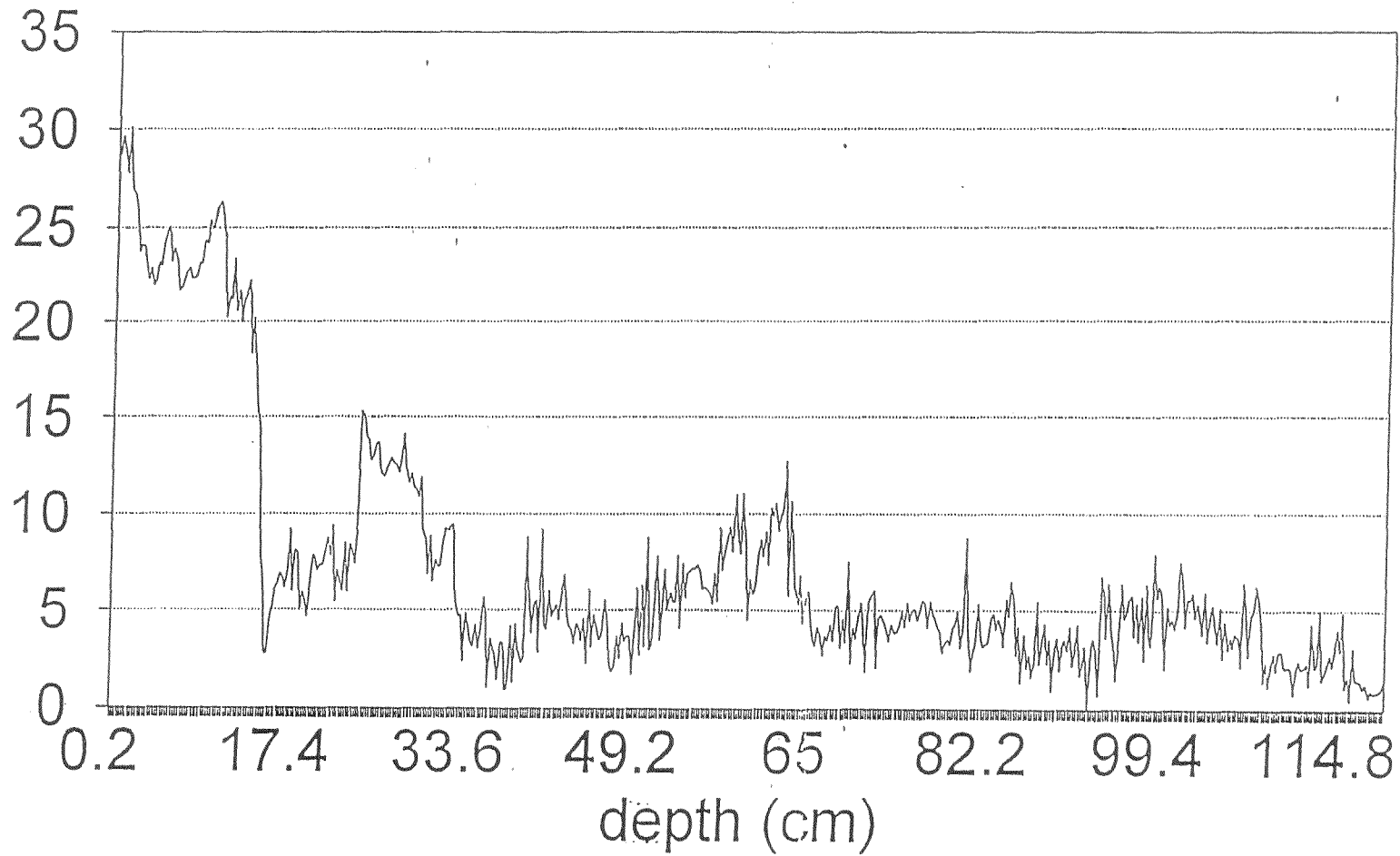
Lochan Uaine

soft



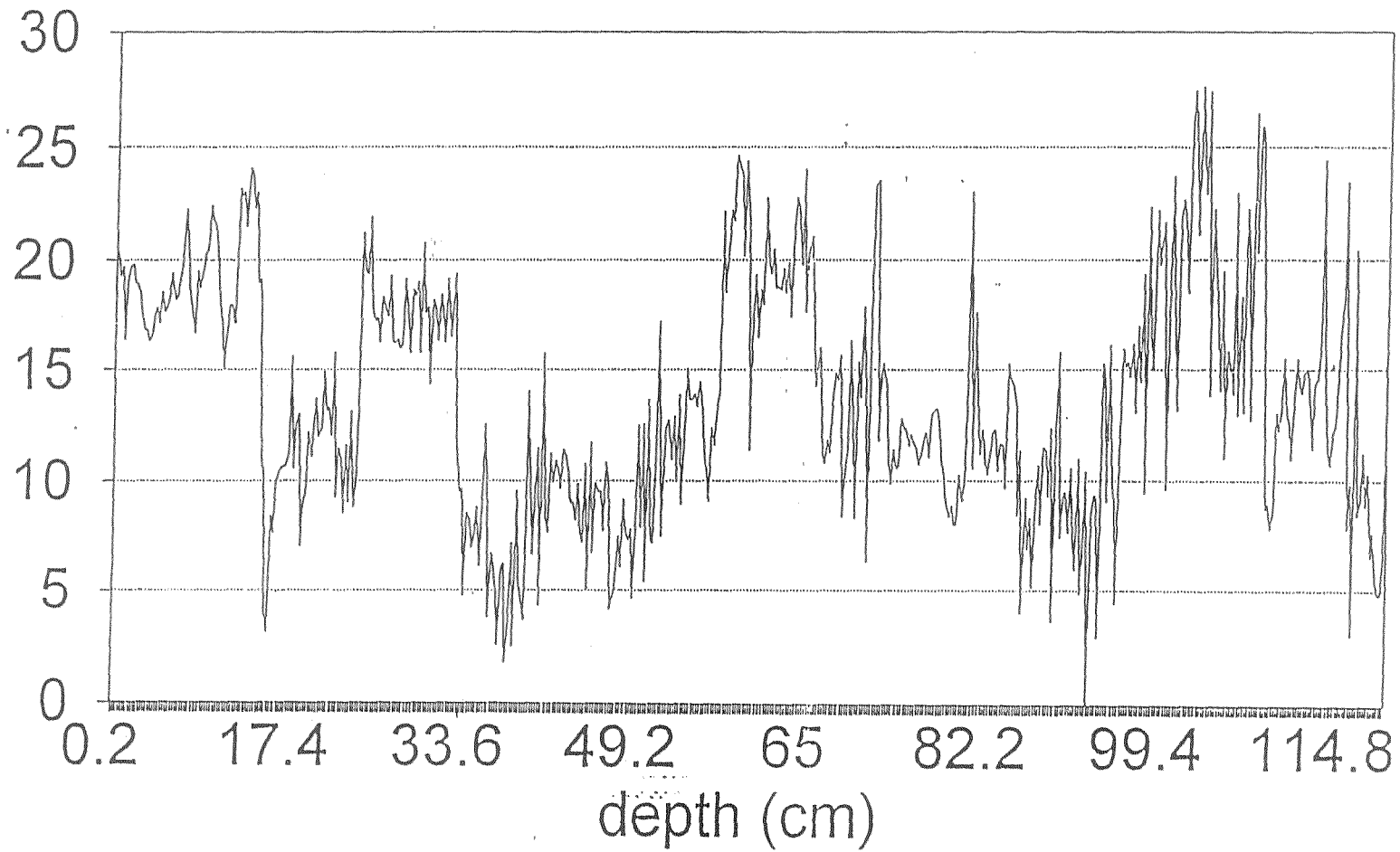
Lochan Uaine

HIRM



Lochan Uaine

Hard%



Lochan Uaine

Xarm/soft

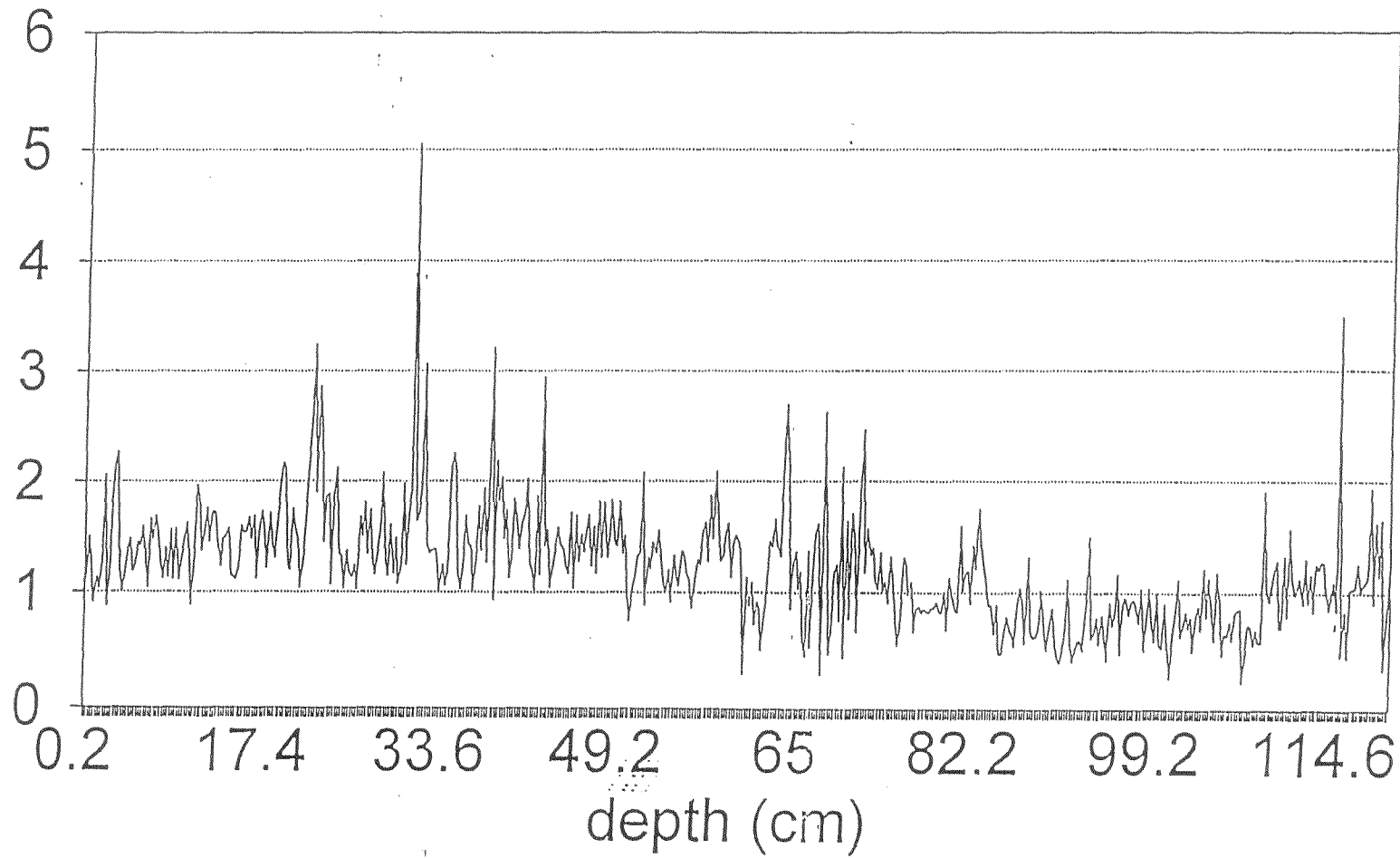


FIG 5.18

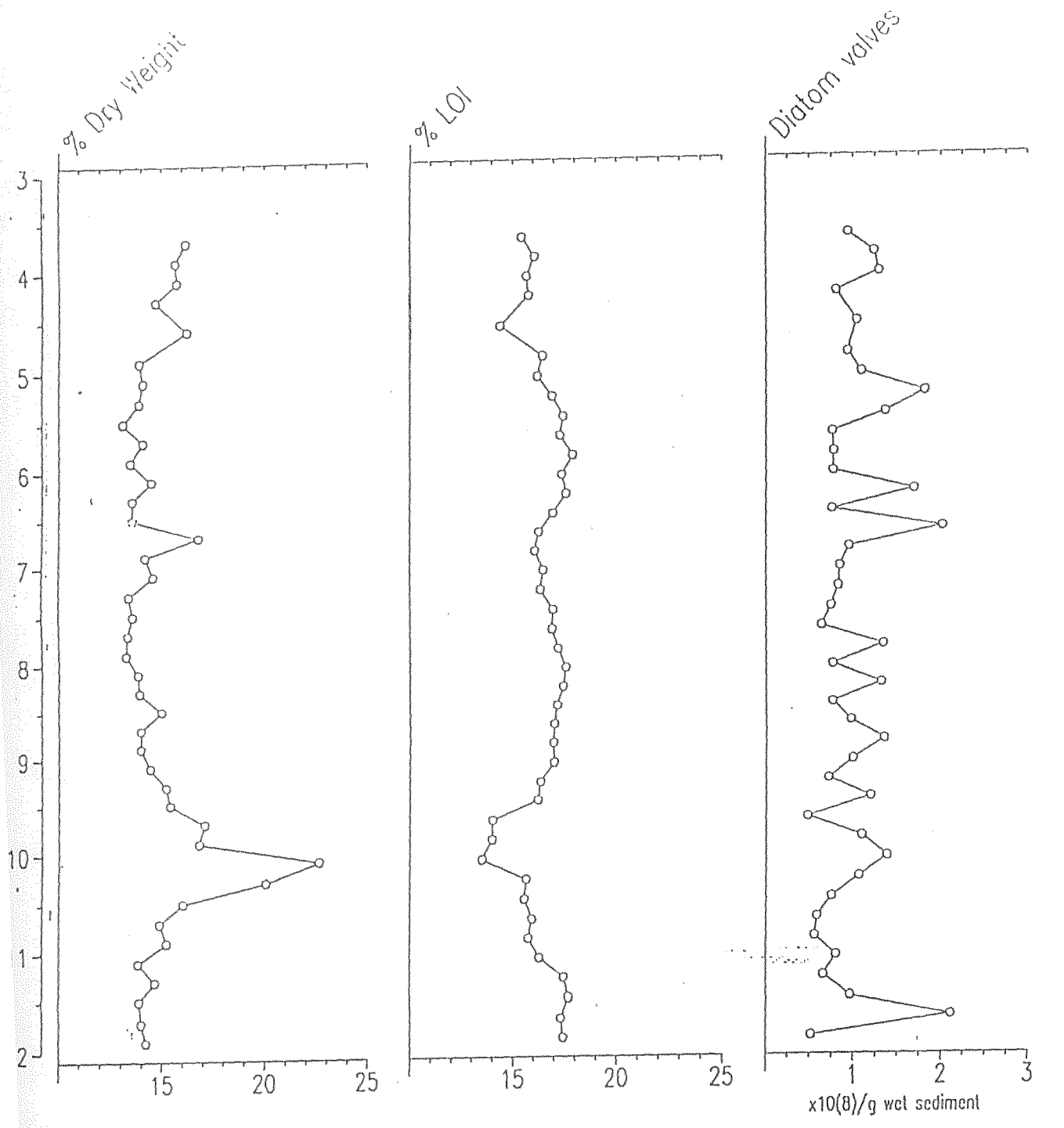
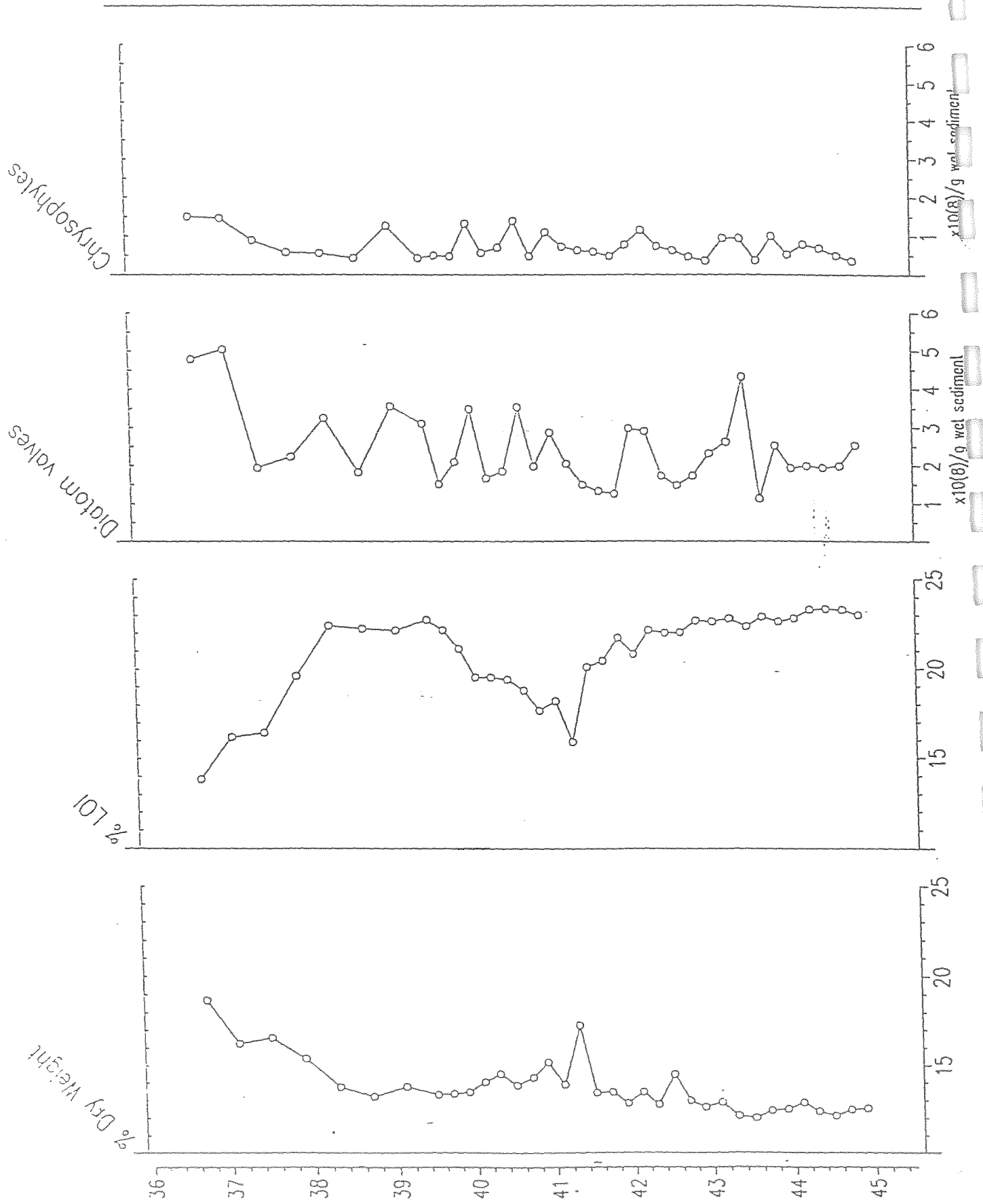
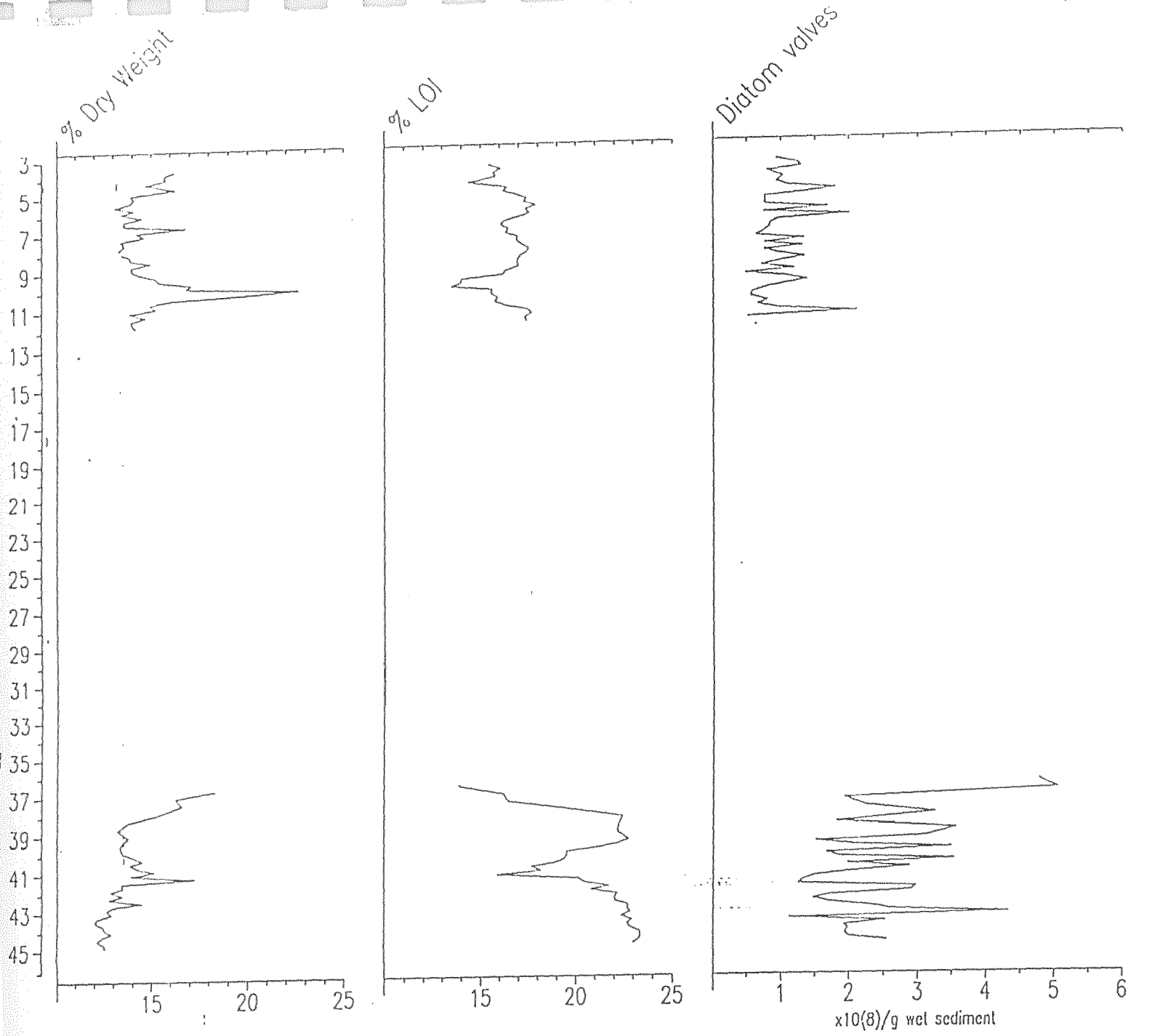
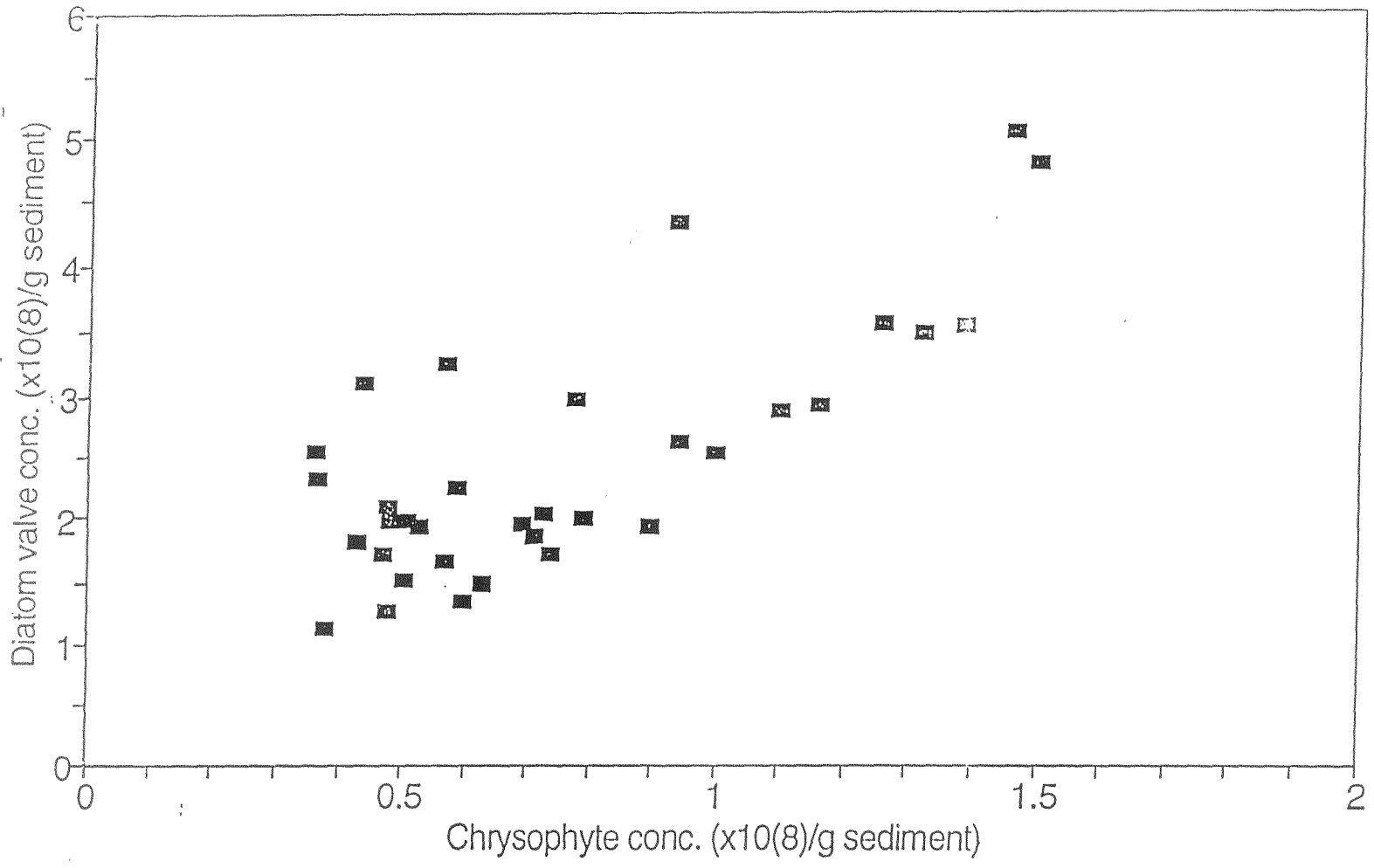


FIG 5.19

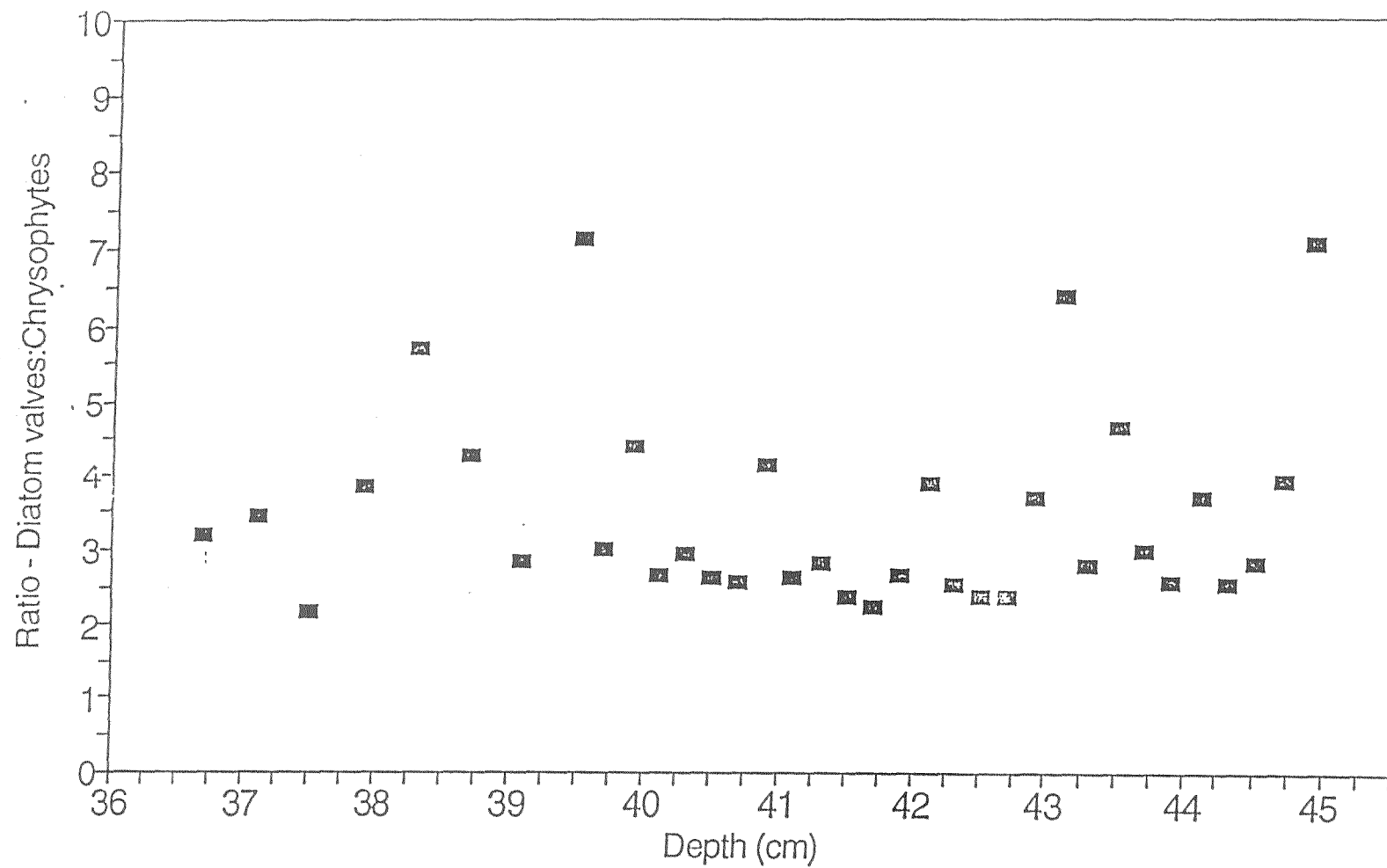




Lochan Uaine - UACT 4



Lochan Uaine - UACT 4



Frustulia rhomboides var. *saxonica*
Gymbella perpusilla & *gaurmanti*
Aulacoseira distans & var. *rivialis*
Peronia fibula
Fragilaria virescens var. *exiguu*
Eunotia pectinidis var. *minor*
Gymbella lunata
Gymbella brebissonii & *serians modesta*
Brachysira vitrea
Brachysira marginulata & *major*
Achnanthes curtissima
Achnanthes scotica
Achnanthes minutissima
Achnanthes ostrica var. *helvetica*

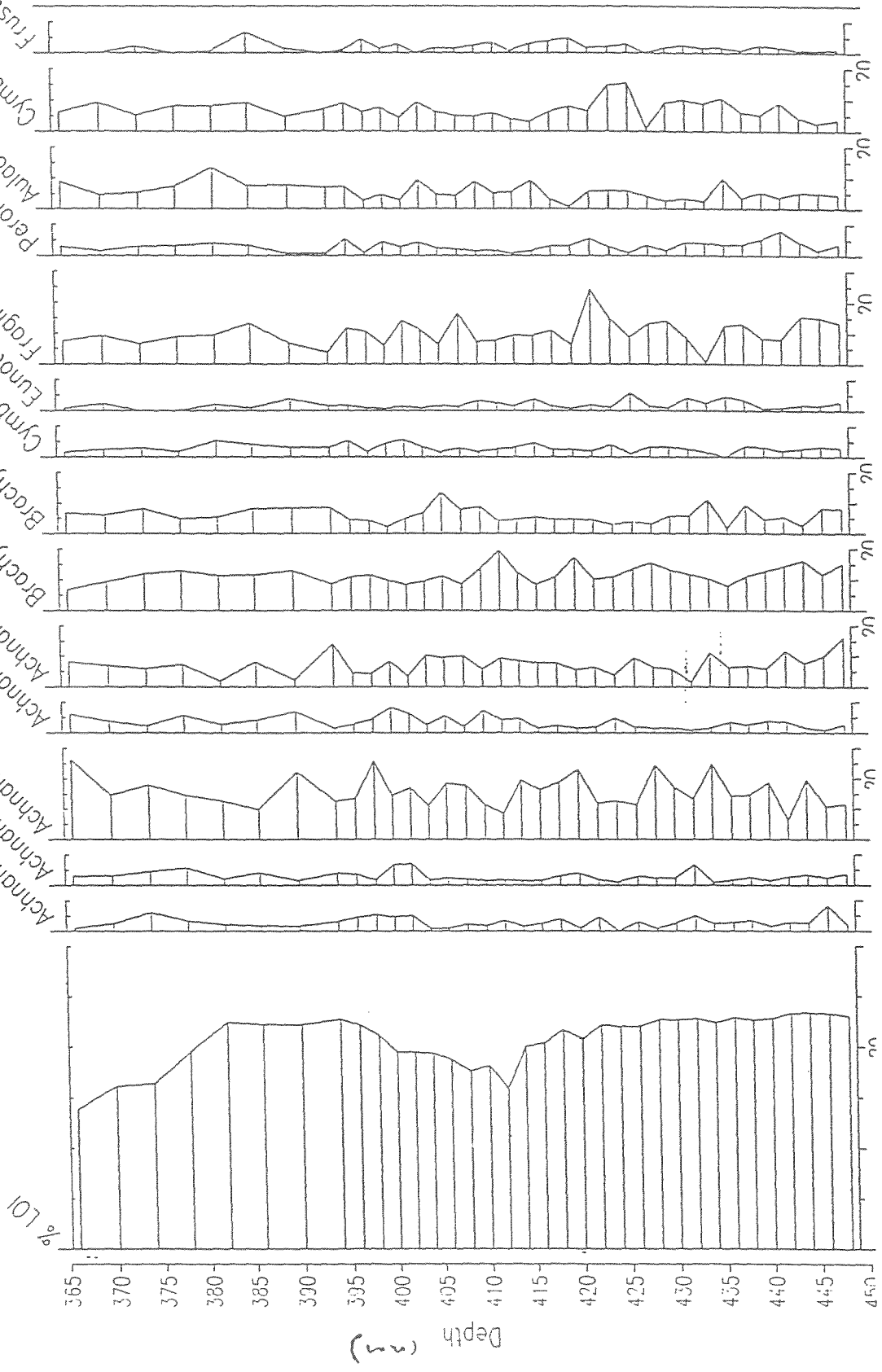
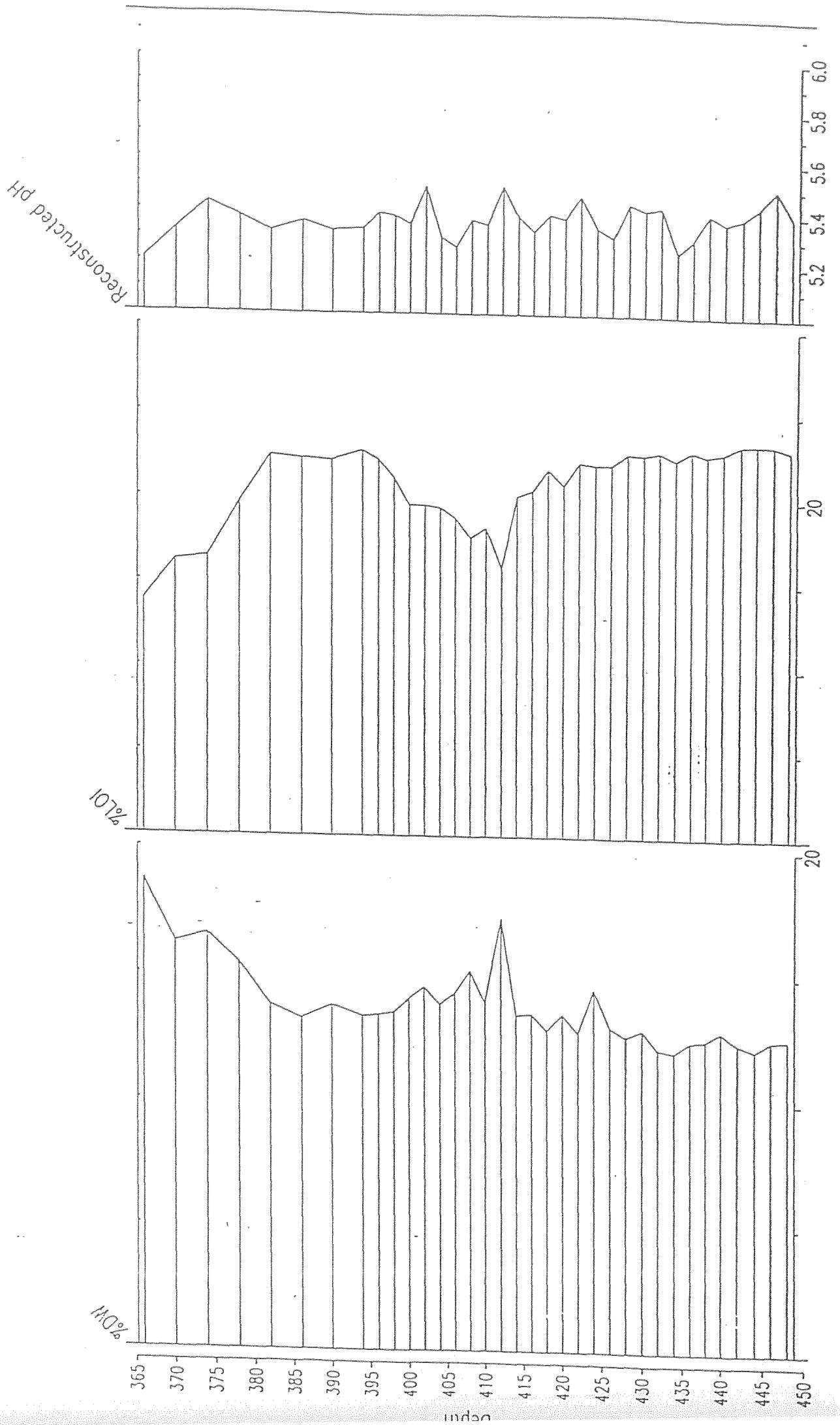


FIG 5.24



Lochan Uaine

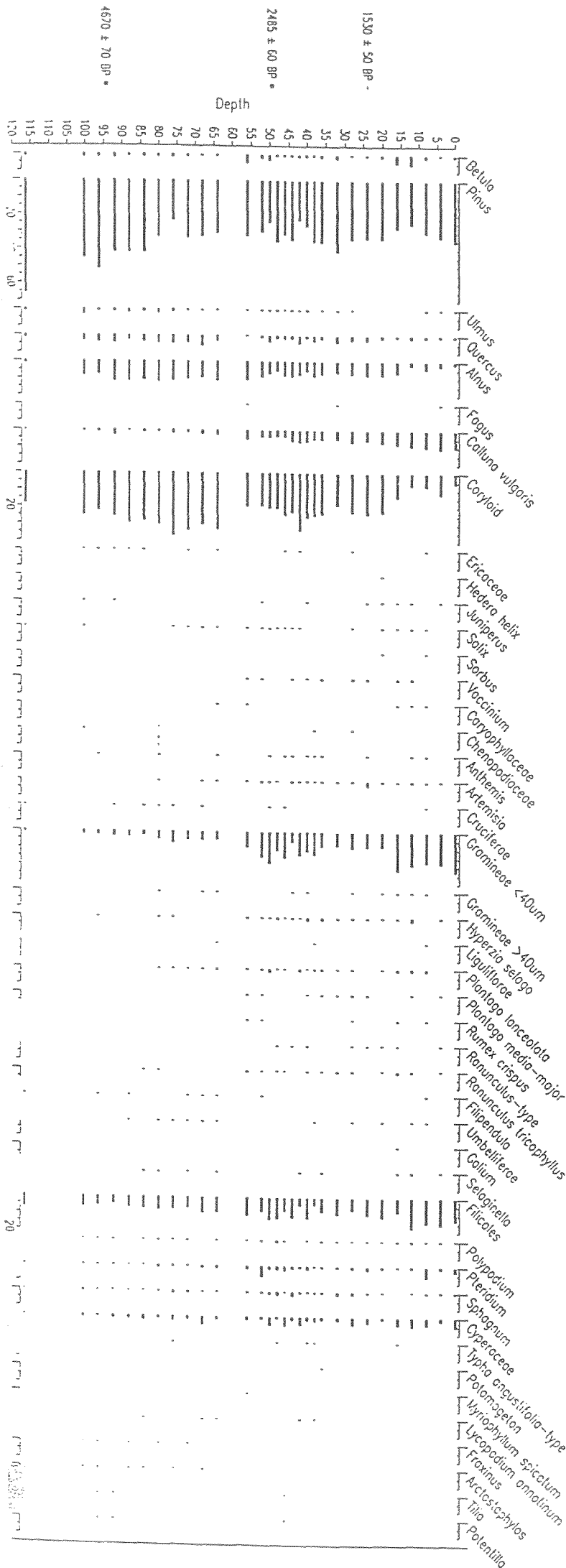


FIG 5.26

6. Proxy climate indicators from montane bogs (Project leader: Keith Barber)

Keith Barber, Rob Stoneman, & Darrel Maddy (University of Southampton); Neil Rose (UCL), Tony Stevenson (Newcastle) and Kath Ficken (Bristol).

6.1 Bulk density, humification, macrofossil, tephra and pollen analysis.

This montane bog is about 6 km west of Lochan Uaine and was sampled by Rob Stoneman at the same time as the lake coring. Analyses of bulk density, humification and macrofossils were carried out by Darrel Maddy, and 17 radiocarbon assays were performed at the NERC RCL, East Kilbride. Again the profile covers the last 2,000 years, with a basal date of AD 30 (uncalibrated). The main points may be summarised as:

1. The bulk density and humification profiles (Figure 6.1) show substantial and largely coincident changes, the most recent of which is dated to AD1640-1800. This profile is thought to be representative; test cores showed up the banded nature of the top 25 cm of peat over quite a large area of bog.

2. The peat contained abundant plant macrofossils, unusual for a blanket bog. It has accumulated at an average rate of 34 years/cm (see dating profile, Figure 6.2) and six main macrofossil zones are apparent (Fig. 6.3):

A: from AD30 to 650 the bog was sedge dominated with fluctuating *Sphagnum* amounts;

B: from AD650 to 1050 sedge remains generally fall and *Sphagna* increase, but with a low point at the top of the zone;

C: the 1st band of *Sphagnum* domination is associated with low sedge remains and virtually no UOM (Unidentifiable Organic Matter). This dates from approx. AD1100-1300;

D: The bog was again dominated by sedge, but also with *Racomitrium* and constant presence of UOM, between AD1300 and 1640;

E: there was an abrupt shift to almost total *Sphagnum* domination with no UOM, as well as low bulk density and humification, between 1640 and 1800;

F: another abrupt change occurred at AD1800 to a *Racomitrium*-dominated bog with more UOM and some sedges. This lasted until very recently when sedge began to replace moss.

This part of Moine Mhor is a water-shedding site at 950 metres and these changes are most likely to be climatically-driven, the bog being wetter during the high *Sphagnum* phases at around AD1080-1300 and AD1640-1800. Many other factors were considered at a useful discussion meeting in Edinburgh with Des Thompson and Richard Lindsay of SNH, but it was concluded that such striking and abrupt changes in the bog water-table must reflect climate. The coincidence of the changes in both Fallahogy and Moine Mhor between AD1600 and 1800 is noteworthy, as is the similar pattern of the tephra profiles (Figure 6.4). The pollen

diagram for Mhoine Mhor is shown in Figure 6.5).

6.2 Remaining work

1. Using the three remaining radiocarbon assays to try and resolve the blip in the age profile in Medieval times;
2. Carbonaceous particle counts on the uppermost peat, by Neil Rose;
3. Geochemical typing of the tephra analyses (Edinburgh);
4. DCA and time-series analyses;
5. Carbon sequestration values over time will be worked out using the bulk density figures when the chronology is complete.
6. Six samples have been extracted for organic geochemical analysis (Bristol) (see Section 4.5 for details).

Whilst the results from the two bog sub-projects are interesting in themselves the combination of analyses from a lowland raised bog and a montane bog some 300 km apart are really exciting. Both bogs demonstrate a distinct signal between AD1600-1800, which must surely be climatically-driven by the cooler, wetter years of this part of the Little Ice Age. The possibilities of linking lesser changes throughout the rest of the last 2,000 years will be explored when the chronologies are complete, and in this regard the similarities of the tephra-occurrence records are very hopeful signs. The linkages with the limnic records must also be explored and discussed.

Figure captions

Figure 6.1 Bulk density and humification profiles for Mhoine Mhor

Figure 6.2 Mhoine Mhor ^{14}C time-depth curve

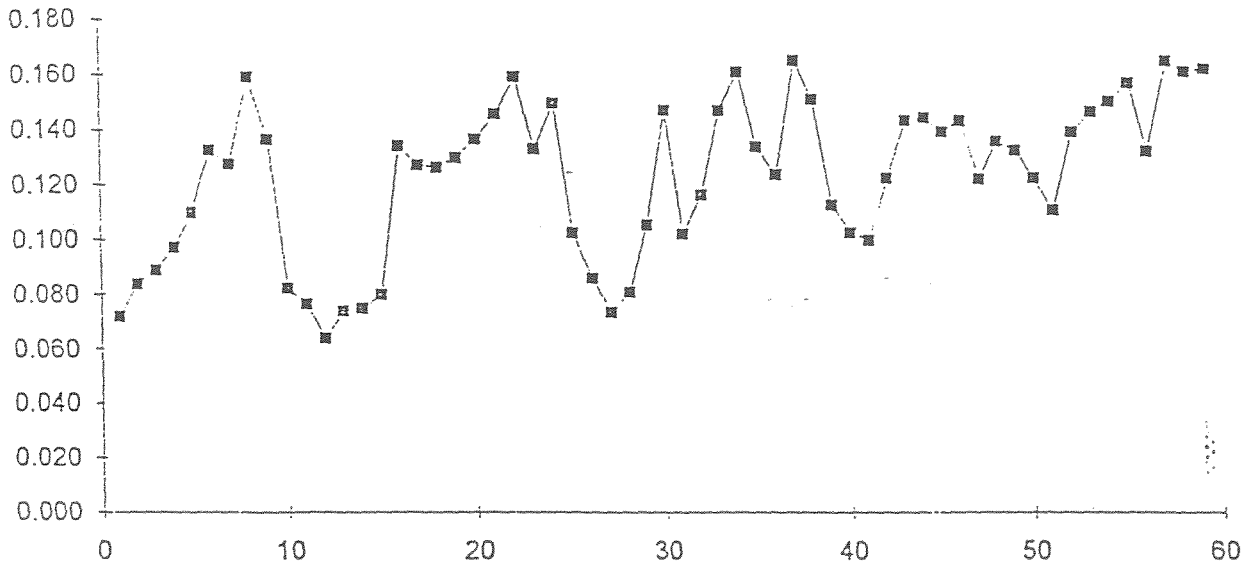
Figure 6.3 Macrofossil diagram for Mhoine Mhor

Figure 6.4 Tephra diagram for Mhoine Mhor

Figure 6.5 Pollen diagram for Mhoine Mhor

FIGURE 6.1

Moine Mhor, Cairngorm Mountains. 950m.
Bulk density



Moine Mhor, Cairngorm Mountains. 950m.
Humification

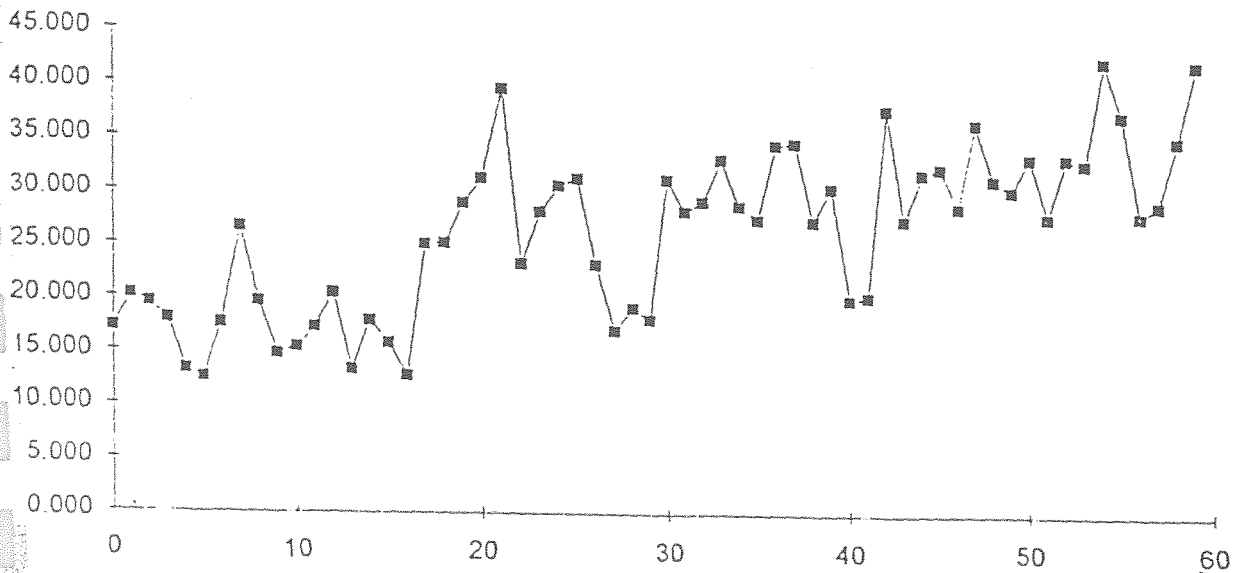


Figure 6.2

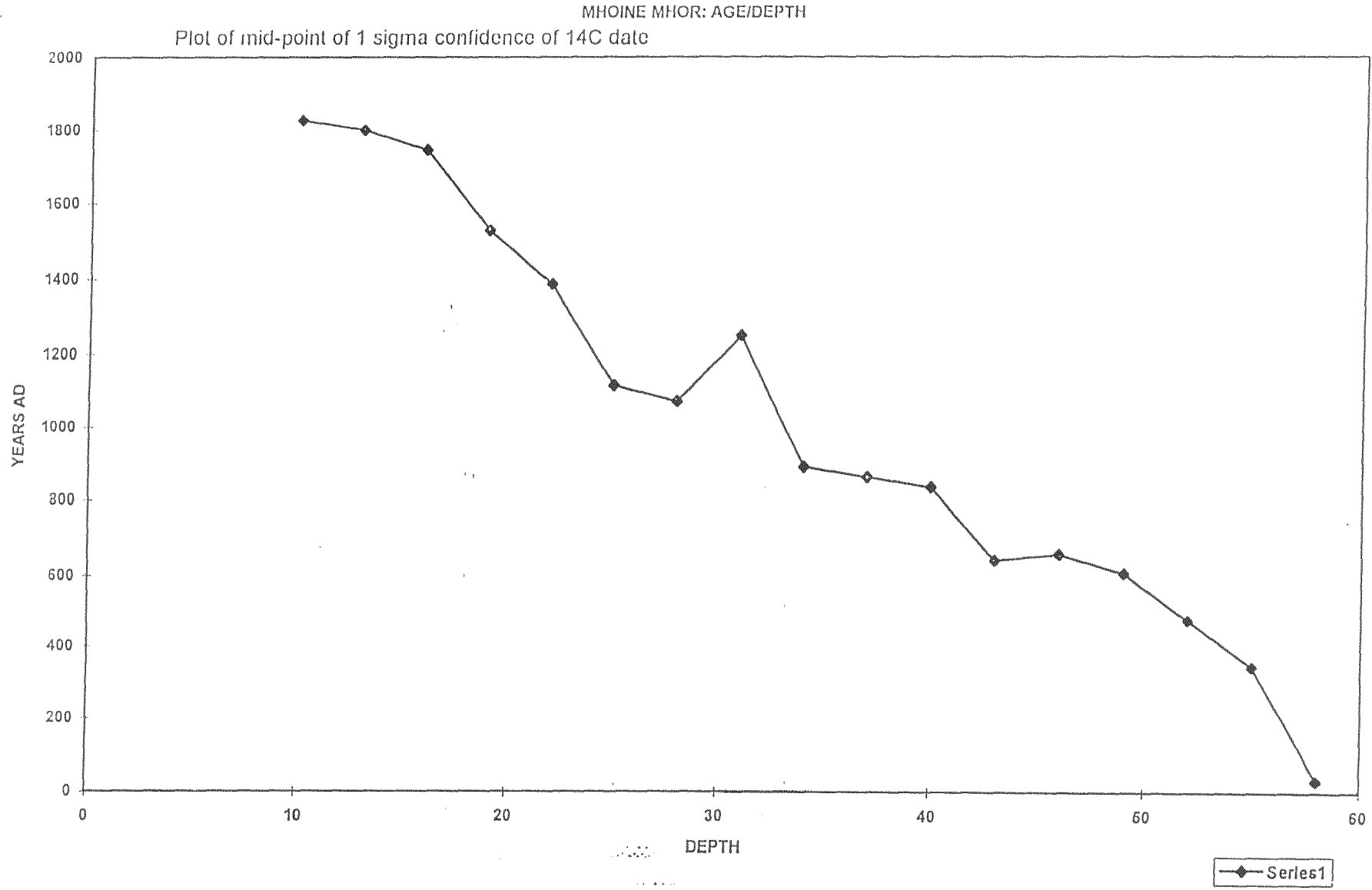
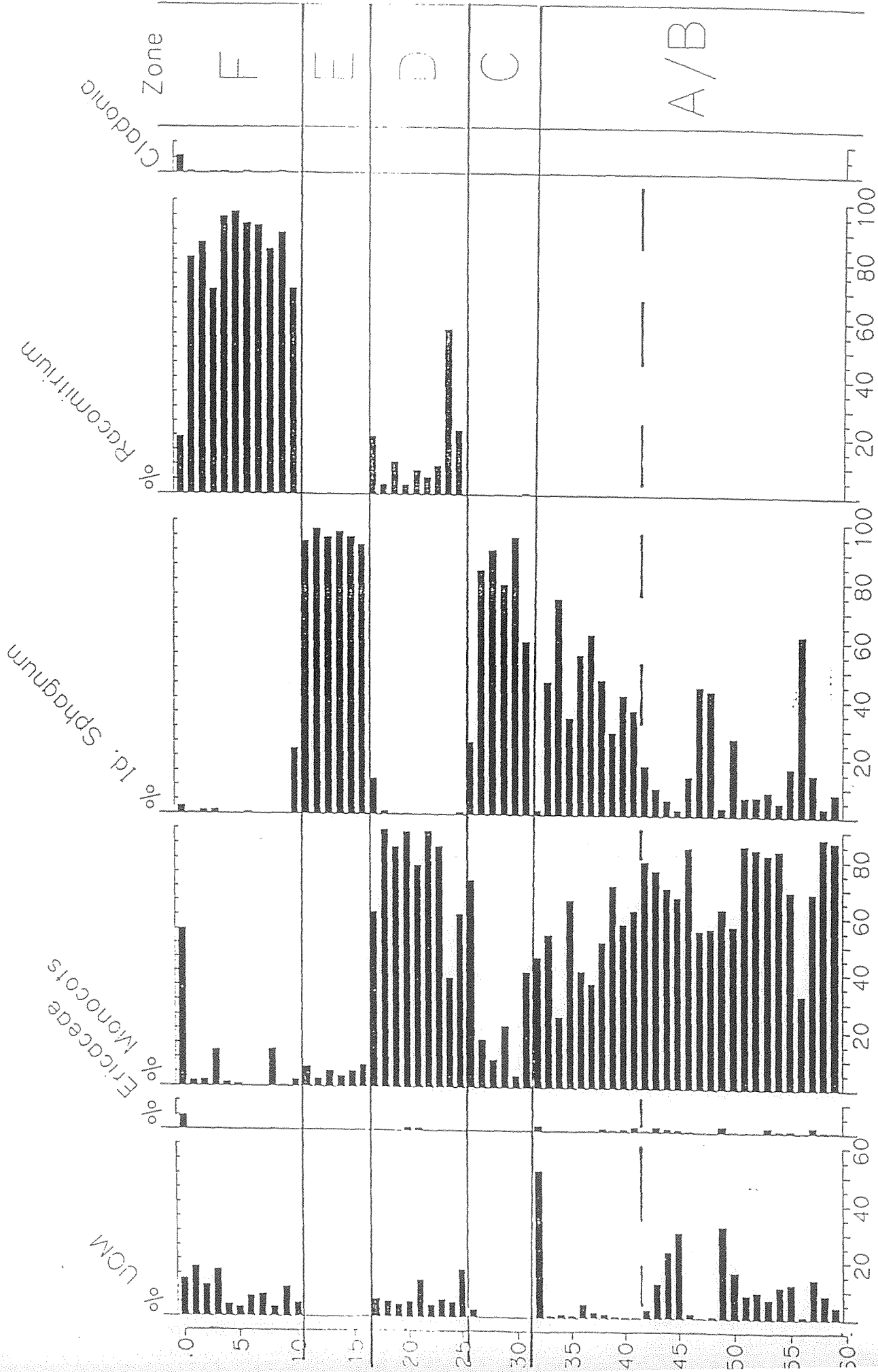


FIGURE 6.3



Analyst: Dr Darrel Maddy

Moine Mhor
Tephra analysis

FIGURE 6.4

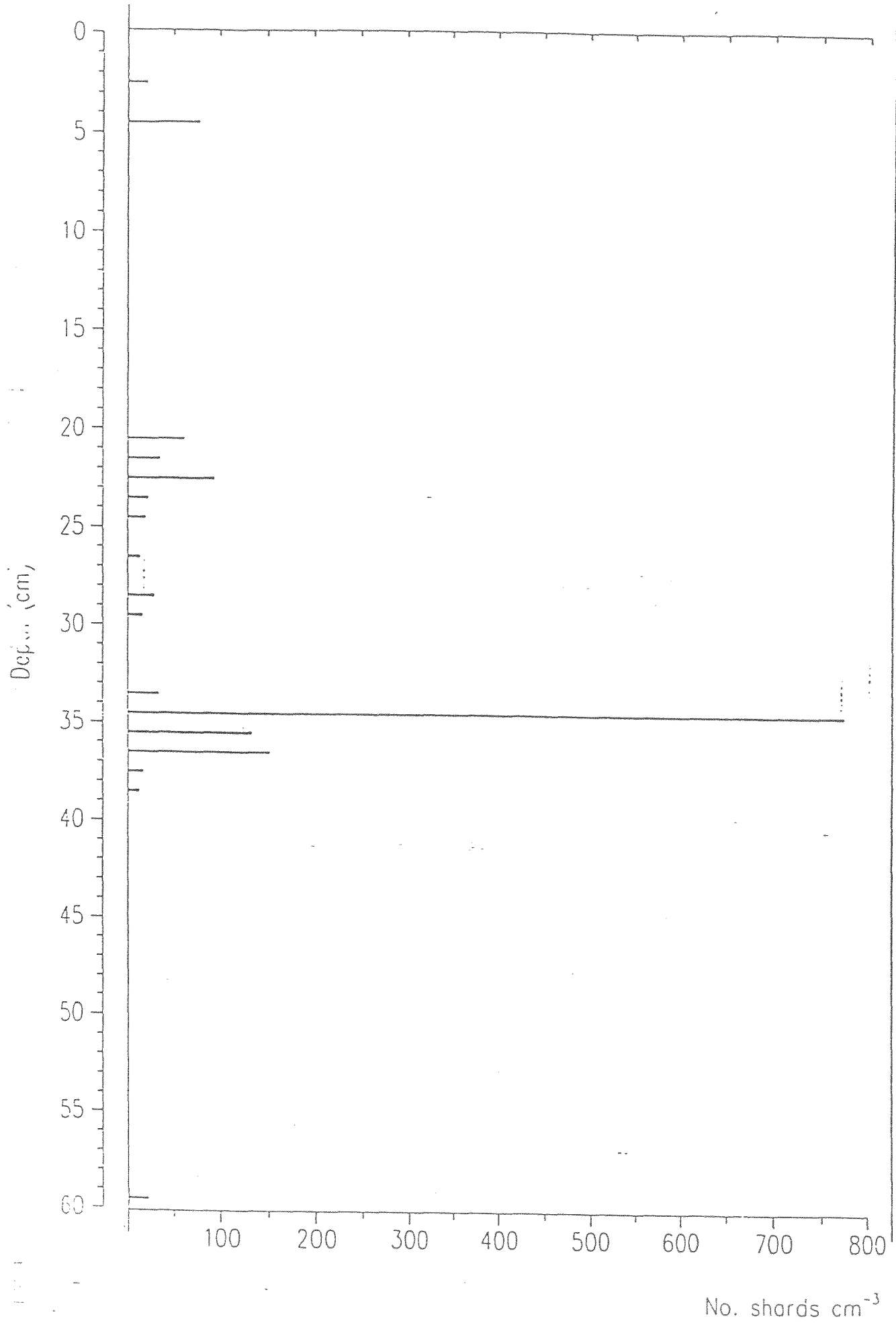


FIGURE 6.5



7. High resolution plankton records from Windermere sediments (Project leader: Liz Haworth)

Liz Haworth, Jean Lishman, D.P. Hewitt (IFE Windermere); Clive Pinder & D Leach (IFE Monks Wood); Roy Thompson (University of Edinburgh).

7.1 Introduction

Various limnological parameters have been closely monitored in several lakes of the English Lake District since the 1940's, especially Windermere. These have detailed changes in algal and faunal plankton populations, as well as some related physical and chemical aspects, that are indicative of aquatic responses over various time periods. The resultant database has thus provided details that show that, as well as a series of changes in algal composition and the encouragement of algal growth by increased nutrient availability, there are different planktonic population responses to the complex interactions of physical and chemical situations as well as biological relationships (Reynolds 1984, Bailey-Watts personal communication). One of the simpler physical situations is that of water temperature - itself a function of sunlight, day-length and wind speed - and algae grow better as temperature rises; in winter this affects the amount of ice-cover, in summer the depth of stratification and stability, these in turn dictate the composition and biomass in the plankton. These and other factors are reflected in the differences observed in annual patterns of species composition.

Microfauna - chironomids, Crustacea etc - compete for available food and provide a food source for the next link in the food chain so that population changes are the product of both aspects. Although less carefully monitored than the algae we have some early records from 1936-7 and samples have been collected and stored since the 1940's. Some of these are presently being processed providing data over a period of some 20 years (George, personal communication). Records include the taxa; *Diaphanosoma brachyurum*, *Daphnia hyalina*, *Bosmina coregoni* var. *obtusirostris*, *Leptodora kindti*, *Bythotrephes longimanus*, *Eudiaptomus gracilis*, *E. laticeps*, *Cyclops leuckarti* and *C. strenuus*.

Diatom assemblage profiles of the recent, upper c. 50 cm, sediments which have been studied in relation to the long-term algal records (Haworth 1980, 1984; Sabater and Haworth, in press.) show good overall correlation in the timing of a succession of diatom taxa and correlation of some peaks in sediment concentrations with years of high populations.

Recently, comparison of the sedimentary profile of *Asterionella* and *Fragilaria crotonensis* with the three-year running mean of planktonic populations in the South Basin of Windermere has shown the very good correlation between the two types of record (Maberly *et al.* 1994).

7.2 This Study

This project, within the TIGGER programme that is considering the last 2 millenia, was planned so as to compare close interval, detailed analyses of the sedimentary profiles of diatoms and aquatic microfauna with the long-term records of plankton populations and to try to identify and link biotic responses to local weather patterns with the sedimentary record.

Diatom and faunal profiles have been analysed using a sediment core from Windermere North Basin which has been sliced at 1/4 cm intervals. The core has been dated by radio-isotope analysis of ^{210}Pb and geochemical aspects have also been examined.

7.3 Methods

A 1 metre core of sediment was collected, using a Mackereth corer 10 cm in diameter, from the north basin of Windermere, in 53 m water depth, National Grid Ref. NY382008, September 1992. This was extruded and sliced into 1/4 cm slices, which were divided into subsamples for: diatom analyses (0.6 cm^3); faunal analyses (5.5 cm^3); and dating, magnetics and chemical analyses (c. 14.33 cm^3).

The diatom subsamples were cleaned by adding hydrogen peroxide and rinsed in distilled water. Two microscope slides were made from each sample using Naphrax diatom mountant (Refractive Index 1.74) the volume of each being equivalent to 0.0001 cm^3 of the original wet sediment. Percentage analyses are based on the sum of 500, and a rough comparison of concentration based upon the number in the widest transect of the sample. Concentrations of certain taxa, eg. *Aulacoseira subarctica* are based on numbers per volume on the slide.

For faunal analysis, 0.5 cm^3 was extracted from each 1/4 cm subsample, sieved through a $65\mu\text{m}$ mesh to remove fine clays etc and diluted. The volume analysed was thus equivalent to 0.05 cm^3 of the wet sediment. For the 13 taxa profile, the data from the 1/4 cm samples were combined to represent 1 cm slices of 0.2 cm^3 volume; the depths are given as the mid-point.

For radio-isotope dating, mineral magnetic and chemical analyses, the subsamples were dried and water content and wet density determined and these were first sent to Liverpool University for radio-isotope and magnetic particle analyses before being returned for geochemical analysis. Carbon was measured on dry samples, using a Carlo Erba elemental analyser Model 1106. Other elements analysed using ICP-MS (inductively coupled argon plasma- mass spectrometry) after sequential digestion with nitric, perchloric and hydrofluoric acids.

7.4 Results

7.4.1 Sediment lithology

A visual description was made as the core was extruded and sliced. Depths are expressed in centimetres.

0	>Brownish-green flocculant material
0.75	>dark brown, soft sediment
2.0	

4.0	>blackish soft sediment
6.75	>streaked grey black, stiffer below 5 cm
9.5	>streaked brown black, stiffer sediment
11.25	>blackish sediment
21.25	>black sediment
23.0	>lighter colour, layer of coal/clinker at 22.5 cm
28.25	>greyish sediment
30.25	>lighter grey
31.75	>brownish transition to grey
32.5	>brown sediment, some black streaks
	>brown sediment

7.4.2 Radiometric dating

Analyses of ^{134}Cs , ^{137}Cs and ^{210}Pb have provided the chronology and accumulation rates for the 1992-2 core from the north basin of Windermere (Figures 7.1). This has compared well with earlier estimations of a similar profile from the southern basin (Sabater & Haworth in press, P. Appleby, personal communication).

7.4.3 Geochemistry

The carbon percentage profile of the upper 21 cm (Figure 7.2) indicates increasing organic matter between 21 and 18 cm, a minimum of carbon, i.e. an increase in mineral matter around 8.5 cm, the mid 1960's, and steadily increasing carbon above 6 cm, i.e. since the mid 1970's. Total phosphorus is clearly increasing through the profile but is also markedly reduced in concentration between 7 and 8.5 cm. Geochemical analyses of both soil minerals and metals also differentiate this horizon as having higher concentrations of magnesium, potassium, aluminium, iron and sodium, and decreases in manganese, copper, lead and zinc (Figure 7.2). Turned into yearly increments, the sediments are richest in iron and aluminium and the differentiation of the minerogenic layer of 7 to 8.5 cm is very marked (Figure 7.3). Apart from higher levels in the present surface sediment and at 21 cm, most elements show little change through the remainder of the profile. The minerogenic section clearly dates from the Langdale flood of 1966, which is highlighted by the timescale based on the algal slotted sequence (Figure 7.3)

7.4.4 Diatoms

Percentage analyses of the diatom composition include every 1/4cm down to 15 cm, to cover the time period since 1940, and every 3 cm down to 35cm (Figure 7.4). The results show the increase and dominance of *Asterionella formosa*; the decrease of *Cyclotella comensis*; several distinct peaks in taxa such as *Cyclotella glomerata*, *Aulacoseira subarctica*, *Fragilaria crotonensis*; and the recent appearance and increases in both *Stephanodiscus parvus* and *Aulacoseira islandica* ssp. *helvetica*. A rough estimate of concentration of the last taxon suggests that there are now several thousand in 10^{-4}cm^3 , the same being true for *A. subarctica* (Figure 7.5), which concurs with our understanding of the plankton populations (J. Parker, personal communication).

Instead of the steady increase in the succession of taxa new to the community, the profile of changing percentages includes a series of increases and decreases (Figure 7.4). These are most clearly seen in the taxon *Cyclotella glomerata* but all show some degree of variation. To some extent this may reflect sediment averaging of single very good population such as the maximum of *Aulacoseira subarctica* in 1967 but, even underlying this, there is a cycle of several years of better populations (Figure 7.4). It is these annual differences that reflect the differences in climate and nutrient levels.

Several diatom taxa may be hard to distinguish at all times, eg. *Cyclotella comensis* and *C. atomus* may represent difference in size and silica thickness, and various *Synedra* spp are very similar to *Fragilaria crotonensis*. Some taxa which have been analysed separately have been merged for purposes of correlation with phytoplankton records where such specific distinctions have not been recognized, such as the differentiation of *Fragilaria crotonensis* var. *prolongata* from the species.

Ecologically there have been several shifts to more alkaline diatom taxa since the transition from brown to blackish sediment, such that the pH inferred from the dominant taxa (Figure 7.6) has increased from 6.5 at 33 cm to a maximum of 8.0 at 3.5 cm, the latter due to an increase in the alkalibiontic forms of *Stephanodiscus*. These calculations are in extremely good agreement with the annual averages for the 1953 - 1978 period (Carrick and Sutcliffe 1982).

7.4.5 Long-term algal monitoring

Phytoplankton in Windermere has been sampled at weekly or fortnightly intervals since 1945 (Talling *et al.* 1986). The data include 5 diatom taxa for which there are complete records, smaller centrics being rather intermittantly monitored. The annual maximum of cells/ml provides a good guide to the changes in the populations from year to year (Figure 7.7). There is clearly a period when *Asterionella* populations were low, c 1960 to 1974, *Tabellaria flocculosa* ssp *asterionelloides* has several years with very high populations, especially in the 1950's and 1960's, *Fragilaria crotonensis* has two periods with higher maxima and *Aulacoseira subarctica* was extremely abundant in 1967. The patterns of change in the sedimentary record clearly reflects the changes in actual plankton populations extremely well and are similar to the profile correlation in the southern basin of the lake (Maberly *et al.* 1994).

7.4.6 Slot sequencing diatom plankton and sediment records from Windermere

Although visual agreement between the two data sets is good, percentaged data have also been matched, using a formalized sequence slotting algorithm (Thompson and Clark 1989). This uses a dynamic programming technique to adjust the sediment accumulation in the core to maximize the fit between the two data sets, while retaining the stratigraphic integrity of the core.

A good fit is found for all 5 taxa (Figure 7.8) with specific seasonal peaks clearly visible in the sediment record, e.g. the *Aulacoseira subarctica* and *Fragilaria crotonensis* blooms of 1967 and 1969 - 1970 preserved as distinct peaks. The Windermere sediment is thus seen to preserve the fluctuating algal record with the remarkably high resolution of 3 years or less.

^{210}Pb provides a completely independent check on the slotting procedure. Figure 7.8 compares sediment ages derived from the sequence slotting algorithm and Figure 7.9 the radio-active decay of ^{210}Pb . The two approaches are in excellent agreement. Sediment deposition is found to be continuous, there is no evidence for any hiatus in the Windermere record. The small inflections in the sequence slotting time-depth relationship (Figure 7.9) point to several short-term changes in sediment accumulation during the last 50 years. For example, there is a period between 1966 and 1969 where accumulation rises to 5 mm yr^{-1} , compared to the pre-1966 rate of 2 mm yr^{-1} . This clearly relates to the storm event in Langdale in 1966, as confirmed by an haematite peak in magnetic studies (Oldfield, personal communication). Subsequent increases can be related to the dredging activities associated with the sand and gravel assessments in the early 1970's, when redeposited material was seen on the surface of sediment cores.

7.4.7 Fauna

In the faunal analyses the only recognizable fragments that have consistently been found in large numbers are of *Bosmina* heads and carapaces and *Daphnia* claws. Numbers fluctuate considerably from sample to sample up the core with a maximum of c. 3400 *Bosmina* fragments in cm^3 and 600 *Daphnia* claws in cm^3 (Figure 7.10). Sediment profiles of both taxa include short term increases and decreases in numbers. Numbers of *Bosmina* fragments appear to increase slowly from 35 to 24 cm and are most abundant between 24 and 14 cm, 1890 to 1940. There is an abrupt drop in numbers per sample above 13 cm, following the *Asterionella* decline, to levels at or below those at the base of this profile. The minimum at 9 cm corresponds to the increased sedimentation of minerogenics in the mid 1960's. *Daphnia* remains fluctuate inversely with *Bosmina* and appear to be most abundant between 14 and 3 cm with a peak c. 7 cm (1974). There is some difference in the relative proportions of these two taxa in sediments as compared with recent plankton samples, since *Daphnia* appears much more abundant in the latter and, although it is possible that either material has been missed in the plankton sampling of the sediment analysis, it is not easy to account for the difference.

Only the Cladocera, *Daphnia* and *Bosmina*, together with the Rhizopoda are truly planktonic,

the remainder occurring in sediment or in association with littoral vegetation. Most occur too infrequently for reliable conclusions as to changes in populations in Windermere (Figure 7.11). *Chydorus* and *Graptoleberis* occur more frequently in the lower part of the core, pre-1930. The Rhizopoda are one of the major groups in the plankton and appear to decline steadily throughout the 19th century. The numbers recover over the period 1900 - 1940 but decline again in the late 1970's. Nematoda should perhaps be excluded since they may move within the sediments and it is therefore difficult to judge how far this profile reflects present distribution rather than past population changes. *Alonella* occurs throughout but is best represented between 24 and 10cm

7.4.8 Climate records

Various local weather records have been collated at the Institute of Freshwater Ecology covering the period 1950 to the present. Some water temperatures and wind speeds are already computerized for the period 1940 - 1990, other records, such as solar radiation, ice-cover, lake levels etc may be less complete. It is possible to identify periods that were warmer or colder, wetter or drier, rougher or calmer than average, from the initial diagrams but not to correlate algal change from these 2-way arrays. It should be possible to check the years of high and low populations of *Asterionella* and *Aulacoseira subarctica* against winter and early spring air and water temperatures (Bailey-Watts, personal communication)..

7.5 Discussion

The results of the sediment analyses show a that there is a good record of short-term plankton responses. Correlation with the Windermere Algal Database (Lund 1964, Talling *et al.*; 1986) required careful consideration to ensure that like was matched to like and the Slot Sequencing has shown a very good match with both diatoms and ²¹⁰Pb dating. Correlation between the faunal remains and the zooplankton records of Smyly, George *et al.* (Macan 1970, and unpublished data) has not yet been made. It is apparent that small centrals can be more readily identified to species level in palaeolimnological samples than in the routine monitoring of general phytoplankton than in preserved plankton samples and this has limited their value in this study although they could be re-evaluated from stored samples.

The further stage of identifying plankton responses to changing weather patterns still requires some study to sort out and correlate long-term weather and plankton records (George and Harris 1985, George *et al.* 1990).

References

- Carrick, T.R. & Sutcliffe, D.W. (1982) Major Ions in Lakes and Tarns of the English Lake District (1953-1978). *F.B.A. Occ. Sci. Pub* 16, pp 168.
- George, D.G. & Harris, G.P. (1985) The effect of climate on long-term changes in the crustacean zooplankton biomass of Lake Windermere, UK. *Nature* 316, no. 6028, 536-539.

- George, D.G., Hewitt, D.P., Lund, J.W.G. & Smyly, W.J.P. (1990) The relative effects of enrichment and climate change on the long term dynamics of *Daphnia* in Esthwaite Water, Cumbria. *Freshwater Biology* 23, 55-70.
- Goulden, C.E. (1964) The history of the cladoceran fauna of Esthwaite Water (England) and its limnological significance. *Arch. Hydrobiol.* 60, 1-52.
- Hamsworth R. (1968) The developmental history of Blelham Tarn (England) as shown by microfossils, by special reference to the Cladocera. *Ecol. Monogr.* 38, 223-241.
- Haworth, E.Y. (1980) Comparison of continuous phytoplankton records with the diatom stratigraphy in the recent sediments of Blelham Tarn. *Limnol. Oceanogr.* 25, 1093-1103.
- Haworth, E.Y. (1984) Stratigraphic changes in algal remains (diatoms and chrysophytes) in the recent sediments of Blelham Tarn, English Lake District. In: Lake Sediments and Environmental History, Eds Haworth, E.Y. & Lund, J.W.G.; Leicester University Press; pp 165-190.
- Lund, J.W.G. (1964) Primary production and periodicity of phytoplankton. *Verh. Int Ver. Limnol.* 15, 37-56.
- Maberly, S.C., Reynolds, C.S., George, D.G., Haworth, E.Y. & Lund, J.W.G. (1994). The sensitivity of freshwater plankton to environmental change: monitoring, mechanisms and models. In: Long-term experiments in agricultural and ecological sciences, Rothamstead 150th Anniversary Symposium, Eds. R.A. Leigh & A.E. Johnson) CAB International, Wallingford.
- Macan, T.T. (1970) Biological studies of the English Lakes. London, Longman, pp. 260.
- Pennington, W. (1943) Lake sediments: the bottom deposits of the north basin of Windermere, with special reference to the diatom succession. *New Phytologist* 42, 1-27.
- Reynolds, C.S. (1984) The Ecology of the Freshwater Phytoplankton. Cambridge Univ. Press pp. 384.
- Talling, J.F.T., Atkinson, K.M., Elliott, J.M., George, D.G., Jones, J.G., Haworth, E.Y., Heaney, S.I., Mills, C.A. & Reynolds, C.S. (1986) A general assessment of environmental features of Windermere and their susceptibility to change. Report to North West Water.
- Thompson, R. and Clark, R.M. 1989. Sequence slotting for stratigraphic correlation between cores: theory and practice. *J. Paleolimnology* 2, 173-184.

Figures

Figure 7.1 Depth/Age curve for Windermere north basin core 92-2

Figure 7.2 Geochemical data for Windermere north basin core 92-2

Figure 7.3 Geochemical accumulation rates for Windermere north basin core 92-2: (a) using ^{210}Pb dating; (b) using algal sequencing.

Figure 7.4 Diatom percentage diagram for Windermere north basin core 92-2

Figure 7.5 Diatom concentrations for Windermere north basin core 92-2

Figure 7.6 Diatom inferred pH for Windermere north basin core 92-2

Figure 7.7 Long-term planktonic diatom records for Windermere north basin

Figure 7.8 Slot sequencing between algal records and sediment records

Figure 7.9 Chronology comparison between algal sequences and radio-isotope dates.

Figure 7.10 *Bosmina* and *Daphnia* concentrations for Windermere north basin core 92-2

Figure 7.11 Faunal remains from Windermere north basin core 92-2

Windermere North Basin Depth v Age

FIGURE 7.1

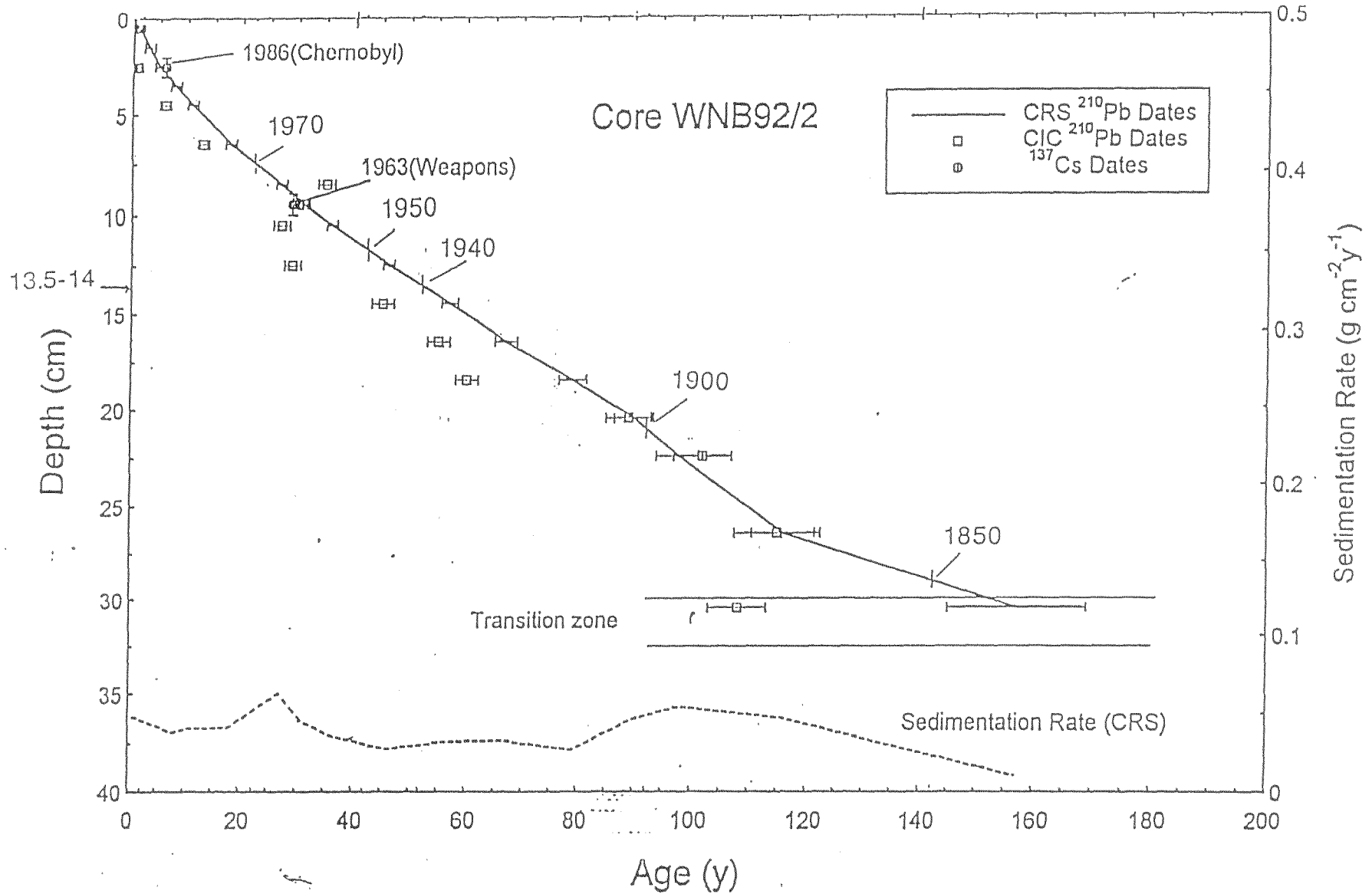
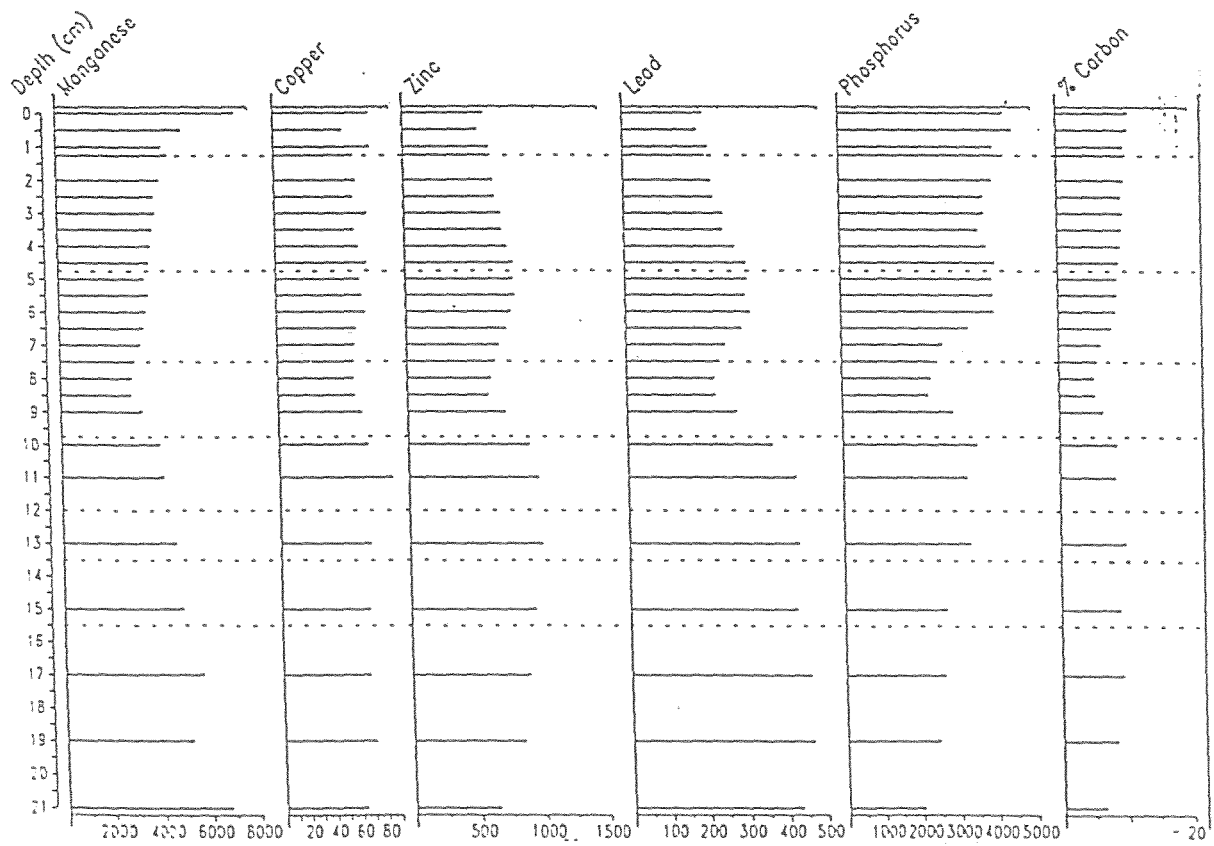
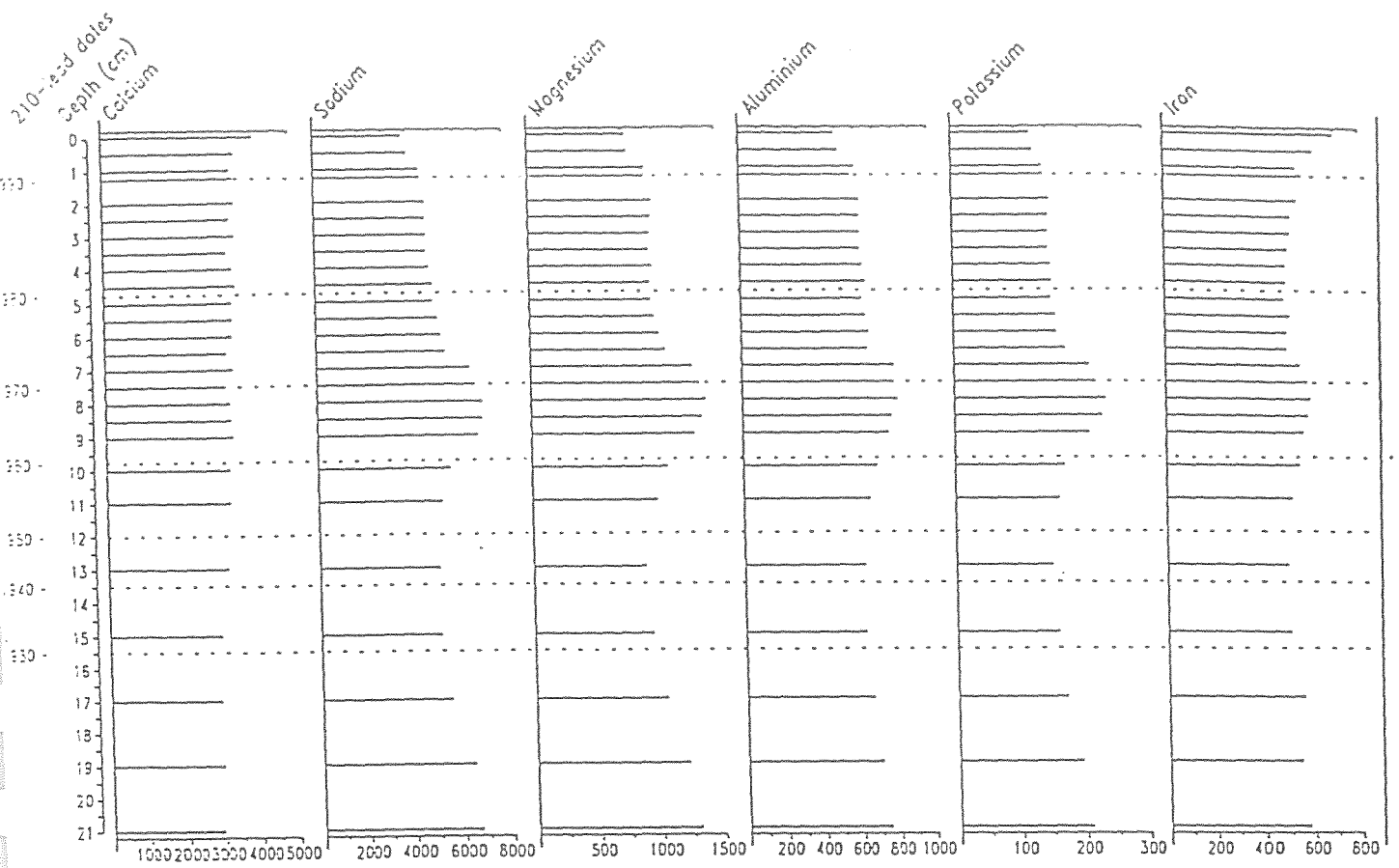
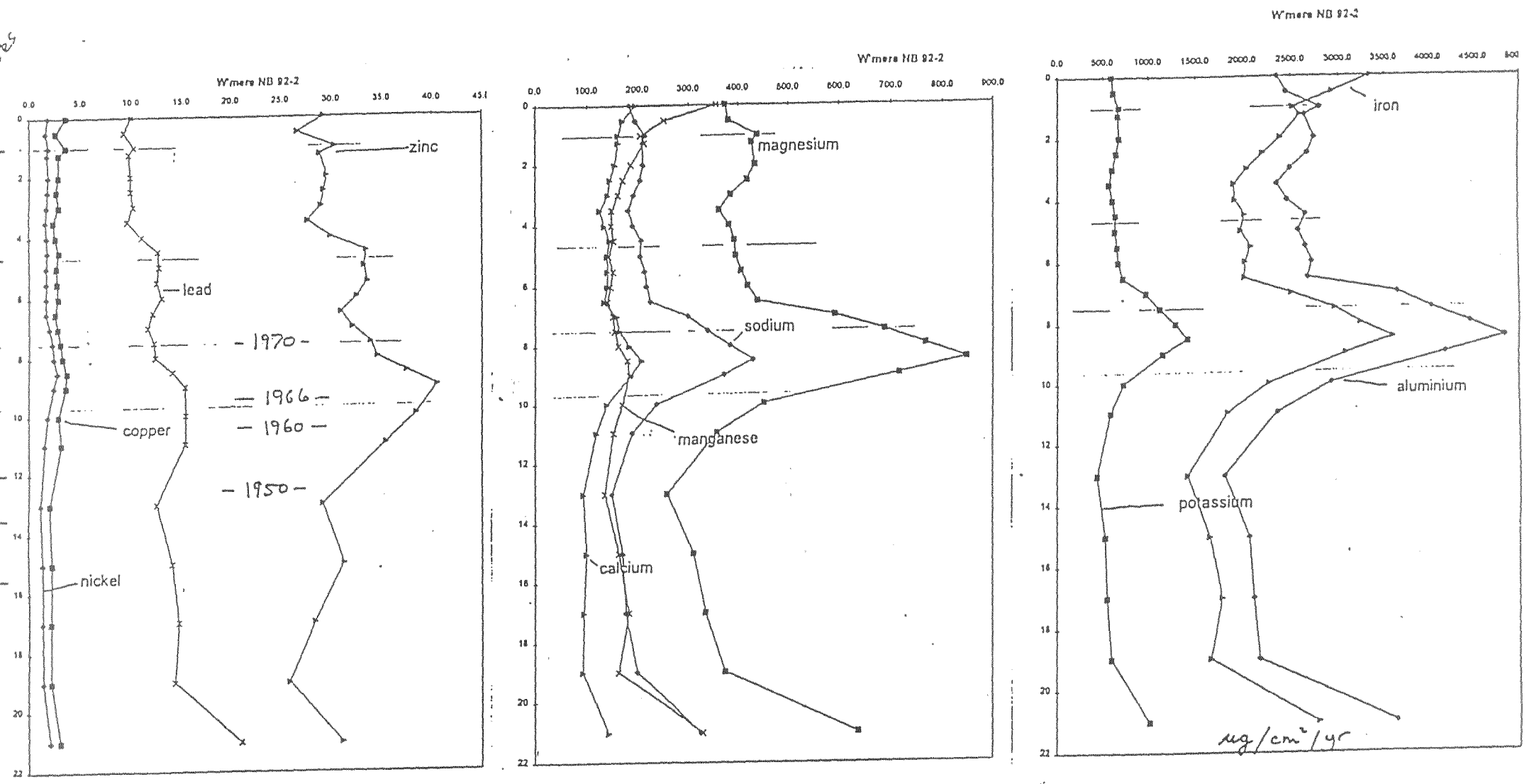


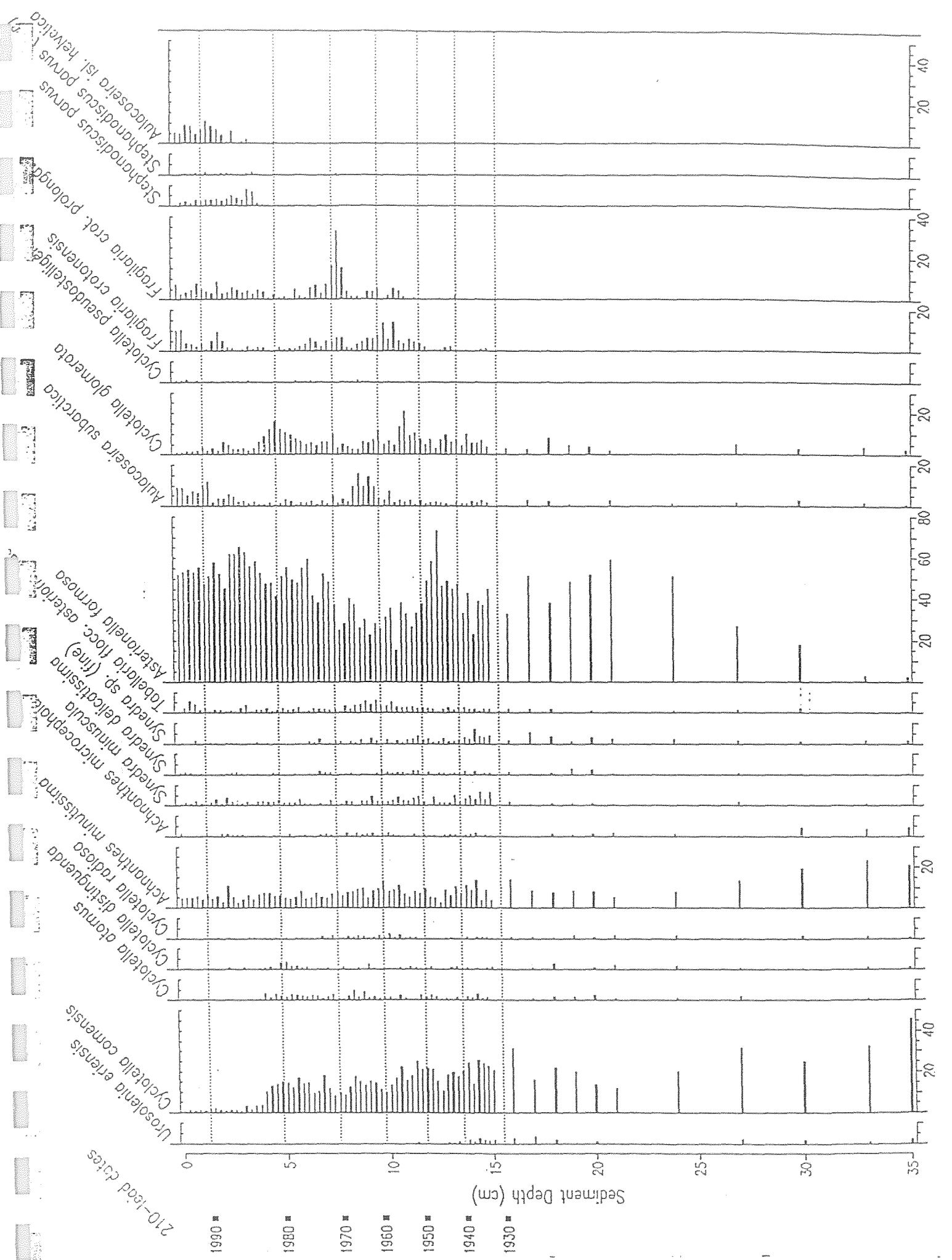
FIG 7.2



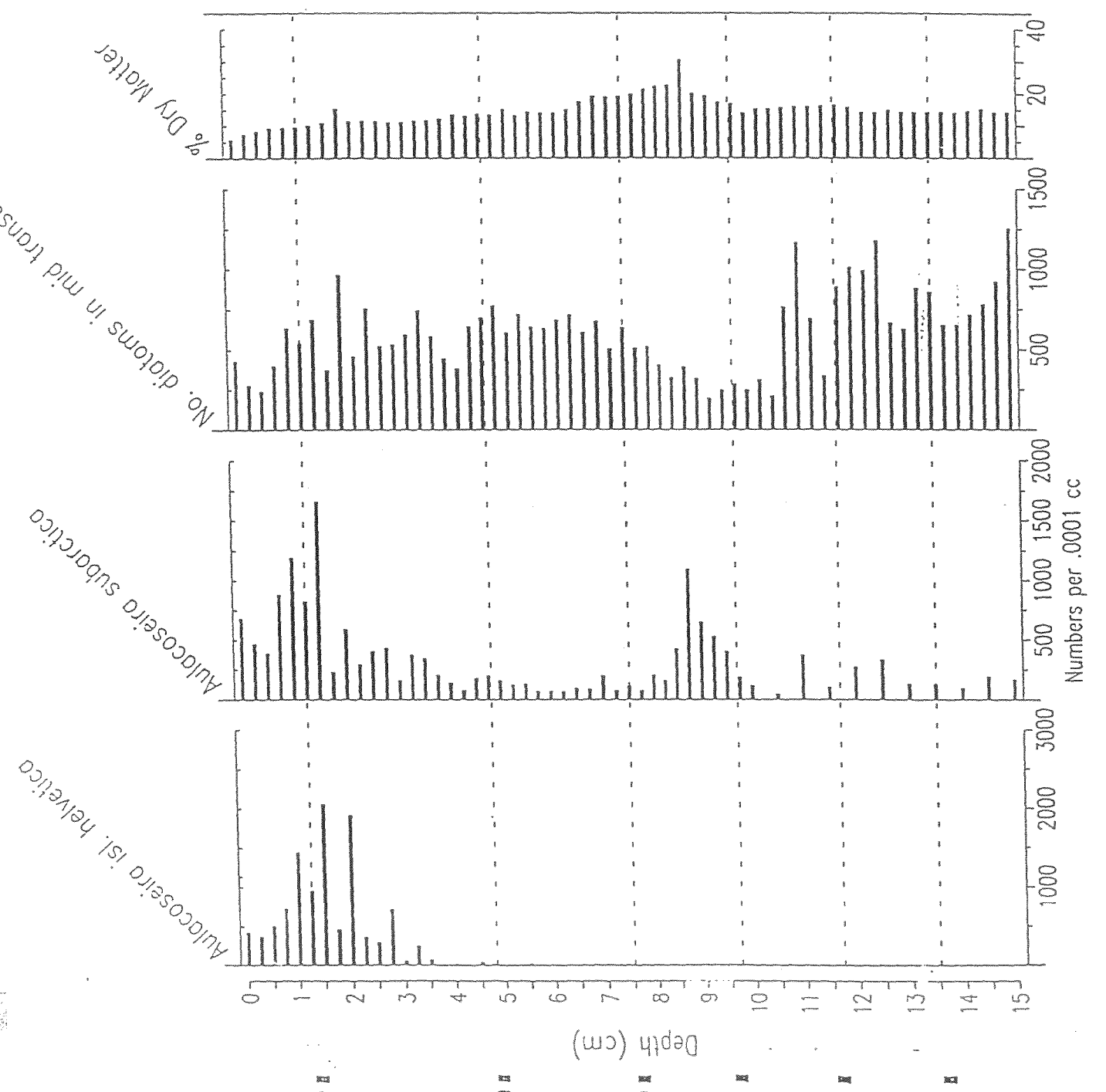
lead dates



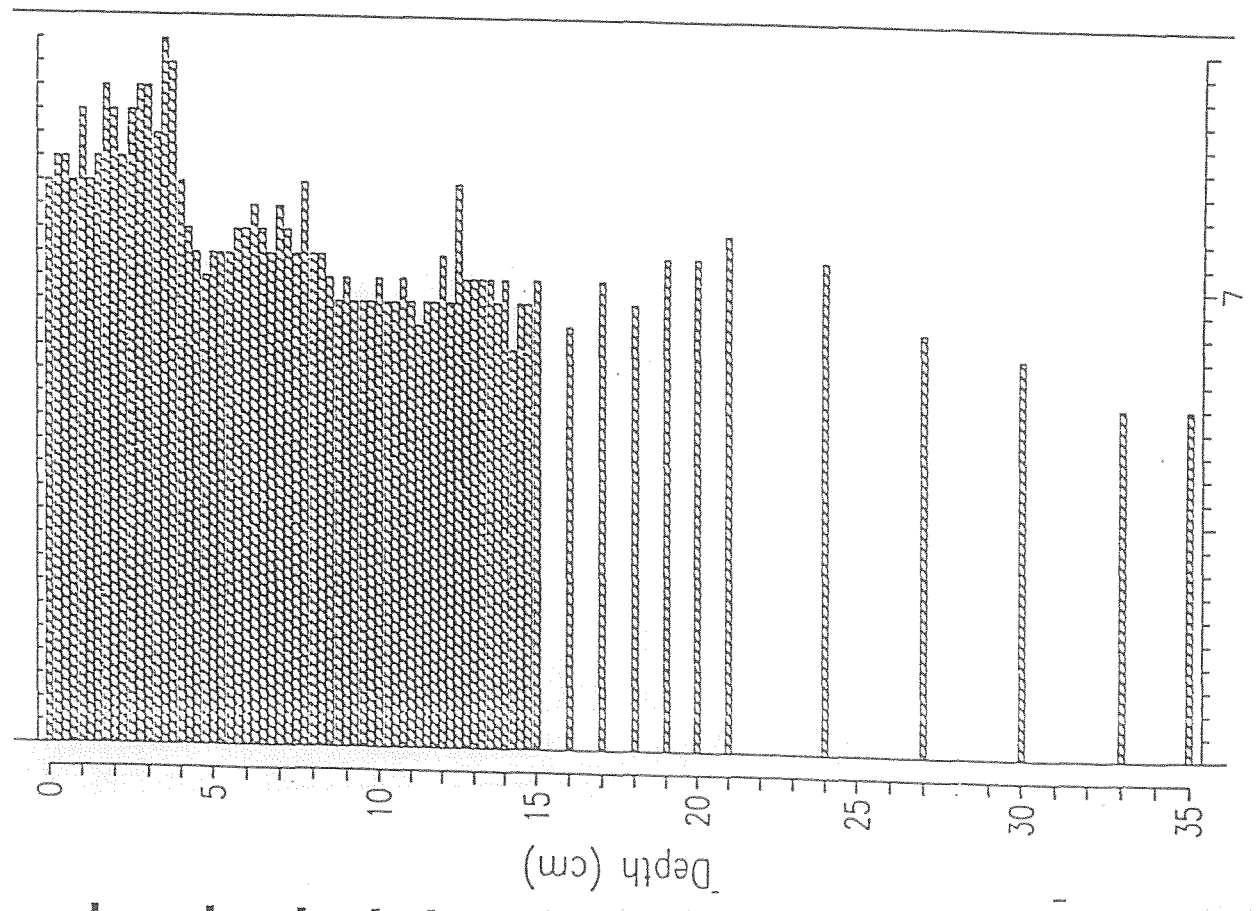
Windermere North Basin core 92-2: geochemical influx dated: a) by lead isotope and b) by algal sequencing.



Diatom concentrations and % dry matter



210-lead dates
H. ...



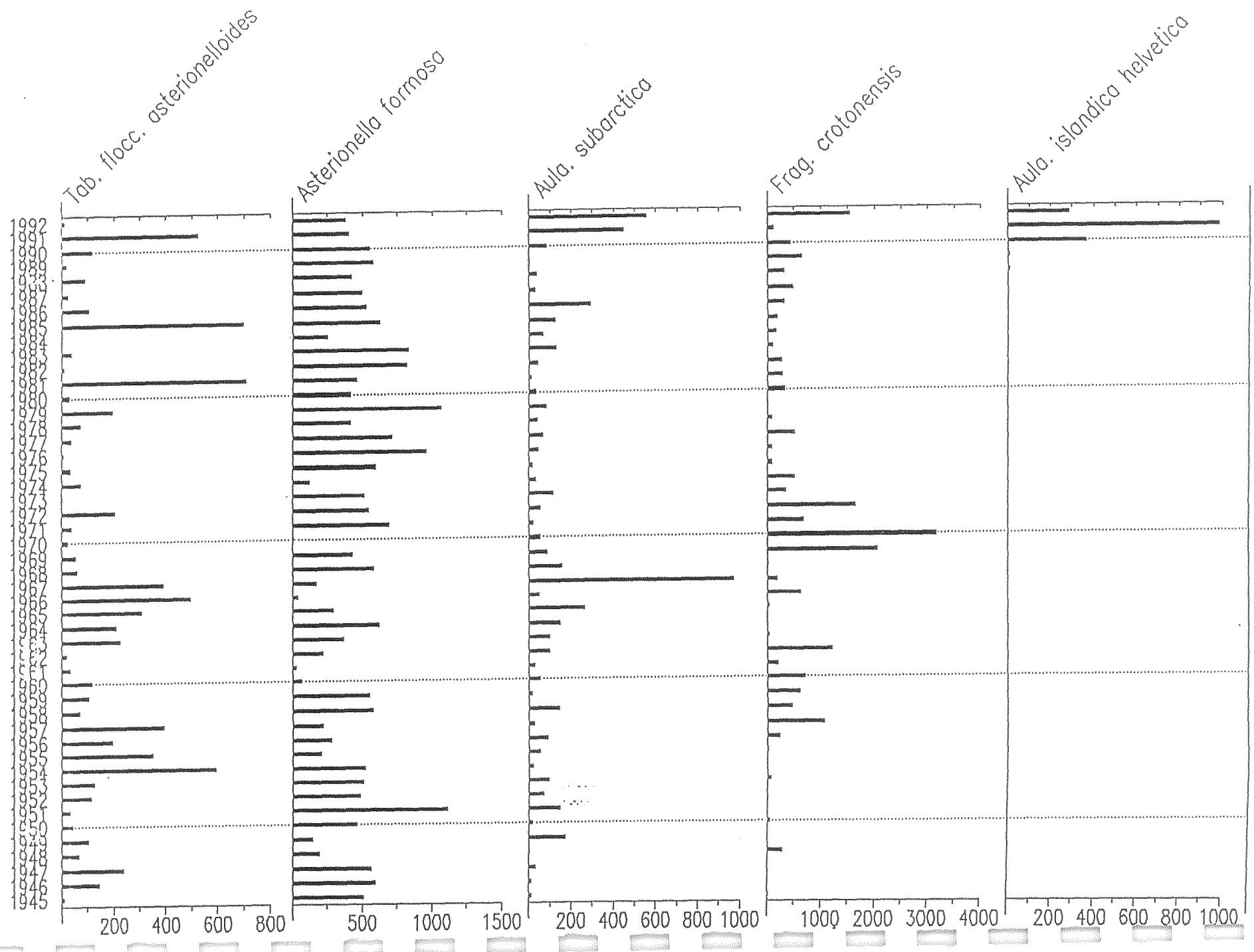
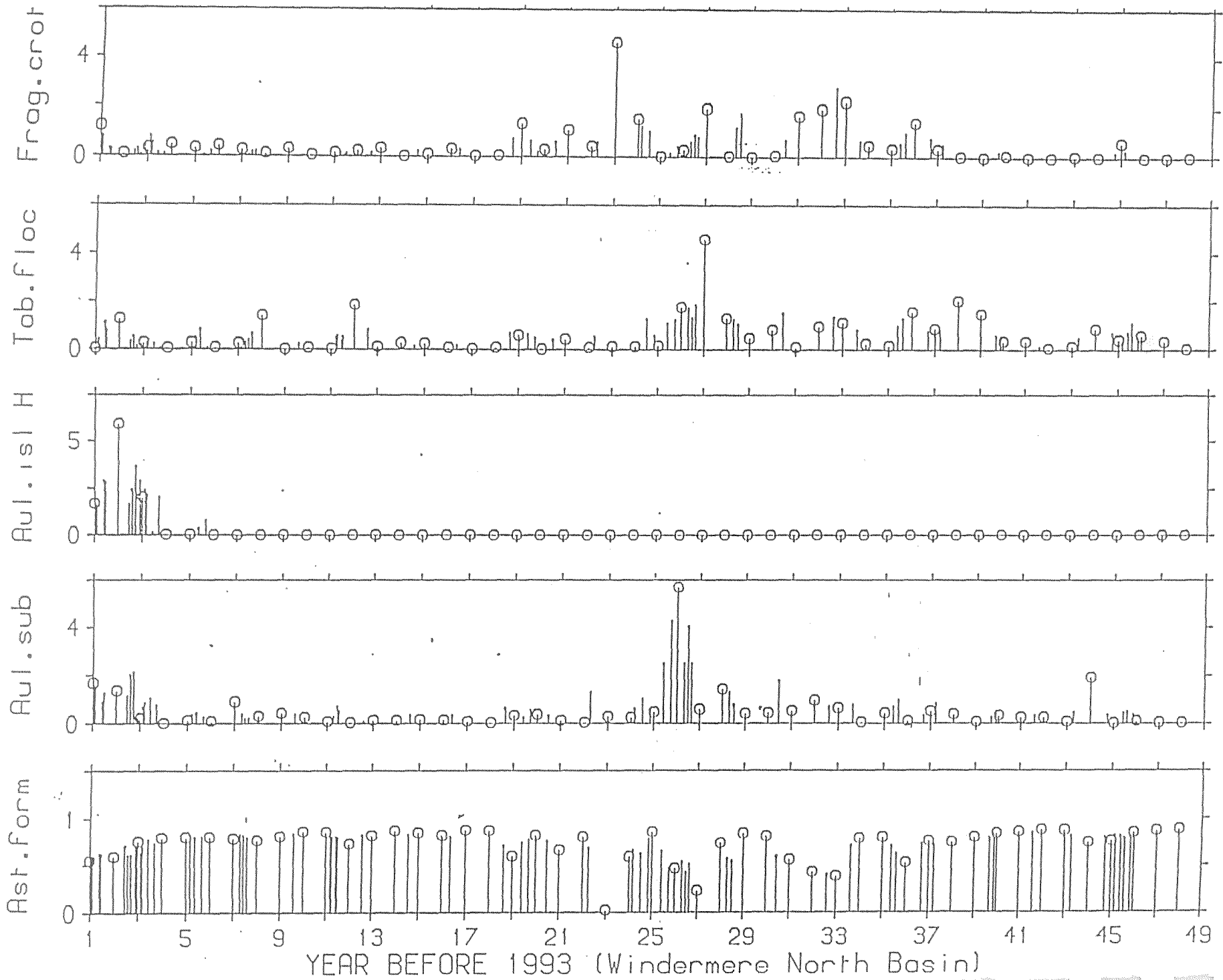


FIGURE 7.8



ALGAE SEQUENCE SLOTTING VS LEAD-210

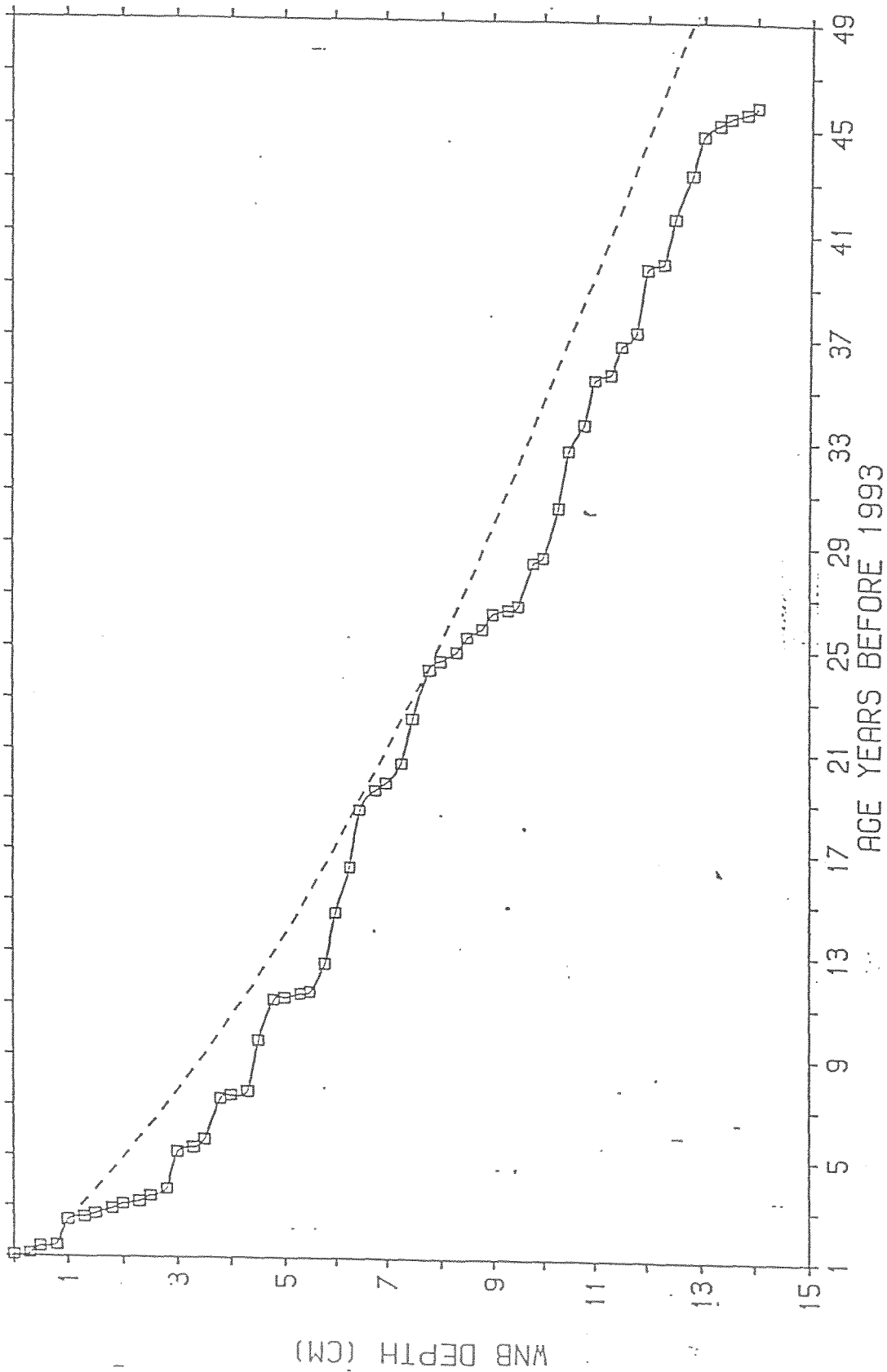
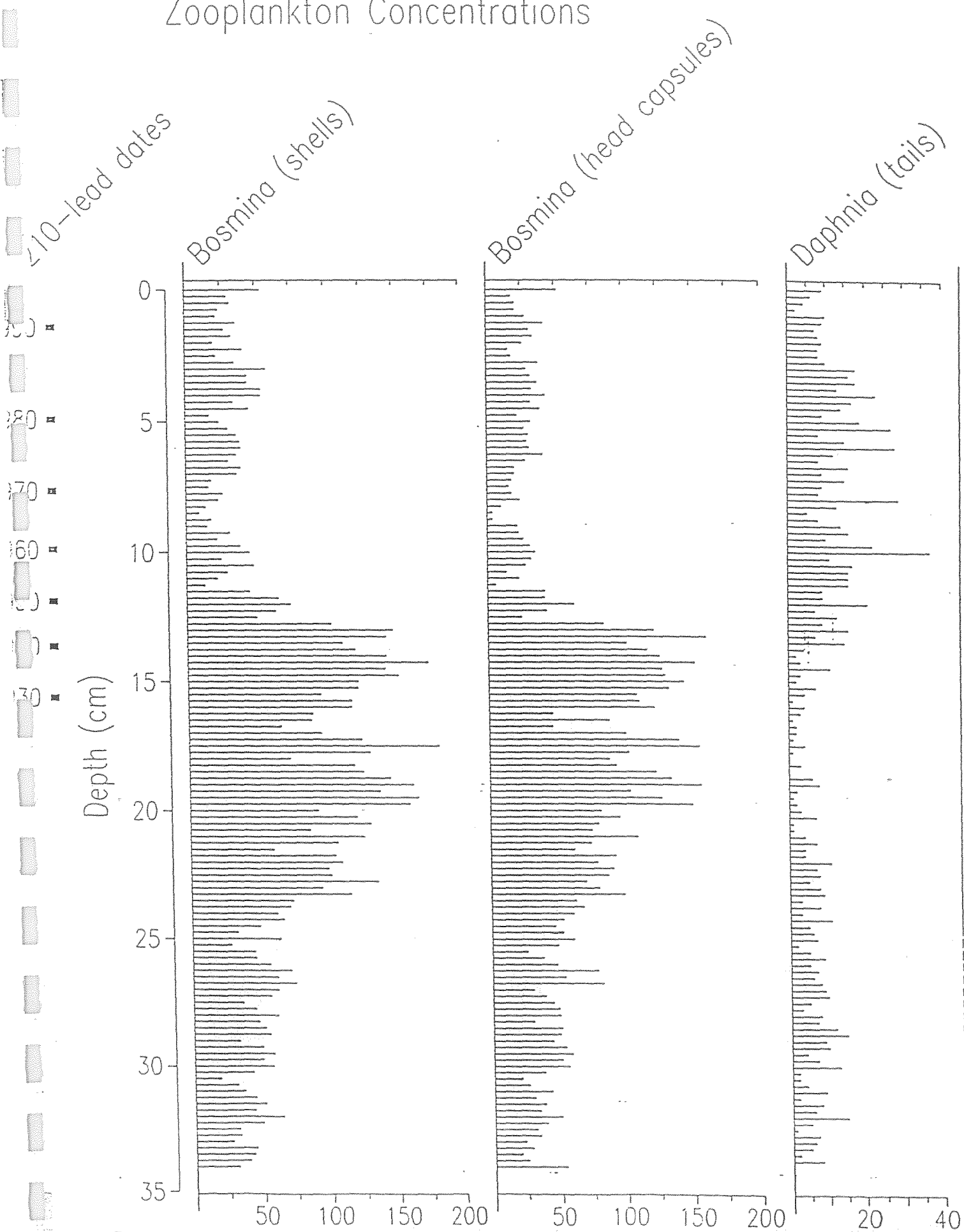


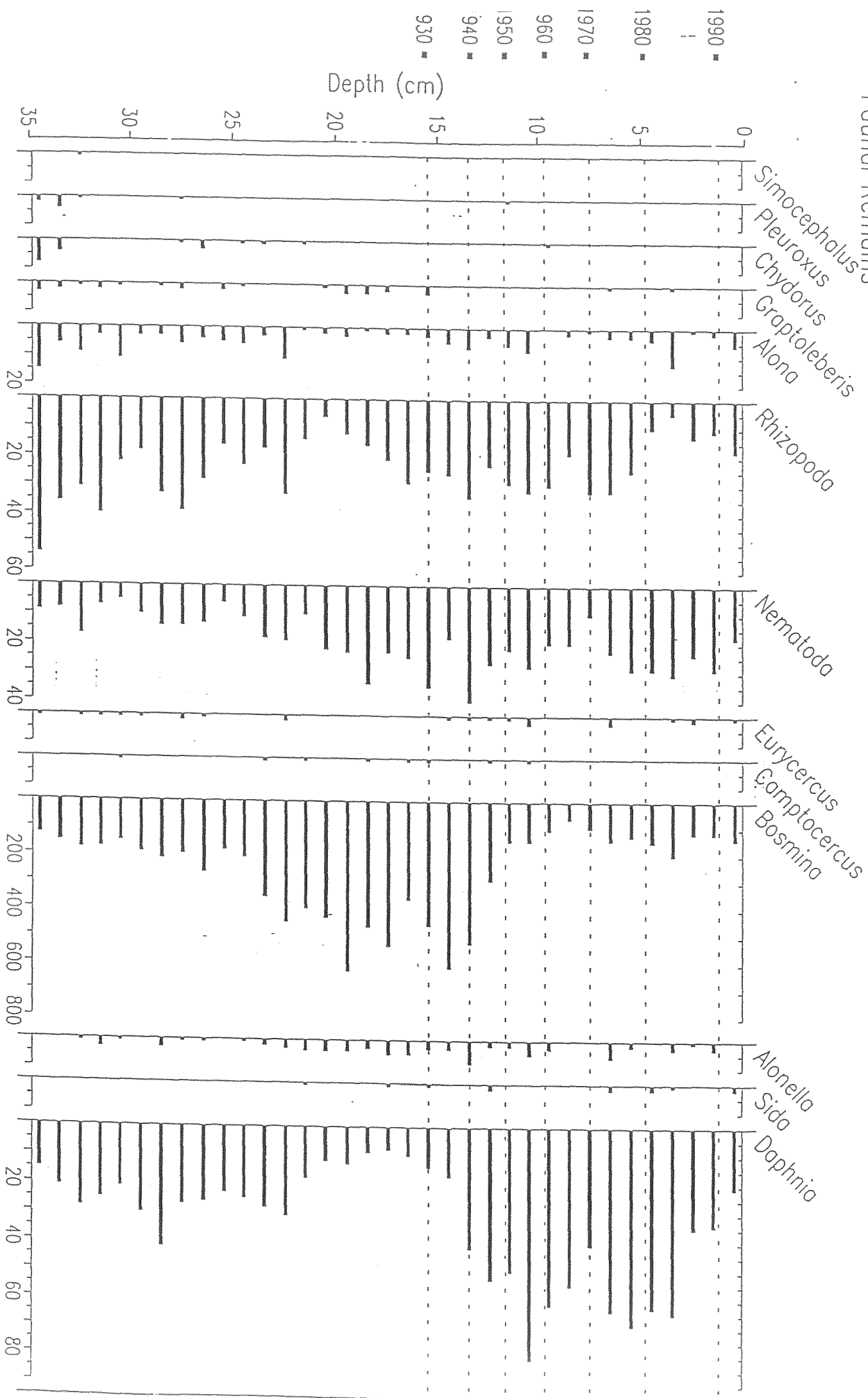
FIGURE 7.10

Windermere North Basin 92-2 Zooplankton Concentrations



Numbers per 0.5 m³

Found Remains



Numbers per cc wet sediment

8. Tephra analysis (Neil Rose)

Neil Rose & Paul Golding (UCL); Roy Thompson (University of Edinburgh)

Using the methods outlined in previous Newsletters three of the four cores have now been analysed. A paper describing these methods for the extraction of tephra from lake sediments has been submitted to *The Holocene*.

The profiles for Fallahogy and Moine Mhor peat cores have been shown earlier (Figures 4.3 and 6.4 respectively). Both show major peaks, Fallahogy at 86-87cm and Moine Mhor at 34-35cm. The peak in this latter core is clearly defined whereas there are many levels in the Fallahogy core in which tephra have been found. This is consistent with the earlier work of Val Hall on this site (Pilcher & Hall 1992).

Samples from the peak of each core were sent to Edinburgh for geochemical analysis but it was found that the shards were too small to do this satisfactorily and so for the present at least they remain anonymous. However, size distributions of the shards for the two peaks are very similar (Figures 8.1 and 8.2) and this implies that the material might be from the same source.

The Loughnashade core has not been analysed yet but this is our next priority.

References

- Pilcher, J.R. & Hall, V.A. 1992 Towards a tephrochronology for the Holocene of the north of Ireland. *The Holocene* 2, 255-259.
- Rose, N.L., Golding, P.N.E. & Battarbee, R.W. Selective concentration and enumeration of tephra shards from lake sediment cores. (submitted to *The Holocene*).

Figure captions

Figure 8.1 Tephra size analysis for Fallahogy peat core sample 86-87 cm

Figure 8.2 Tephra size analysis for Moine Mhor peat core sample 34-35 cm.

Tephra size analysis

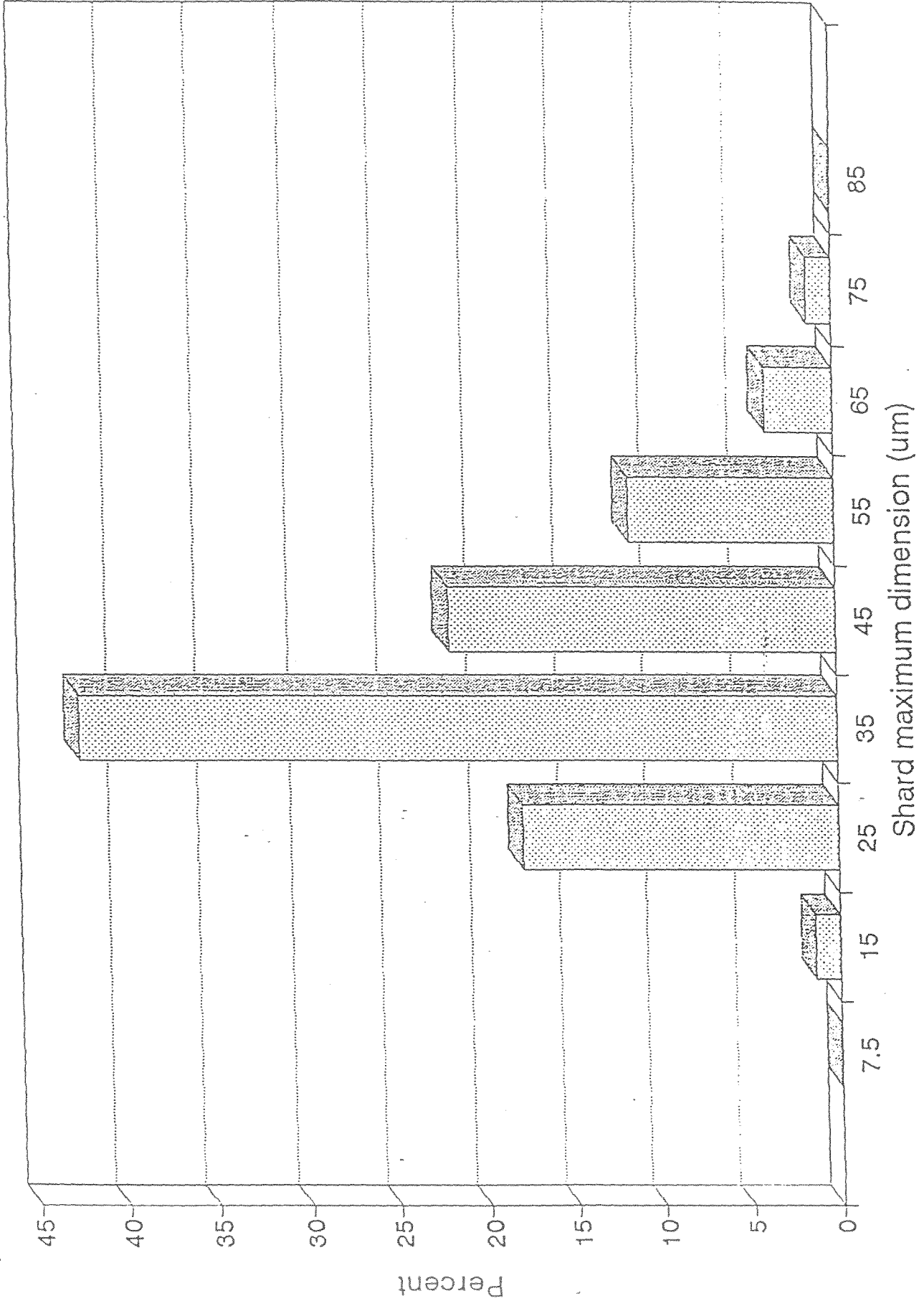
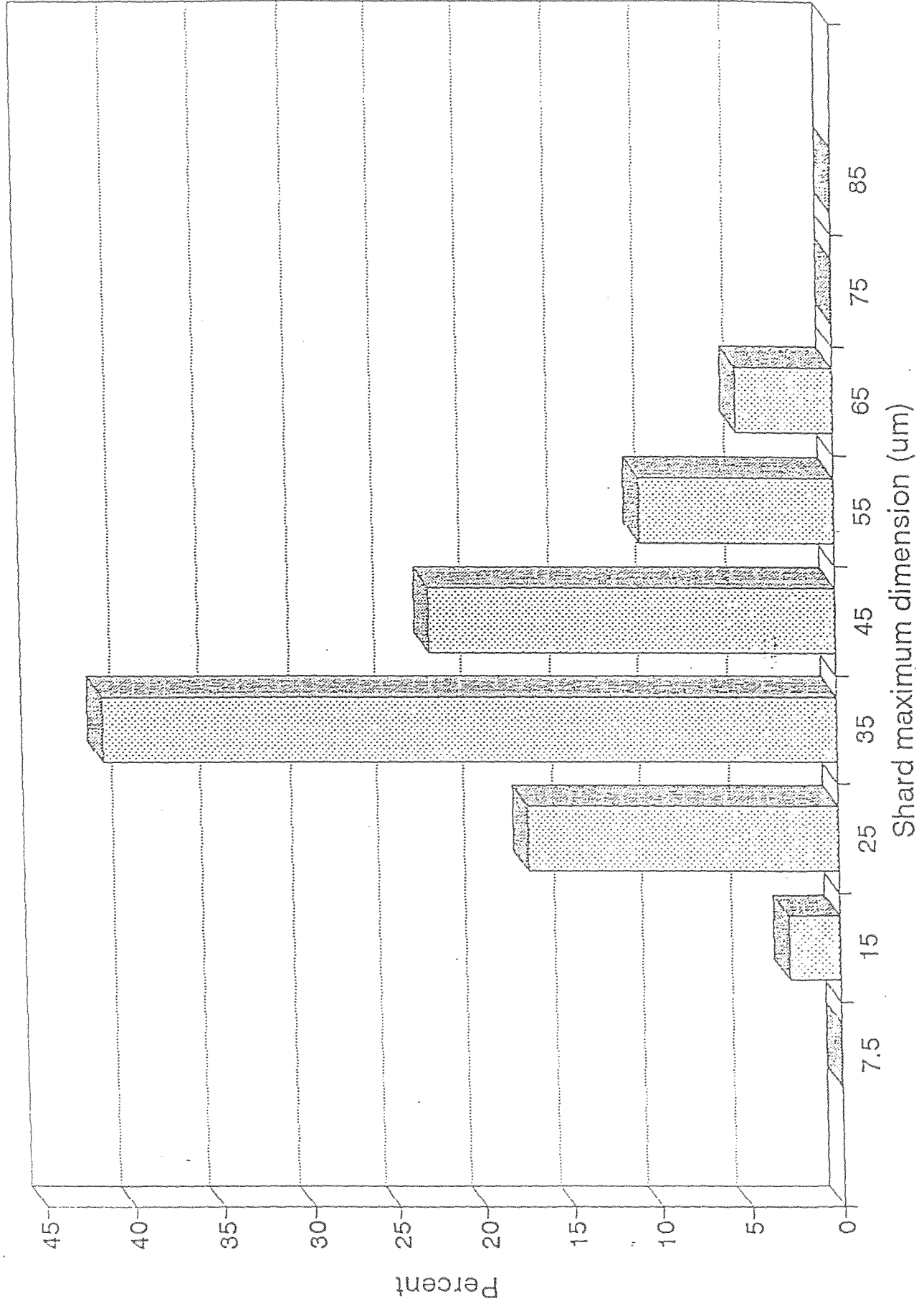


FIGURE 8.2

Tephra size analysis



Selective concentration and enumeration of tephra shards from lake sediment cores.

N.L. Rose, P.N.E. Golding & R.W. Battarbee

(Environmental Change Research Centre, University College London, 26 Bedford Way, London WC1H 0AP)

Holocene (in press)

Abstract

This paper describes a technique for the enumeration of tephra shards from lake sediment cores whereby approximately 85% of unwanted sediment fractions (organic matter, biogenic silica, carbonates) are removed by selective stepwise chemical attack. The order of 100 samples can be prepared simultaneously in a modest sized water-bath and the recovery rate of the technique is greater than 90%. The procedure is applicable to all lake sediment types.

Key words: tephra, tephrochronology, lake sediments

Introduction

Since 1944, when Thorarinsson suggested the term tephra as a collective term for pyroclasts and tephrochronology as the dating method based on tephra layers (Thorarinsson, 1944), increasing use has been made of the technique as a tool for dating individual sediment sequences and to link sediment levels across geographical space. Use has been made of tephrochronology in peats (e.g. Blackford *et al.*, 1992; Dugmore & Newton, 1992; Hall *et al.*, 1993; 1994), soils (e.g. Einarsson *et al.*, 1980; Dugmore, 1989a, Dugmore & Buckland, 1991; Dugmore & Erskine, 1994), marine sediments (e.g. Kvamme *et al.*, 1989; Gulchard *et al.*, 1993) and lake sediments (Oldfield *et al.*, 1980; Welch *et al.*, 1985; Bennett *et al.*, 1992; Stihler *et al.*, 1992).

In cases where tephra layers are not obvious by visual inspection, techniques for their identification within sediment sequences are varied. For peats two techniques appear in the literature, a H_2SO_4 extraction (Persson, 1971, Dugmore, 1989b) and an ashing method followed by suspension in 10% hydrochloric acid (Pilcher & Hall, 1992). This latter approach is thought to affect shard chemistry by altering the alkali content and so once the tephra layer has been identified, if geochemical analysis is required, then another sample of peat must be subjected to the acid digest to permit accurate analysis (Dugmore, 1989b; Dugmore *et al.*, 1992). Peats have the advantage over marine and lacustrine sediments in that the matrix within which the tephra are recorded is almost exclusively organic and thus easy to remove leaving very little inorganic material. Where tephra layers are present the shards represent a high proportion of the remaining inorganic particulates thus making identification of the layers relatively simple.

The techniques for the identification of tephra layers within marine sediments are either visual or the method used is not reported (e.g. Seirup *et al.*, 1989; Gulchard *et al.*, 1993), leading to the assumption that this has not been a significant problem. Kvamme *et al.*, (1989) however, used a sieving approach followed by a density separation of the $> 63\mu m$ fraction using C_2Cl_4 , retaining the $> 1.62 gcm^{-3}$ portion for tephra.

Where lake sediments have been studied for tephra the layers have been identified by visual inspection (Welch *et al.*, 1985; Stihler *et al.*, 1992) and by variations in magnetic susceptibility (Oldfield *et al.*, 1980; Stihler *et al.*, 1992). Reported identification of microscopic tephra layers in lake sediments are rare and only Bennett *et al.* (1992) suggest a method for a treatment of sediments such that microscopic identification is made easier for the analyst. This approach is a hydrogen peroxide (H_2O_2) attack and removes the organic material from the sediment. Tephra are then counted under a light microscope and expressed in the unit of "number of shards per 50 inorganic particles". This technique was successful at the Dallican Water site where loss-on-ignition values of up to 60% were recorded (Bennett *et al.*, 1992).

At sites where there is significantly less organic content in the sediments such an approach may be less effective. Sufficient material would not be removed to allow identification of low concentrations of tephra shards.

As interest in tephrochronology increases so the search for tephra levels moves both increasingly away from sources and to increasingly less favourable sites. At present, the use of lake sediments in tephrochronological studies lags behind that of other sediment types, especially peats, and this in part may be due to a lack of a suitable procedure for the concentration and enumeration of shards from lake sediments. In particular, it is important to remove biogenic silica (mainly from diatom frustules) that can constitute a substantial proportion of the inorganic fraction in many lake sediments. Lakes are geographically widespread in the United Kingdom, as in many countries, and so an effective method for the identification of tephra layers in lake sediments of all types would aid future tephra studies and may be a step towards the development of a tephrochronology for the whole of the U.K.

This paper describes a method for the identification of low concentrations of tephra shards in any lake sediment using a stepwise selective chemical attack to remove unwanted fractions.

The Method

The need for an alternative and more sensitive method for the identification of microscopic tephra layers arose following the development of the Natural Environment Research Council (NERC) funded research programme 'Proxy records of climate change in the U.K. over the last two millennia' known as TIGGER IIa. In this programme tephra analysis was to be used to help date two peat cores and sediment cores from adjacent lakes and to provide a correlating sediment level between the two pairs of sites. One of these lake sites was an upland corrie lake Lochan Uaine (NGR NN 960 980) in the Cairngorm Mountains of Scotland. The sediment core taken from this site shows loss-on-ignition values of 10-25% and consequently a simple removal of organic matter would still leave a large amount of the original sediment. Further fractions of the sediment therefore needed to be removed in order to facilitate tephra enumeration.

Tephra, being a siliceous material with varying amounts of other major element oxides (MgO, Al₂O₃, K₂O, FeO, TiO₂ etc.) is chemically similar to many other minerals present within lake sediments and so the reagents must be carefully selected so that they do not also dissolve the shards themselves. At present it is unknown whether the method described below alters the chemistry of the shards but it is likely that there is some minor effect. Steen-McIntyre (1977) reports that treatment with H₂O₂ dissolves MnO₂ minerals and mobilises iron and aluminium but the technique appears to have no effect on their physical appearance (Figure 1) and so it is

assumed that no major dissolution of the shards is occurring. However, even if some minor dissolution does take place or if the shard chemistry is slightly changed, the method remains an efficient way of identifying microscopic tephra layers and identified levels can subsequently be treated in a way appropriate for geochemical analysis (e.g. Dugmore, 1989b; Dugmore *et al.*, 1992) in the same way that identified peat levels are, following the ashing technique of Pilcher & Hall (1992).

Laboratory procedure

- 1) 0.1 - 0.2g of dried lake sediment is accurately weighed into a 12ml glass test-tube and 2ml of 30% H_2O_2 is added to each sample. This is left covered overnight at room temperature.
- 2) An additional 5ml of 30% H_2O_2 is added to each sample. This is heated in a water-bath at 80 - 90°C for 3 hours.
- 3) Cool, top up each tube with distilled water and centrifuge for 5 minutes at 1500 r.p.m. Pipette off the supernatant.
- 4) To each tube add 5ml 0.3M NaOH and heat in a water-bath at 80 - 90°C for 3 hours. This stage removes biogenic silica (e.g. diatoms, chrysophyte cysts etc.).

Previous work (e.g. Rose, 1990) has shown 0.3M NaOH to be the most suitable reagent for the removal of biogenic silica whilst leaving more robust forms (e.g. amorphous, minerogenic) undissolved. Experiments following the course of silica dissolution from lake sediments show that using 0.3M NaOH, rapid dissolution occurs between 0 and 2 hours followed by a 'plateau' period between 2 and 6 hours where no further silica is dissolved. The former period is where dissolution of biogenic silica takes place and by taking sub-samples at intervals the gradual disappearance of diatom frustules can be observed. After 2 hours only a few, if any, heavily eroded fragments of diatoms remain. After 6 hours silica starts to dissolve once again and this is likely to be the start of the dissolution of minerogenic and amorphous silica. A period of 3 hours for this stage of the preparation procedure was therefore decided upon. Other tested reagents, for example 0.3M Na_2CO_3 , failed to reach the plateau stage even after 6 hours.

- 5) Cool, top up each tube with distilled water and centrifuge for 5 minutes at 1500 r.p.m. Pipette off the supernatant.

6) To each tube add 5ml 3M HCl and heat in a water-bath at 80 - 90°C for 1 hour. This stage removes the less robust carbonates and bicarbonates in the sediment.

7) Cool, top up each tube with distilled water and centrifuge for 5 minutes at 1500 r.p.m. Pipette off the supernatant.

8) Repeat the washing and centrifuging procedure and finally transfer the residue of each sample into a separate pre-weighed glass vial.

Counting procedure

A known fraction of the final residue is evaporated onto a coverslip and the glass vial reweighed so that the amount of suspension evaporated is known. This is then mounted onto a microscope slide with Naphrax, a diatom mountant, and all the shards on the coverslip are counted at 100x magnification using a transmitted light microscope. It is then a simple matter to calculate the concentration of shards in 'per gram dry mass sediment' (gDM⁻¹) units. i.e.

$$\text{Concentration} = \frac{100N}{\% \times M}$$

where N = number of shards on the coverslip

% = percentage of final residue evaporated onto coverslip

M = mass of dried sediment used

Tephra was identified and distinguished by characteristic morphology and vesicularity and its isotropy under cross-polarised light.

This counting approach enables the size distribution of the shards to be determined and allows the analyst to count shards to whatever size limit is desired.

Detection limit

The detection limit for the method is 200-300 gDM⁻¹. This relates to the Lochan Uaine sediment core where peak concentrations are in the range 12,000 - 15,000 gDM⁻¹.

Recovery rate

A suspension of tephra shards was made from a sediment sample from Kråkenes, Norway known to be rich in Vedde Ash tephra. After homogenisation a known fraction of the suspension was

removed and counted at x100 under a light microscope to calculate the tephra concentration. A known volume of the homogenised suspension was then added to an unprepared sediment sample, known to be tephra-free. After preparation, the tephra concentrations were calculated and compared with the initial concentration to give a percentage recovery. This was done for four separate preparations and gave a recovery of over 90.8% in all cases.

Concluding remarks

The method described allows a large number of samples to be analysed at a time. A modest sized water-bath (30 x 20cm available area) enables up to 100 samples to be prepared with relative ease within two days including the weighing of the sediment into the test-tube and the overnight H₂O₂ stage. A large proportion of the sediment is removed during the procedure with 0.1 - 0.2 g of dried sediment typically being reduced to 15 - 30 mg, i.e. 85% of the unwanted sediment is removed leaving a residue containing the tephra shards.

The technique represents a significant improvement on previous methods for the enumeration of tephra shards from lake sediments and is applicable to all lake sediment types.

Acknowledgements

We would like to thank Hilary Birks for providing the Kråkenes sample and Chris Cromarty for photographic assistance. Funding for this work was supplied by NERC under Special Topic Grant GST/02/701, also known as TIGGER IIa.

References

- Bennett, K.D., Borcham, S., Sharp, M.J. and Switsur, V.R. 1992: Holocene history of environment, vegetation and human settlement on Catta Ness, Lunnasting, Shetland. *Journal of Ecology* 80, 241-273.
- Blackford, J.J., Edwards, K.J., Dugmore, A.J., Cook, G.T. and Buckland, P.C. 1992: Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in northern Scotland. *Holocene* 2, 260-265.
- Dugmore, A.J., 1989a: Tephrochronological studies of Holocene glacier fluctuations in south Iceland. In: Oerlemans, J., editor, *Glacier fluctuations and climatic change*. 37-55. Kluwer Academic Publishers.
- Dugmore, A.J., 1989b: Icelandic volcanic ash in Scotland. *Scottish Geographical Magazine* 105, 168-172.
- Dugmore, A.J. and Newton, A.J., 1992: Thin tephra layers in peat revealed by X-radiography. *Journal of Archeological Science* 19, 163-170.
- Dugmore, A.J. and Erskine, C.C., 1994: Local and regional patterns of soil erosion in southern Iceland. In: Stötter, J. and Wilhelm, F. (editors). *Environmental change in Iceland*. Münchener Geographische Abhandlungen, Reihe B, Band B12, 63-78.
- Dugmore, A.J., Larsen, G., Newton, A.J. and Sugden, D.E., 1992: Geochemical stability of fine-grained Holocene tephras in Iceland and Scotland. *Journal of Quaternary Science* 7, 173-183.
- Einarrson, T., Larsen, G. and Thorarinsson, S., 1980: The Solheimer tephra layer and the Katla eruption of 1357AD. *Acta Naturalia Islandica* 28, 1-24.
- Gulchard, F., Carey, S., Arthur, M.A., Sigurdsson, H. and Arnold M., 1993: Tephra from the Minoan eruption of Santorini in sediments of the Black Sea. *Nature* 363, 610-612.

Hafliðason, H., Larsen, G. and Ólafsson, G., 1992: The recent sediment history of Thingvallavatn, Iceland. *Oikos*, 64, 80-95.

Hall, V.A., Pilcher, J.R. and McCormac, F.G., 1993: Tephra-dated lowland landscape history of the north of Ireland, A.D. 750-1150. *New Phytologist*, 125, 193-202.

Hall, V.A., Pilcher, J.R. and McCormac, F.G., 1994. Icelandic volcanic ash and the mid-Holocene Scots pine (*Pinus sylvestris*) pollen decline in north of Ireland: no correlation. *Holocene* 4, 79-83.

Kvamme, T., Mangerud, J., Furnes, H. and Ruddiman, W.F., 1989: Geochemistry of Pleistocene ash zones in cores from the North Atlantic. *Norsk Geologisk Tidsskrift* 69, 251-272.

Oldfield, F., Appleby, P.G. and Thompson, R., 1980: Palaeoecological studies of lakes in the highlands of Papua New Guinea. I. The chronology of sedimentation. *Journal of Ecology* 68, 457-477.

Persson, C., 1971: Tephrochronological investigations of peat deposits in Scandinavia and on the Faroe Islands. *Sveriges Geologiska Undersökning* 656(c), 1-34.

Pilcher, J.R. and Hall, V.A., 1992: Towards a tephrochronology for the Holocene of the north of Ireland. *Holocene*. 2, 255-259.

Rose, N.L., 1990: A method for the selective removal of inorganic ash particles from lake sediments. *Journal of Paleolimnology* 4, 61-67.

Seirup, H.P., Sjøholm, J., Furnes, H., Beyer, I., Eide, L., Jansen, E. and Mangerud, J., 1989: Quaternary tephrochronology on the Iceland plateau, north of Iceland. *Journal of Quaternary Science* 4, 109-114.

Stihler, S.D., Stone, D.B. and Beget, J.E., 1992: "Varve" counting vs. tephrochronology and ^{137}Cs and ^{210}Pb dating: A comparative test at Skilak Lake, Alaska. *Geology* 20, 1019-1022.

Thorarinsson, S. (1944). Tefrokronologiska studier på Island. *Geogr. Ann. Stockh.* 26, 1-217.

Welch, E.B., Tomasek, M.D. and Spyridakis, D.E. (1985). Instability of the Mount St. Helen's ashlayer in Moses Lake. *Journal of Freshwater Ecology* 3, 103-112.

Figure Captions

Figure 1. Scanning electron microscope photograph of a tephra shard extracted from Lochan Uaine (40.6 - 40.8cm)

Three Thousand Years of Environmental History in a Cairngorms Lochan Revealed by Analysis of Non-biting Midges (Insecta: Diptera: Chironomidae)

STEPHEN J. BROOKS

*Biodiversity Division, Department of Entomology,
Natural History Museum, Cromwell Road,
London SW7 5BD*

Summary

The larvae of non-biting, chironomid midges (Insecta: Diptera: Chironomidae) are ubiquitous, abundant and diverse in most aquatic environments. Larval head capsules are well preserved in lake sediments. Temporal changes in the chironomid community can be reconstructed following sediment core analysis and can be used to infer past environmental change. Chironomids have long been known to be useful indicators of eutrophication but in recent years attention has focused on their use as indicators of climate change. In this paper the biology and ecology of Chironomidae are briefly reviewed and put into the context of their usefulness as indicators of environmental change. The results of a preliminary analysis of chironomid assemblages during the last 3000 years in Lochan Uaine, Cairngorms, are described. They indicate that there was a significant change in the chironomid fauna about 2500 years ago, possibly associated with a change in trophic conditions or climatic cooling. Since then no major changes are apparent. However, further fine resolution analysis of the core is planned that may reveal more subtle changes in the chironomid assemblages.

Introduction

The larvae of non-biting midges (Chironomidae) are common, abundant and species rich in most freshwater ecosystems. They are useful indicators of past environmental change because their head capsules are well-preserved in lake sediments and characteristic species assemblages can be related to particular environmental conditions. The value of Chironomidae as palaeoecological indicators has recently been reviewed by Elias (1995) and Walker (1995).

In this paper I will discuss the results of an analysis of the remains of chironomid larvae recovered from a sediment core from Lochan Uaine (GR NO960980) in the Cairngorms and discuss how the results may be used to infer environmental changes during the last 3000 years. This is the first site in the Cairngorms for which such a study has been carried out. However, Brodin & Gransberg (1993) reported the results of an analysis of the chironomids from the Round Loch of Glenhead, in south-west Scotland, which was used to reconstruct the history of acidification in that lake.

This study is part of a larger multi-disciplinary project to investigate the use of montane lake sediments in reconstructing climate change using a wide range of physical, chemical and biological methods. Some of the results of the Lochan Uaine diatom analysis are described in Battarbee (this volume). Like these diatom studies, the work described here is still in progress so the results must be regarded as preliminary. Before discussing the results of the chironomid analysis

fresh and saline water, while some are semi-terrestrial, living in damp leaf litter or moss. They are able to exploit extremes of pH and temperature and can survive both at high altitude and in deep lakes.

2. Abundant. They are abundant in aquatic systems. A eutrophic lake may support larval populations of up to 100,000 m² (Bryce & Hobart, 1972). Only oligochaetes may be more abundant among benthic macro-invertebrates but they preserve poorly (Walker, 1993). In contrast the thick, chitinized head capsule of a chironomid larva preserves very well in lake sediments.

3. Species rich. Chironomid assemblages are usually species rich. A lake might be expected to support at least 50 species.

4. Stenotopic and faithful. Many species favour particular habitats and/or environmental conditions to which they exhibit considerable fidelity making it possible to draw ecological conclusions about the prevailing environmental conditions from the composition of the chironomid fauna.

5. Identifiable. The larvae are relatively easy to identify, at least to generic level, and often to species or species-group.

6. Complementary. The environmental signals reflected by the chironomid assemblage complements the record of other indicator groups such as diatoms. Diatoms are good indicators of the photic zone and the pelagic environment. Chironomids on the other hand are good indicators of benthic and profundal conditions.

7. Sensitive indicators. In temperate regions most chironomids complete their life-cycles within one year, while many species may complete several generations in one year. This, together with the ability of the winged adults to move readily between sites, means that chironomids respond rapidly to changing environmental conditions. Environmental reconstructions based on analysis of the pollen record may be less sensitive because most plants respond more slowly to environmental change and because of the uncertain provenance of the pollen grains which may have been blown a considerable distance before becoming incorporated into the lake sediment. In contrast there can be no doubt that the chironomid larvae developed *in situ*.

Most of the head capsules recovered from a lake sediment core are not the remains of dead larvae. During development a chironomid larva sheds its skin, together with the head capsule, four times and these are deposited in the sediment as a record of the species living in that lake.

In order to investigate the effects of climatic change and other natural phenomena on lake biota it is essential to select a study site remote from possible human influence. Lochan Uaine, a high corrie loch at 920 m on Cairn Toul (GR NO960980), largely meets this criterion. Nevertheless, even here there has been substantial post-1800 contamination from air pollution (Jones *et al.*, 1993). Prior to this, however, it is likely that any variations in sediment record are attributable to the direct or indirect effects of climatic factors.

Methods

Chironomid head capsules were extracted from the sediment following the procedures described by Walker, Smol, Engstrom & Birks (1991). After weighing each sub-sample, a small amount of sediment was deflocculated in hot 10% KOH

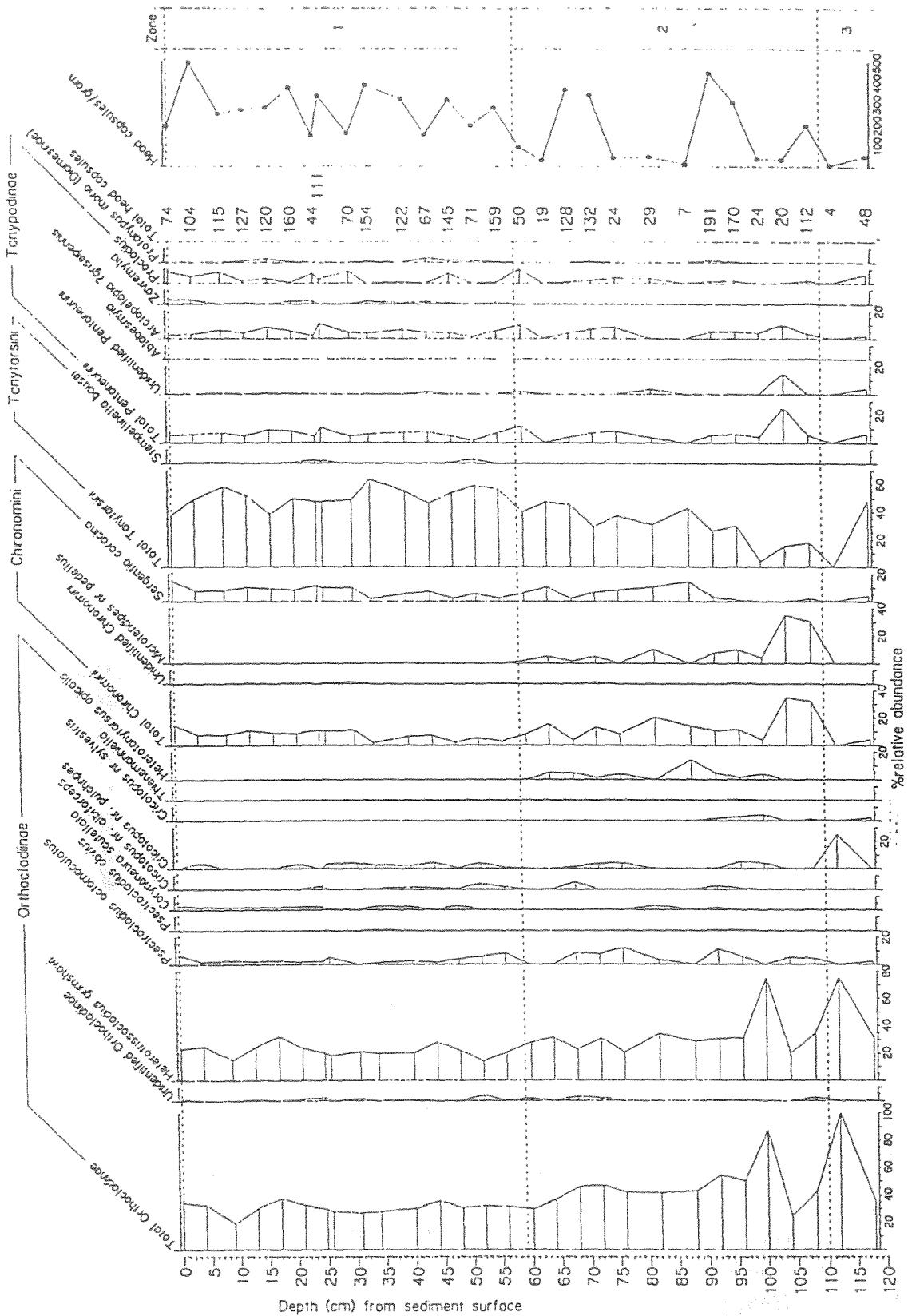


Fig. 1. Stratigraphical diagram showing relative abundance (percentage) of Chironomidae head capsules in a sediment core from Lochan Uaine, Cairngorms.

In some sediments the head capsules are well preserved and these structures are present. Unfortunately, the Lochan Uaine material is poorly preserved and only a few specimens had the full complement of mandibles and other cephalic structures. This may be due to the sediments being heavily oxidized since chitinized insect remains preserve best in anaerobic sediments (Elias, 1995). In particular this has frustrated efforts to identify specimens of Tanytarsini even to generic level. This group is an important component of the chironomid community in Lochan Uaine and comprises 30-50% of the chironomid fauna throughout the core.

Identification of a few specimens of Tanytarsini to species was possible and five species were distinguished in the core (*Micropectra* sp. B, *Tanytarsus* sp. B, *Tanytarsus lugens*, *M. coracina*, *T. chinensis*). These taxa can only be distinguished from one another on the basis of mandibular and premandibular morphology and by the presence or absence of a spur on the basal antennal segment. Each of these species may have a different larval ecology which might be reflected in differential changes in their relative abundance in response to environmental change. Further undetected taxa may also present in the sediment samples. For this reason the total Tanytarsini grouping has limited value in data analysis. The tanytarsine genus *Stempelinella* also has an antennal spur but can be distinguished from the other tanytarsine taxa in the samples by distinctive characters of the mental teeth and ventro-mental plates.

The presence in one sample of *Thienimaniella*, which usually occurs in montane streams, may be an accidental wash-in although the taxon might survive in the splash-zone of the lochan.

Ecological interpretation

The chironomid assemblage in Zone 3, dominated by *Heterotrissocladius* and with a low abundance of Chironomini, is indicative of a cool, oligotrophic lake (Saether, 1979). The change in the assemblage in Zone 2 suggests that temperatures may have increased at the beginning of this zone. *Microtendipes*, *Heterotanytarsus* and *Corynoneura*, which all appear in Zone 2, typically occur in temperate lakes (Moller-Pillot & Buskens, 1990; Walker, Mott & Smol, 1991). Brundin (1949) describes *Heterotanytarsus apicalis* as a warm stenotherm. If there was a warming during this period a contemporaneous decline in the abundance of cold adapted taxa might be expected. This inference is supported by the relatively low abundance of Tanytarsini, *Heterotrissocladius grimshawi* and *S. coracina* at the beginning of Zone 2. However, these taxa recover when the warm adapted chironomids are still abundant in the lochan. This result suggests that a progressive cooling may have occurred in the latter part of Zone 2, which is reflected by the gradual rise in Tanytarsini. The disappearance of *Heterotanytarsus* and *Microtendipes* may be as a result of temperatures falling to sub-optimum levels.

Heterotanytarsus occurs in γ -oligotrophic to η -mesotrophic, humic lakes (Brundin, 1949; Saether, 1979; Cranston, 1982) and the presence of *H. apicalis* in Zone 2 may indicate an increase in humic substances entering the lochan. These may have been derived from the development of bog around the lochan resulting from an increase in precipitation, leaching of soils and poor drainage.

but these results are not applicable outside that region. No such data are currently available for Scottish midges.

Acknowledgements

I would like to thank Pat Haynes (Natural History Museum) for assistance in the field, for sorting and mounting the chironomid head capsules and for lively discussion. Mark Davison (Natural History Museum) helped with identification of pupal exuviae. Peter Hammond (Natural History Museum) made helpful suggestions to improve the text. I also thank Professor Rick Battarbee and his colleagues at the Environmental Change Research Centre for inviting me to participate in this project. Pat Haynes was funded by an NERC grant (GST/02/701) as part of the TIGGER initiative.

References

- Armitage, P., Cranston, P.S. & Pinder, L.C.V. [ed.] (1995). *The Chironomidae. The Biology and Ecology of Non-biting Midges*, 572 pp. London: Chapman & Hall.
- Brodin, Y-W. & Gransberg, M. (1993). Responses of insects, especially Chironomidae (Diptera), and mites to 130 years of acidification in a Scottish lake. *Hydrobiologia* **250**, 201-212.
- Brundin, L. (1949). Chironomiden und andere Bodentiere der südschwedischen Urgebirgsseen. Ein Beitrag zur Kenntnis der bodenfaunistischen Charakterzüge schwedischer oligotropher Seen. *Report. Institute Freshwater Research, Drottningholm* **30**, 5-185.
- Bryce, D. & Hobart, A. (1972). The biology and identification of the larvae of the Chironomidae (Diptera). *Entomologist's Gazette* **23**, 175-217.
- Clair, R. & Paterson, C.G. (1976). Effect of a salt water intrusion on a freshwater Chironomidae community: a palaeolimnological study. *Hydrobiologia* **48**, 131-135.
- Cranston, P.S. (1982). A key to the larvae of the British Orthoclaadiinae (Chironomidae). *Freshwater Biological Association Scientific Publication* **45**, 1-152.
- Elias, S.A. (1995). *Quaternary Insects and their Environments*. Smithsonian Institution Press, Washington. xiii + 284 pp.
- Hofmann, W. (1971). Zur taxonomie und Palökologie subfossiler Chironomiden (Dipt.) in Seesedimenten. *Archiv für Hydrobiologie* **6**, 1-50.
- Jones, V.J., Flower, R.J., Appleby, P.G., Natkanski, J., Richardson, N., Rippey, B., Stevenson, A.C. & Battarbee, R.W. (1993). Palaeolimnological evidence for the acidification and atmospheric contamination of lochs in the Cairngorms and Lochnagar areas of Scotland. *Journal of Ecology* **81**, 3-24.
- Kansanen, P.H. (1985). Assessment of pollution history from recent sediments in Lake Vanajavesi, southern Finland. II. Changes in the Chironomidae, Chaoboridae and Ceratopogonidae (Diptera) fauna. *Annales Zoologici Fennici* **22**, 13-55.
- Kowalyk, H.E. (1985). The larval cephalic setae in the Tanypodinae (Diptera: Chironomidae) and their importance in generic determinations. *Canadian Entomologist* **117**, 67-106.

ECRC RESEARCH REPORTS

- 1 Mackay, A., Flower, R.J., Appleby, P.G., Boyle, J., Dearing, J.A., Kuzmina, A., Monteith, D., Rose, N. & Battarbee, R.W. 1993 Recent environmental change in Lake Baikal, Eastern Siberia, with special reference to the sedimentary diatom record. *Report to the Leverhulme Trust on Grant F.134 AZ.*
- 2 Jones, V.J., Juggins, S. & Battarbee, R.W. 1993 The palaeolimnology of Antarctic lakes using diatom-water quality transfer functions. *Report to NERC AST Award GST/02/448.*
- 3 Juggins, S., Battarbee, R.W. & Fritz, S.C. 1993 Diatom/water chemistry transfer functions for salinity, water-level and climate reconstruction. *Report to NERC Palaeoclimate Special Topic Award GST/02/494*
- 4 Cameron, N.G., Rose, N.L., Appleby, P.G., Battarbee, R.W., Patrick, S.T., Flower, R.J. & Juggins, S. 1993 Lake sediment analyses. *Report to EC AL:PE 1 Contract.*
- 5 Allott, T.E.H. & Rose, N.L. 1993 A palaeolimnological study of recent water quality changes in lochs with black-throated diver populations. *Report to the Royal Society for the Protection of Birds.* 59pp.
- 6 Patrick, S.T., Allott, T.E.H., Duigan, C.A., Harriman, R., Kirika, A., Lancaster, J., Monteith, D.T. & Seda, M. 1994 Integrated classification and assessment of lakes in Wales: Phase 1. A preliminary data report to the Countryside Council for Wales under contract No. **FC 73-01-71.** 82pp.
- 7 Rose, N.L., Battarbee, R.W., Bennion, H., Boyle, J.F., Cai, S., Harlock, S., He, B., Oldfield, F., Yang, H., Yi, Z., Yu, L. & Zhou, X. 1994 Palaeolimnological investigations of lakes on the Jiangnan Plain, Central China. *Report to the Royal Society Project Q 607/KB.*
- 8 Allott, T.E.H., Monteith, D.T., Patrick, S.T., Duigan, C.A., Lancaster, J., Seda, M., Kirika, A., Bennion, H. & Harriman, R. 1994 Integrated classification and assessment of lakes in Wales: Phase 1. A final report to the Countryside Council for Wales under Contract No. **FC 73-01-71.** 150pp.

- 9 Flower, R.J., Politov, S., Solovieva, N., Rose, N., Battarbee, R.W., Rippey, B., Appleby, P.G. & Rose, N.L. 1994 A palaeolimnological evaluation of the extent and impact of atmospheric contamination and recent environmental change in two remote highland lakes in S.E. Siberia. *A final report for the NERC small research grant GB9/1032.*
- 10 Allott, T.E.H., Golding, P.G. & Appleby, P.G. 1994 Studies of water quality change at Black-throated diver sites. *Progress report to the Royal Society for the Protection of Birds.* 37pp.
- 11 Monteith, D.T., Allott, T.E.H., Harriman, R., Morrison, B.R.S., Collen, P. & Patrick, S.T. 1995 Land-use experiments in the Loch Laidon catchment. *Second report to the Rannoch Trust on stream water quality (UCL/ENSIS Project No. 14).* 26pp.
- 12 Harlock, S. & Rose, N.L. 1994 A preliminary data report of analyses on lake sediment cores from Loch Coire nan Arr. *A report to the AEA National Environmental Technology Centre (UCL/ENSIS Project No. 21)*
- 13 Rose, N.L. & Harlock, S. 1995 Loch Coire nan Arr: the dating of multiple cores using spheroidal carbonaceous particle data. *A report to the AEA National Environmental Technology Centre (UCL/ENSIS Project No. 21)*
- 14 Rose, N.L., Harlock, S., Punning, J-M., Alliksaar, T., Fott, J., Horicka, Z., Vukicova, J., Bowman, J., Watt, J. & St. Clair Gribble, K. 1995 Fly-ash particles and heavy metals in Europe: implications for human and environmental health (FLAME). *Progress report to EU contract CIPA-CT93-0090 (UCL/ECRC Project No. 45).*
- 15 Monteith, D.T. (Ed.) 1995 Integrated classification and assessment of lakes in Wales: Phase II. *A preliminary data report to the Countryside Council for Wales under Contract No. FC 73-01-13.* 74pp.
- 16 Bennion, H. 1995 Quantitative reconstructions of the nutrient histories of three Anglesey lakes. *A report to the Countryside Council for Wales under Contract No. FC 73-01-78A; CCW CVontract Science report No. 87.* 15pp.
- 17 Monteith, D.T. 1995: Integrated Classification and Assessment of Lakes in Wales: Phase II. *Final Report to the CCW under contract No. FC 73-01-13, CCW Contract Science Report No. 128.*

- 18 Mackay, A.W., Flower, R.J., & Battarbee, R.W. 1994: Further high resolution analyses of surface sediment cores from Lake Baikal. *Second Year Report to the Leverhulme Trust on Grant F.134 AZ.* 8 pp.
- 19 Mackay, A.W., Flower, R.J. & Battarbee, R.W. 1996: Stratigraphical evidence of environmental change in Lake Baikal, associated with recent changes in climate. *Final Report to the Leverhulme Trust on Grant F.134 AZ.* pp. 166.
- 20 Cameron, N.G. (1996) Diatom analysis of sediments from Barland's Farm, Magor (Severn Estuary). *Report to the Glamorgan Gwent Archaeological Trust.*
- 21 Bennion, H. & Monteith, D.T. (1996): Nutrient reconstructions in Standing Waters. *Report to English Nature on Contract No. F80-11-02.* 100 pp.
- 22 Bennion, H. (Ed.) (1996): A study of recent environmental change within selected standing waters proposed as Special Areas of Conservation in Wales. *Report to the Countryside Council for Wales on Contract No. FC 73-01-131.* 34 pp.
- 23 Battarbee, R.W., Barber, K.E., Oldfield, F., Thompson, R., Stevenson, A.C., Eglinton, G., Haworth, E.Y., Brooks, S.J., Holmes, J., Cameron, N.G., Rose, N.L. & Maddy, D. 1996: Proxy records of climatic change in the UK over the last two millennia. *Final Report for NERC Special Topic Grant GST 102/701.*