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No. 66

Holocene lake sediment core sequences from Lochnagar, Cairngorm Mts., Scotland - UK Progress Report for CHILL-10,000

Contract No: ENV4-CT97-0642

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Climate History as recorded by ecologically sensitive Arctic & Alpine Lakes in Europe during the last 10 000 years: A multi-proxy approach (CHILL-10 000), Contract No: ENV4-CT97-0642

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1. Aims of CHILL

The CHILL 10,000 project is funded under the EU Framework V, Environment and Climate Programme (Area 1.1.2). The aim of CHILL-10,000 is to investigate quantitatively past climate changes as recorded in lake deposits in ecologically sensitive situations. The biology of the systems (lakes) is used to amplify the climate signal. The objective in CHILL-10,000 is to undertake detailed, quality controlled and high resolution microfossil analyses of Holocene lake-sediment sequences. Biological proxy data include diatoms, chironomids, chrysophytes, pollen and cladoceran. Sedimentological proxies including organic matter, minerogenic matter, mineral magnetism and particle size analysis is also conducted. The lake core sequences are dated using radiocarbon AMS dates of macrofossils or bulk samples of fine organic matter.

The CHILL project is co-ordinated by the University of Helsinki (Project co-ordinator: Dr. Atte Korhola) and project partners include the Institute of Limnology (Austria), University College London (UK), University of Edinburgh (Scotland, UK), University of Barcelona (Spain), University of Bern (Switzerland), Geological Survey of Denmark (Denmark), University of Bergen (Norway). Modern data-sets (or 'training sets') exist for three regions (the Alps, Pyrenees and Scandinavia) (Figure 1). Seven European lakes chosen for long-term climatic reconstructions (Redó D'aiqüestrotes (Spain), Sägistalsee (Switzerland), Unterer Landschitzee (Switzerland), Lochnagar (UK), Bjornfjellvatnet (Norway), Sjuodijaure (Sweden) and Masehjarvi (Finland) are also indicated in Figure 1. The sites are all close to modern timber line, with no glaciers in their catchments and have limited or no anthropogenic disturbance. The sites are generally all oligotrophic, small (< 20 ha), shallow (< 24 m) and clear (TOC < 5 mg l^{-1}).

1.1 Aims at Lochnagar

The Cairngorm and Lochnagar mountain range constitutes the largest continuous area above 600 m, and is the only natural alpine environment, in the UK (Figure 2). The mountain ranges consists of a high tableland dissected by deep steep-sided glens. The geomorphology is ideal for collecting and holding snow. The massif is underlain by granite geology. The high altitude as well as harsh weather conditions have maintained infertile soils with a low carrying capacity.
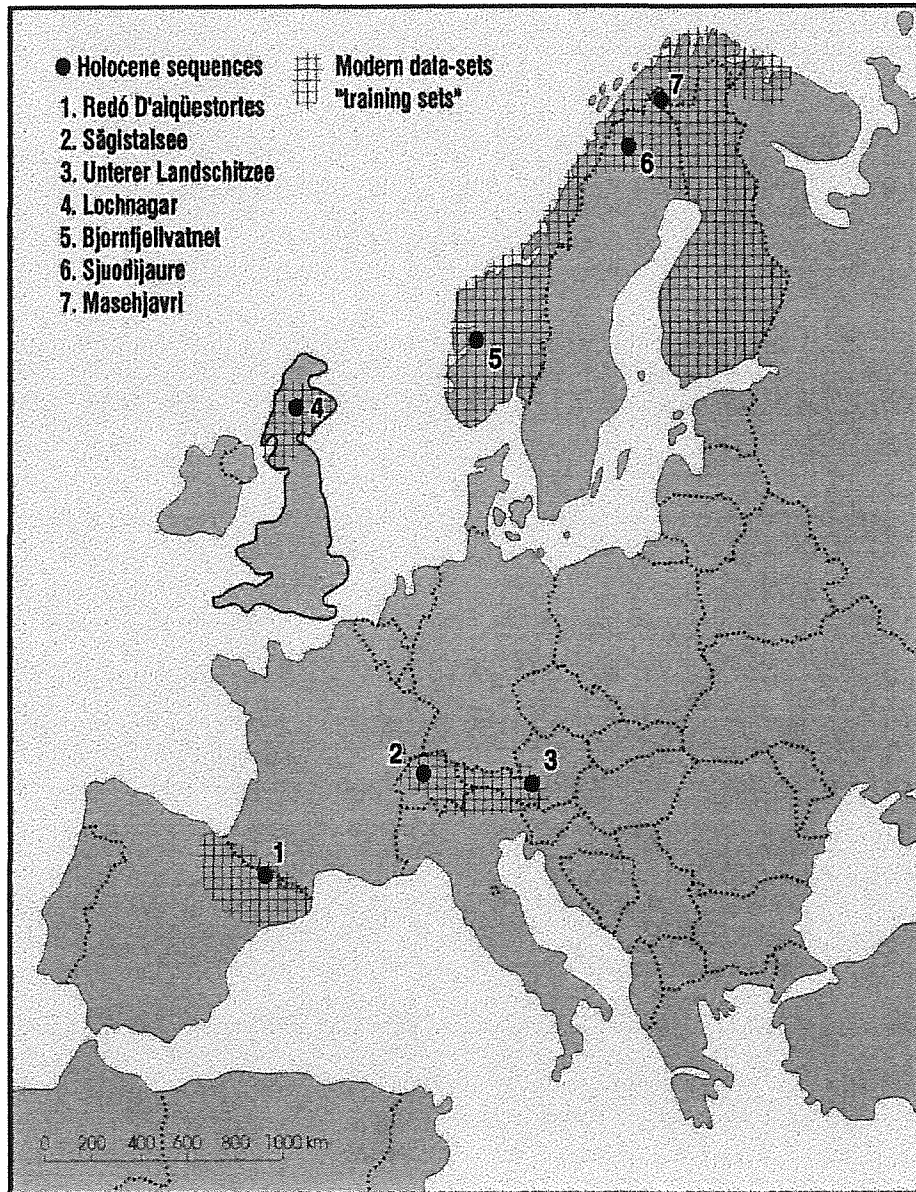
Figure 1: CHILL-10,000 training sets and lakes with Holocene sediment sequences
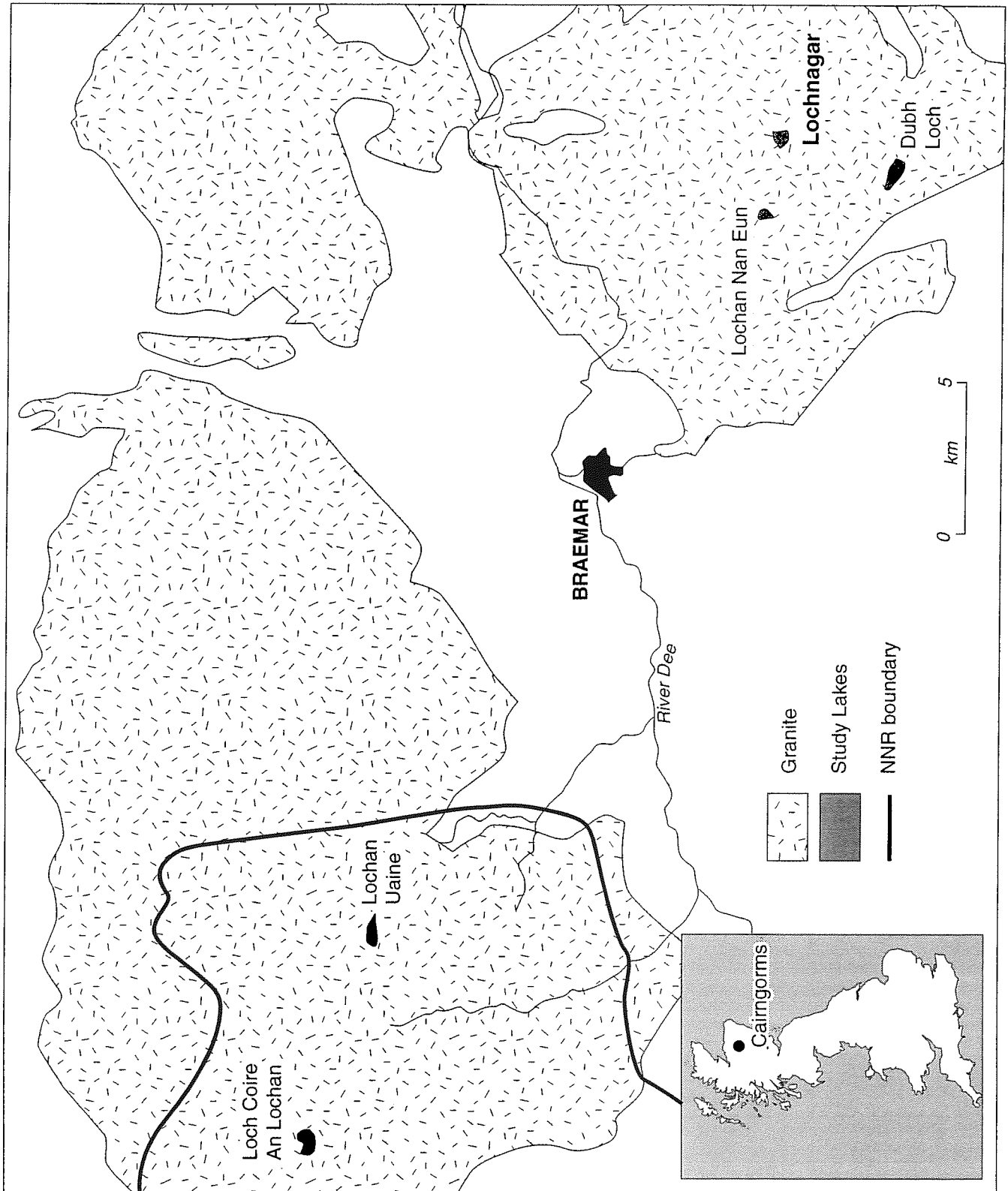
Figure 2: The Caringorms and Lochnagar

Lochnagar:
Catchment

N

Lochnagar

950
800
850
900
1050
1100
1050
950
1000
1050

Contours in metres

0   metres   500

Lochnagar:
Bathymetry

5
10
15
20
22.5

N

Contours in metres

0   metres   100
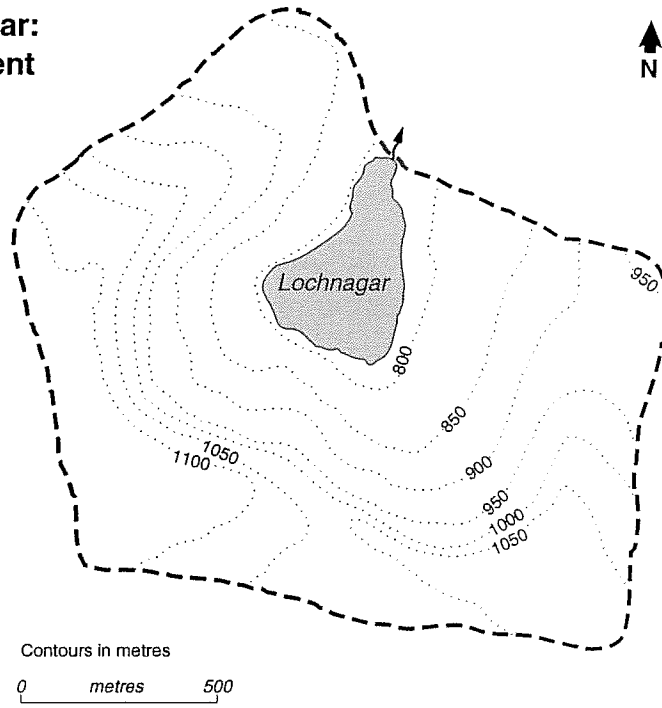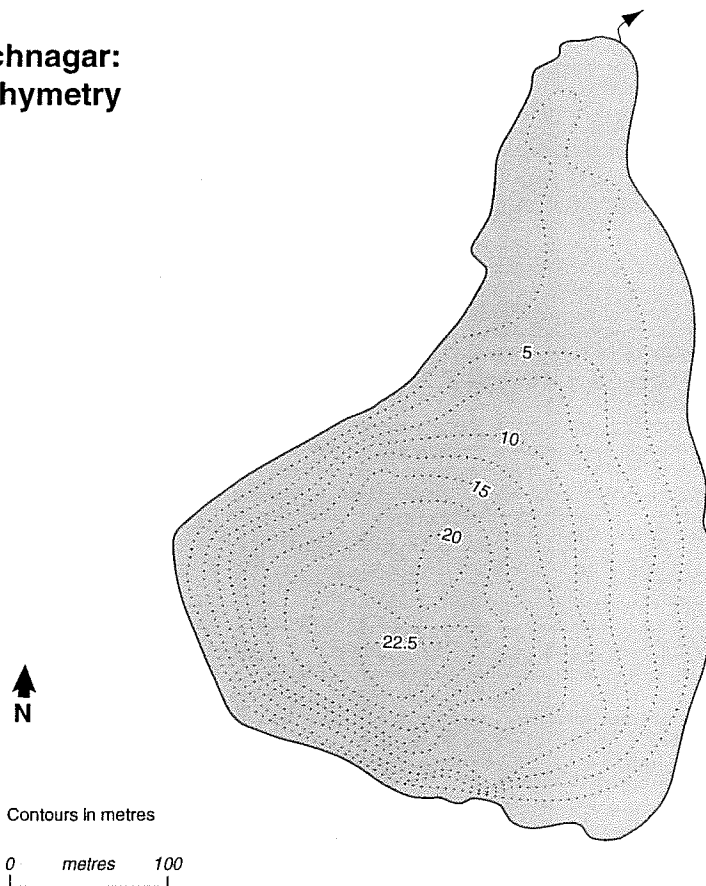
Figure 3: Lochnagar Catchment and Bathymetry

Lochnagar is one of the few lakes in Britain which is suitable for this study (Figure 2). It has a catchment in a high altitude situation where it is susceptible to the effects of climate change and is relatively undisturbed by human activity (Figure 3). In addition Lochnagar is the only high altitude corrie loch for which high quality monitoring data is available.

In collaboration with existing scientific work at Lochnagar, it was planned to retrieve a lake core with a Holocene sediment record. It was anticipated that the maximum depth of sediment accumulation, representing the last 10,000 years, would be contained within about 2.0-2.5 m of lake mud. The sedimentological and biological proxy data examined at Lochnagar are similar to the other CHILL lakes and additionally tephra, sediment geochemistry and biomarker studies, are also being conducted.

1.2   Research Objectives

The CHILL 10,000 research objective at Lochnagar is to examine proxy data for temperature and climate conditions. These proxies include organic and minerogenic matter, chironomids, diatoms, pollen and biomarkers. Changes in lake sediment stratigraphical data can be used to reconstruct past conditions.

All CHILL partners will use sedimentological approaches (organic and minerogenic matter) as indicators of catchment and climate change. It appears that the relative proportions of mineral and organic matter can fluctuate in a cyclical manner and is possibly related to climate (Barber *et al.*, 1999).

Pollen analysis is being used to extend the existing pollen-climate training set for Scandinavia, the Alps and the Pyrenees. All CHILL partners will also study the pollen stratigraphy from Holocene lake sediment sequences in ecologically and climatically sensitive situations.

The research objective for diatoms in the wider CHILL project is to extend and amalgamate the existing modern diatom-climate training sets in the northern Fennoscandia, Pyrenees, Switzerland, Austria and northern Italy that can then be used for climatic reconstructions from diatom-core data at ecologically sensitive high-altitude settings. There is no existing diatom-climate training set for the UK because of the low number of high altitude lakes unaffected by human impact. Diatom-temperature inferences have been criticised on the basis that they lack an

ecophysiological basis (unlike diatom-based pH, salinity and nutrient reconstructions). Therefore, the AL:PE pH training set (Cameron *et al.*, 1999) will be used to reconstruct historical pH. Inferences about climate change will be interpreted via the pH reconstruction and other paleolimnological proxies.

The research objective for chironomids is to expand the chironomid-water temperature training set for European alpine and arctic lakes and to use the modelled response functions to reconstruct past climates from the chironomid data. All partners will examine Holocene fossil records.

Changes in primary productivity are likely to be forced by climatic fluctuations and changes in the duration of ice cover. Organic biomarker techniques are used to explore the sources of mineral (clastic/diatom) and organic (algal/higher plant) fractions and the relative importance of lake and catchment material. Within CHILL biomarkers are used, by the UK partner at Lochnagar only, to develop the use of the technique for lake sediments as a means of identifying sources of organic matter. It is envisaged that this will assist in the investigation of the taphonomy of mountain lake sediments and enable a better understanding of radiocarbon dates and explore their potential as a proxy for climate.

Tephrachronology is also being conducted by the UK partner at Lochnagar to develop the technique for lake sediments. Lake sediment tephra have been counted from two profiles from Lochan Uaine, also in the Cairngorm region, however, shard concentrations were too low at this site for positive peak identification. It is envisaged that the higher concentration of organic matter in the sediments at Lochnagar will facilitate extraction of a better tephra record. This will in turn act as a potentially more precise dating horizon to support the inferred change from high resolution sediment analysis.

Surface sediment cladoceran analysis and chrysophyte analysis are being conducted at other CHILL sites to expand existing training sets and harmonise taxa. Holocene sequences are also being analysed for cladocerans and chrysophytes.

2.   Site Selection

Within the Cairngorm and Lochnagar ranges two sites were suitable for the CHILL project. The first Lochnagar, an AL:PE (Wathne *et al.*, 1995; Cameron *et al.*, 1999) & MOLAR (Patrick,

1997) site. The other site was Lochan Uaine a TIGGER site (Barber *et al.*, 1999). A Lochan Uaine core was already available to work on, however it did not cover the full Holocene sequence. This core consisted of a 95 cm sediment sequence covering c. 5000 years. Problems with dating (a mis-match between extrapolated radiocarbon dates and ^{210}Pb) also made this site unsuitable. More cores from Lochan Uaine are currently being analysed by Andrew McGovern for his PhD at UCL. This work concentrates on organic geochemistry.

It was proposed to seek a full Holocene sequence from Lochnagar. A complete Holocene sediment record was thought potentially retrievable from Lochnagar as a result of previous work on late Holocene sediments at this site (Rapson, 1985) and because of comparable sediment accumulation rates at upland Scottish lakes. The remoteness of the site meant that accessibility with long-coring gear was problematic. Livingstone and Mackereth coring options were considered but both necessitated either helicopter or vehicular access. They were considered too destructive of sediments and too heavy to carry. An alternative was to develop a rope-operated piston corer which would not require rods to operate and would be more portable for transport to this remote site.

Physical access to Lochnagar is facilitated by a track and footpath. The lake is located approximately two hours walk from the carpark at Glen Muick. The lake is located at an altitude of 785 m while Nagar the highest point in the catchment is at 1182 m (Table 1). The catchment area is 9.19 ha and lake area is 9.8 ha. An average pH for the lakewater is 5.4 and clear waters are evident with low mean DOC of 1.0 mg l^{-1}.

Table 1: Location and environmental characteristics of Lochnagar

Site	Lochnagar
Latitude (°N)	59.95
Longitude (°E)	3.3
Altitude (m a.s.l.)	785
Lake area (ha)	9.8
Catchment area (ha)	91.9
Maximum depth (m)	24
July water temperature (°C)	11.2
July air temperature (°C)	2.4
pH	5.4
Conductivity (μS/cm)	21.5
Ca (mg l^{-1})	0.6
DOC (mg l^{-1})	1.0

2.1 Sediment Coring

A tapper corer (for compact sediments) was designed by Jim Chambers and Nigel Cameron (Chambers & Cameron, in press) at the Environmental Change Research Centre, UCL. The tapper corer is a modification of existing percussian and piston-corer designs which can be used from small boats on open water. The device collects enough material for fine-resolution analyses. The core tube is hammered (with weights suspended from a second rope) beyond a piston secured by a rope and holding the core tube in place by friction. Retrieval of the sediment water interface is achieved by suspension of the piston approximately 30-50 cm above the sediment. Upon completion of the drive into the sediment (or when the core tube bottoms out) a lifting-pot is attached and the core tube with sediment and piston are retrieved.

Fieldwork was conducted at Lochnagar between July 14-17th 1998. Two long cores were obtained from the lake (NAG27 and NAG28). It was necessary to take two cores to have enough material for all analyses to fulfill the CHILL objectives. NAG27 and NAG28 were retrieved from 20.4 and 20.6 m of water and were 181.5 and 174.5 cm long respectively (Table 2). Extrusion of the cores resulted in some compaction of the sediment and the final core lengths were approximately 176 cm (NAG27) and 171 cm (NAG28). The cores, taken 2 m apart (see Figure 4), appear to have very similar sediment accumulation rates with obvious matching colour changes offset by about 5 cm (also the difference in overall core length). The piston reached the head of the core tube and therefore the base of the potential sediment record was not retrieved.

A second fieldtrip was conducted between September 27-29th 1999 when a further two cores (NAG29 and NAG30) were collected. These were collected in an effort to extend the sequence to earlier Holocene sediments. The first core (NAG29) is being used for heavy metal analysis by Handong Yang at UCL, while NAG30 is being processed under the CHILL project. NAG30 was retrieved from shallower lake perimeter waters (4.2 m) and measured 155 cm after core extrusion.
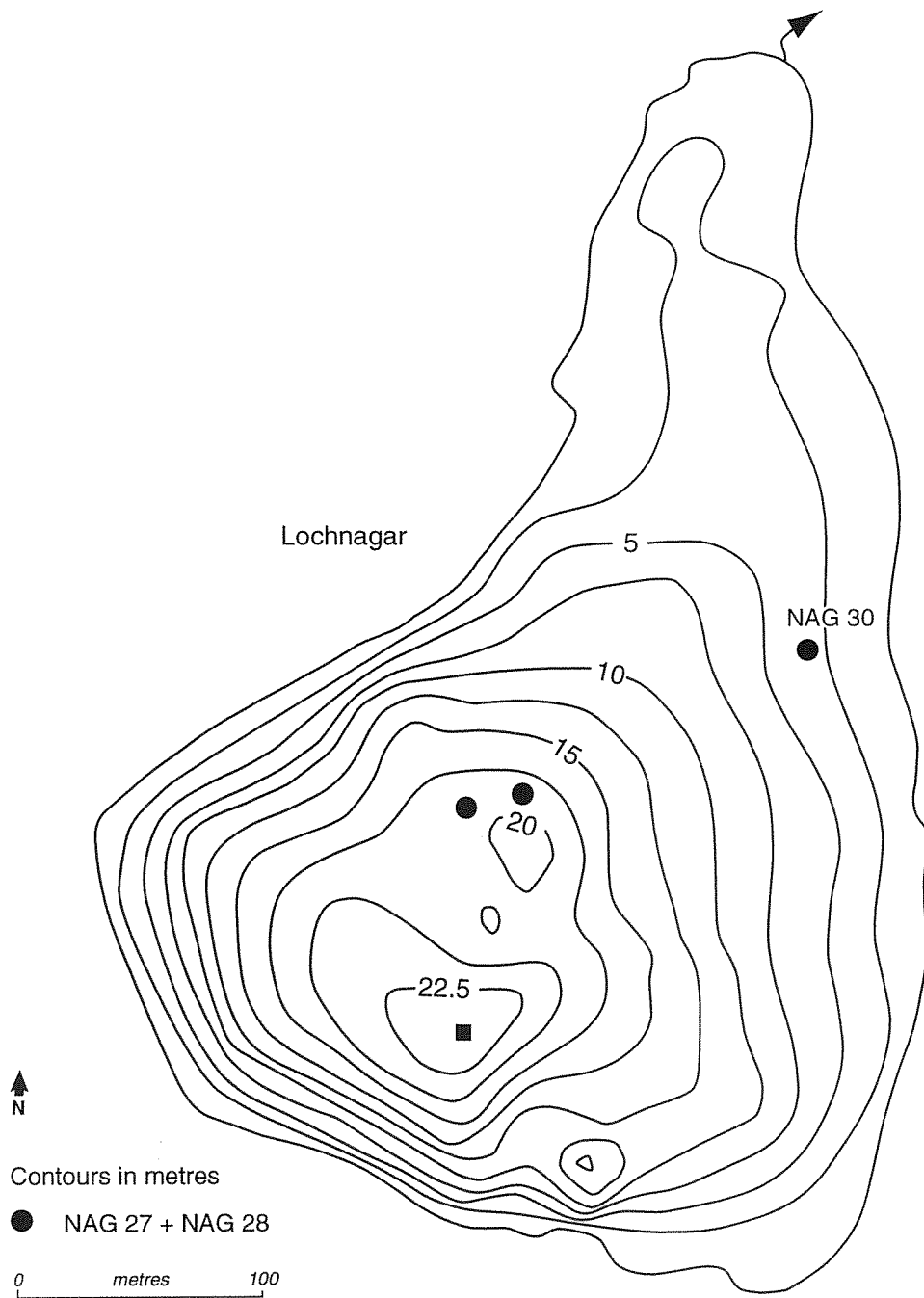
Figure 4: Lake bathymetry of Lochnagar and coring positions

Table 2: Lake sediment core details from Lochnagar.

Core Code	Date Cored	Water Depth (m)	Length of Core (cm)	Length of Core after extrusion (cm)
NAG27	July 16, 1998	20.4	181.5	176.0
NAG28	July 16, 1998	20.6	174.5	171.0
NAG29	Sept 29, 1999	4.4		167.0
NAG30	Sept 29, 1999	4.2		155.0

2.2   Sample Resolution

Sampling at fine intervals is necessary to achieve good resolution for detailed climatic reconstructions. The original CHILL proposal was for c.100 year resolution in contiguous sequences, however, use of finer time-intervals was optional. The Lochnagar cores were sliced at ultrafine intervals of 2 mm to enable fine-resolution examination of periods of environmental change of potential significance.

Table 3: Lochnagar Sediment core sub-sampling (sample resolution in brackets)

Proxy	NAG27	NAG28	NAG30
DW & LOI	1,262 (2 mm)	(1 cm)	154 (1 cm)
Wet Density	27 (5-10 cm)		
Pollen	89 (2 cm)		41 (2 cm)
Chironomids		44 (4 cm)	14 (10 cm)
Magnetics & Particle Size		85 (2 mm)	75 (1 cm)
Organic Geochemistry (isotopes)		354 (4 mm)	34
Biomarkers		35 (5 cm)	
Diatoms	184 (1 cm)		
Tephra Analysis	176 (1 cm)		64 (1 cm)

Core extrusion was limited by a suitable laboratory space and was eventually conducted vertically in a stairwell. Some contamination (smearing) of samples may have occurred from the actual coring as the tube passes down over the sediment and/or from the extrusion when the sediment is forced upwards through the tube. The main effort was made to extrude the core into sample bags and so make the cores safe as soon as possible. The 7.4 cm diameter Tapper cores (NAG27 & NAG28) were sliced at 2 mm intervals resulting in wet sediment samples of between 5-7 g. Efforts were made during sub-sampling to remove the outer ring (1-2 mm) of smeared sediment, to limit sample contamination. Extrusion (with two people) at 2 mm took 10 days for NAG27 and NAG28. NAG30 was sliced at 1 cm intervals and took one day. In addition to scientific consideration sample intervals were determined by the amount of money available within the CHILL budget. Sample resolution was determined by the amount of material required for the particular proxy and the best representation across the core (Table 3). A total of 1,262 samples at 2 mm resolution were available from NAG27 and NAG28 while 154 samples at 1 cm resolution were available from NAG30.

3. Methodology

3.1 Sediment Lithology

Munsell Colour

Attempts at Munsell colour classification were hampered by poor light conditions during sediment extrusion. The colour and textual changes were not marked in NAG27 and NAG28 however, the sediment was very fibrous from 30-35 cm. Some lighter colour were apparent around 70 cm, and 90 cm and 156 cm and a 2 cm mineral layer was found at 84 cm. No description of NAG30 was taken.

Wet Density (WD g cm^3)

The density of the wet sediment is measured using a 2 cm^3 capacity brass phial and a balance weighed to 4 decimal places. The clean phial is weighed empty and then carefully filled with wet sediment. Any air bubbles are removed by tapping the base of the phial on a firm surface and the surface of the sediment is then smoothed to be level with the top edge of the phial. The phial is then re-weighed and the weight of the sediment divided by 2 to determine the density as grams per cm^3. Wet density measurements were made every 5 cm to 90 cm and on every 10 cm to the base of the core (Table 3) due to limited changes.

Percentage Dry Weight (% DW)

Approximately 1 g of wet sediment was placed in clean, dry porcelain crucibles and balance weighed to at least 4 decimal places. The crucible was then placed in the oven for at least 12 hours set to 105°C. Following removal from the oven the samples were allowed to cool in a desiccator (to prevent re-absorption of moisture) before re-weighing. The percentage weight remaining after drying was then calculated. The same sample was then used for loss on ignition analysis. All samples were analysed from NAG27 (2 mm resolution), every 5th sample from NAG28 and every sample from NAG30 (1 cm resolution (Table 3).

Percentage Loss on Ignition (% LOI)

The percentage weight lost on ignition gives a crude measure of the organic content of the sediment. Generally, percentage loss on ignition values show an inverse relationship with percentage dry weight values. The dried sediment samples in crucibles were placed in the furnace and kept at 550°C for 2 hours. Following removal from the furnace, samples were placed in a desiccator and allowed to cool fully before re-weighing. The percentage of the dry weight lost on ignition is then calculated.

UCL participated in an analytical quality control experiment to see how different laboratories within the CHILL project performed % LOI analyses (Heiri *et al.*, in press). The aim was to investigate whether the analyses on the same sediment are comparable between laboratories or only in the laboratory that did the analyses. The experiment was conducted on 20 pre-weighed sediment samples combusted at 550°C and 950°C. The results of this study suggest that within laboratory variation was small and that there is a laboratory specific pattern in the results. A 2% error was also found even when the standardised method was being used suggesting differences in laboratory equipment and/or handling.

3.1.1 Core Correlation

Dry weight and loss on ignition was conducted on all samples from NAG27 (2 mm interval, 1,262 samples) and on samples at 1 cm intervals from NAG28 (182 samples). The cores were subsequently correlated level by level using a slot sequencing program (Clarke & Thompson, 1984). In sequence slotting the aim is to calculate the relative deposition rates in the two cores and to generate a diagram showing the tie lines. Figure 5 shows the correlated cores and their tie lines using dry weights and Figure 6 using loss on ignition. Because of the difference in sampling intervals between the cores the match at the top of the core was constrained. Core integrity, however, was not problematic. The cores are offset by approximately 20 cm according to the tie bars.
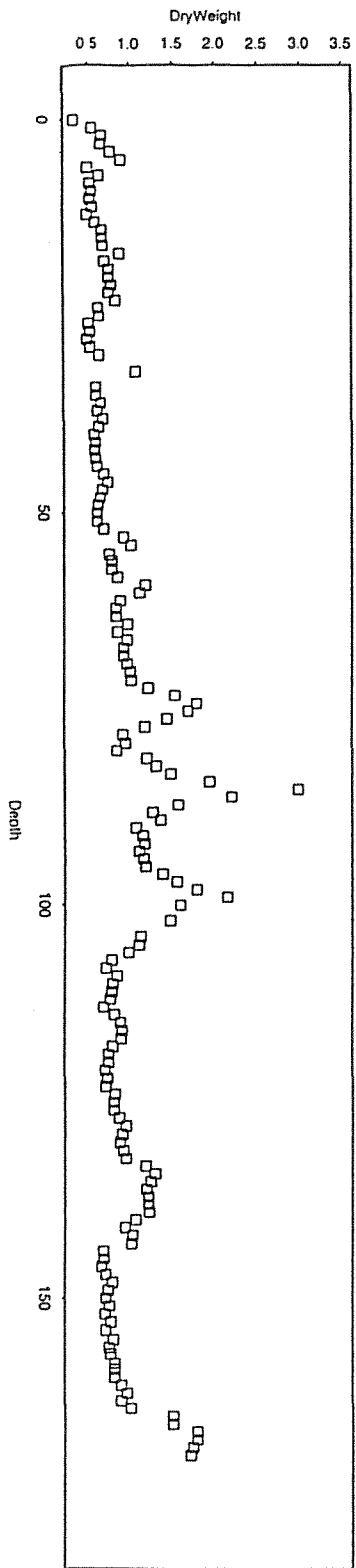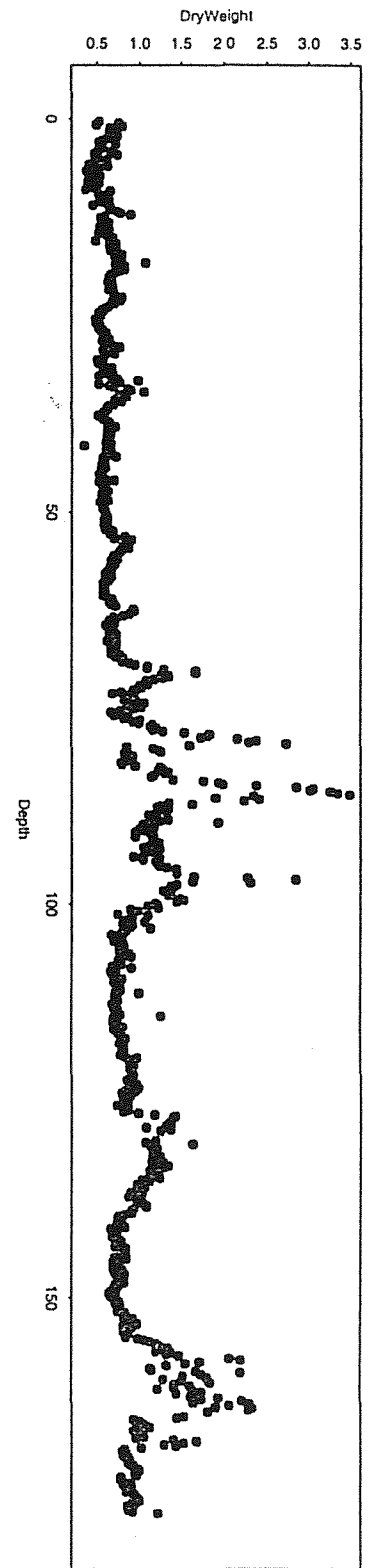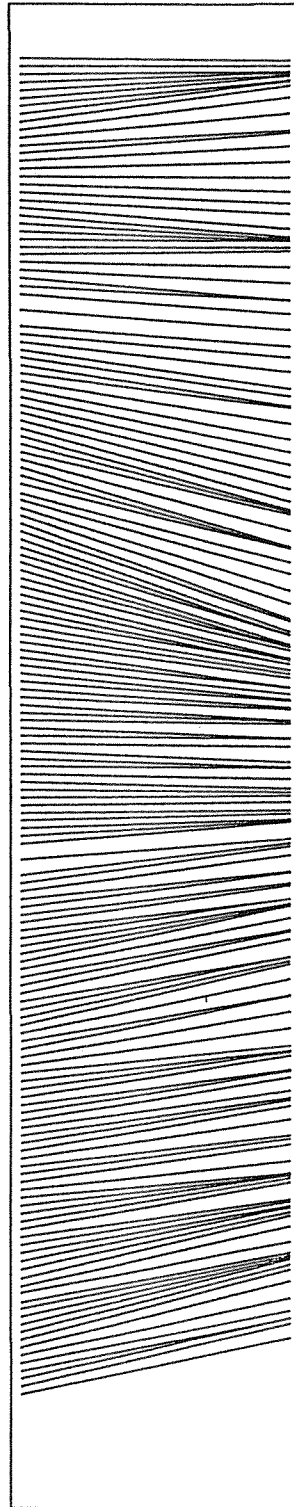
Figure 5: NAG27 & NAG28 %DW measurements correlated using tie lines
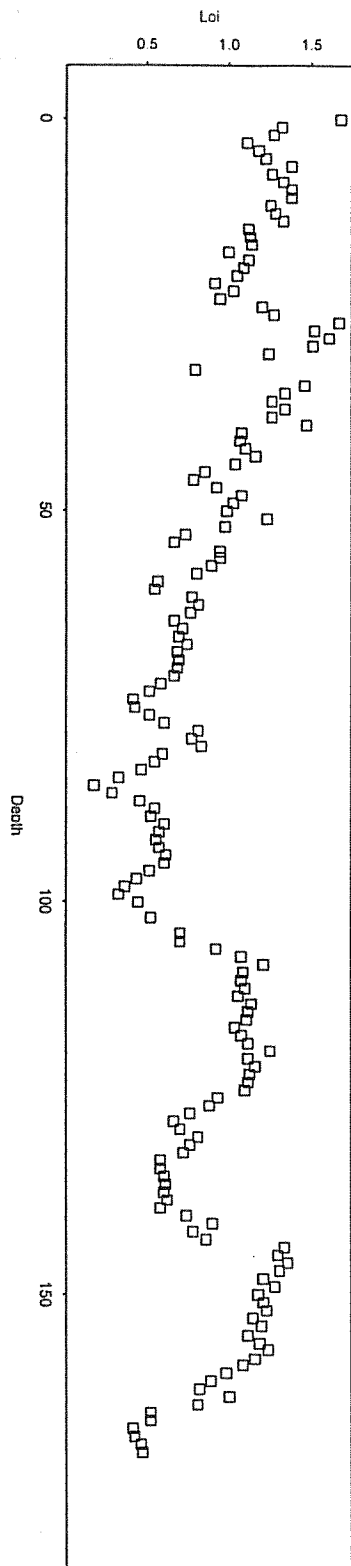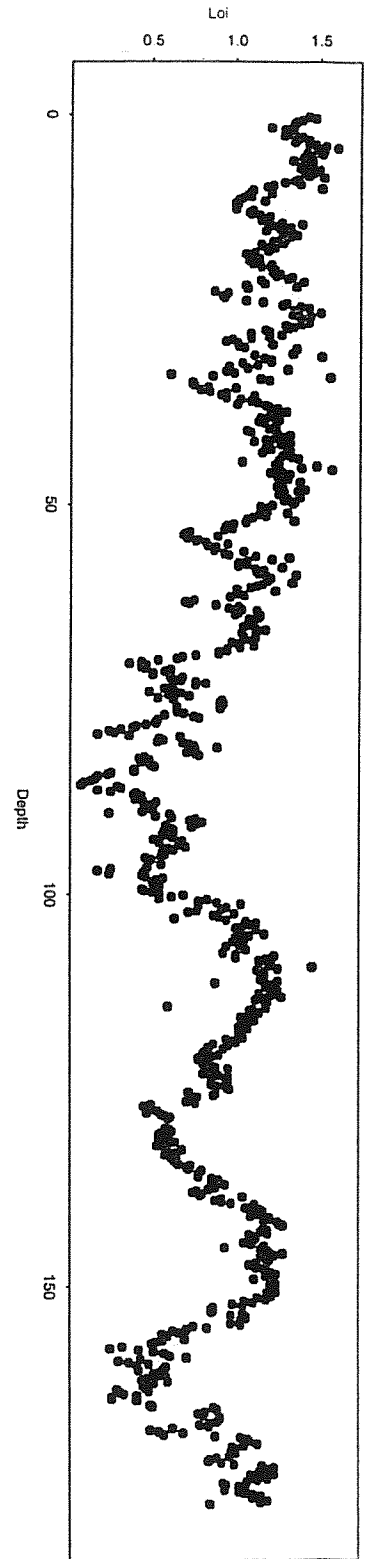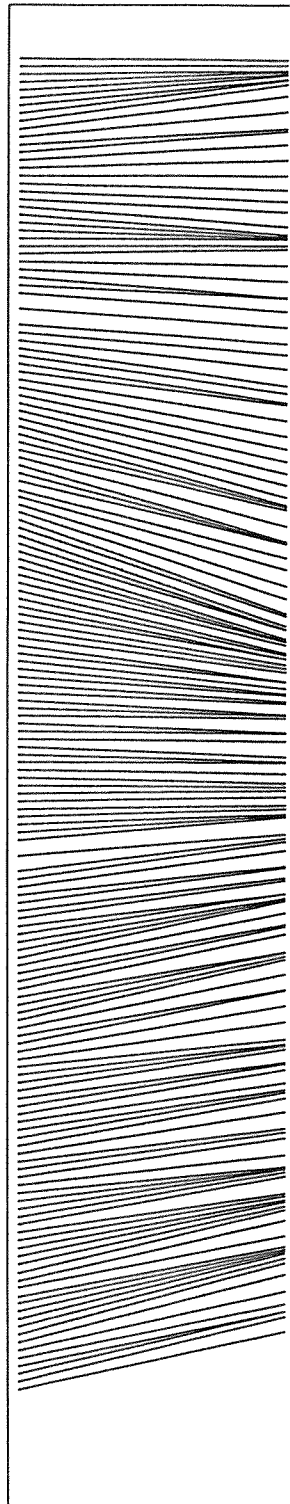
Figure 6: NAG27 & NAG28 % LOI measurements correlated using tie lines

Core correlation between NAG27/28 and NAG30 could not be achieved using slot sequencing because of the major differences in the LOI and DW profiles. Correlation between these profiles is enabled using pollen analysis and slot sequencing (Birks & Gordon, 1985) (see below).

3.2 Particle Size & Magnetics

3.2.1 Sample preparation

Sub-samples for particle size and magnetics were obtained at 2 cm intervals (2 mm resolution) from NAG28 (85 samples) and at 2 cm intervals (1 cm resolution) from NAG30 (75 samples).

For the magnetic measurements approximately 3.5g of wet sediment was wrapped in clingfilm and firmly wedged into a non-magnetic perspex box. Following the magnetic measurements the samples were prepared for particle-size analysis and for the SEM work. Any carbonate was removed overnight in 20% acetic acid, then the sediment slurry centrifuged and washed three times. The organic component was digested using a 30% solution of hydrogen peroxide which was heated in a water bath to 90 $^{\circ}$C for one hour and left overnight. The following day the samples were again centrifuged and washed three times. The samples for particle-size work were stored in a solution of 4% sodium hexametaphosphate in order to disperse the clay fraction. Samples were stored for a maximum of two days and immediately prior to particle-size analysis, using a Coulter LS-100 laser diffractometer, were sonicated for 5 minutes. Samples for SEM analysis was diluted with distilled water following the removal of the carbonate and organic fractions, deposited on a metal stub and gold coated.

3.3 Organic Geochemistry

The cores for biomarker studies were sliced into 2 mm intervals and the samples were freeze-dried, crushed and passed through a 500 μm sieve.

Elemental Analyses

Quantitative carbon, nitrogen and carbonate measurements were performed twice on a 2 mm interval from each centimetre of the core. The percentage reported values are the mean of two

analyses. Total Organic Carbon (%TOC) content was calculated by subtracting the % carbonate value from measured % carbon.

Lipid extraction

0.5 g DW of three contiguous samples were bulked, to give samples of 1.5 g DW spanning 6 mm of core. A five-compound internal standard was added to each sample. Lipids were extracted by sequential sonication (10 mins) and centrifugation (10 min at 3000 rpm). Two extractions were carried out with 100% MeOH, two with 1:1 MeOH/DCM, one with 2:1 DCM/MeOH and two with 100% DCM. Solvents were removed by evaporation under vacuum, and the extract cleaned by passing through a short silica column with 2:1 DCM/Isopropanol. The lipid extract was separated into neutral and acid fractions with an aminopropyl Bond Elut column using 2:1 DCM/Isopropanol and 5-10% acetic acid in diethyl ether respectively. The neutral fraction was further fractionated into hydrocarbon, aromatic, ketone and wax ester, alcohol and sterol, and polar fractions by flash column chromatography (using the following sequence of solvents: hexane; 9:1 hexane/DCM; DCM; 1:1DCM/MeOH; MeOH).

GC-MS

The alcohol/sterol fraction was derivatised in BSTFA prior to GC-MS analyses. Hydrocarbon and alcohol/sterol fractions were run on a Varian 3400 gas chromatograph (70 eV EI, SPI type injector) with a direct interface to a Finnigan TSQ 700 mass spectrometer. A temperature programme of 40°C (1 min) - 200°C @ 10°C/min - 300°C (20 mins) @ 3°C/min was used for standard GC runs and helium was used as the carrier gas. Lipids were identified at first by mass spectral analysis, and thereafter by comparison of GC retention times under constant operating conditions.

Elemental Analyser - isotope ratio mass spectrometry (EA-IRMS)

On-line bulk $\delta^{13}C$ analyses of sediment were performed using a Fisons Carlo Erba NC2500 elemental analyser coupled to a Finnigan MAT Delta S instrument via a ConFlo2 interface. Analysis of each sample (*ca.* 3 mg in tin capsule) was carried out in duplicate to obtain a mean value and nonadecane was run frequently as a standard compound within batches of samples.

3.4 Pollen

Volumetric samples (0.5 cm^2) were taken for pollen analysis using a quantitative sampler. Samples at 2 cm intervals from core NAG27 were obtained by amalgamating material from three consecutive 2 mm sediment slices. Samples from core NAG30 were taken directly from the 1 cm sediment slices. Samples were prepared for pollen analysis using a standard preparation protocol (procedure B in Berglund & Ralska-Jasiewiczowa, 1986) and the residues mounted in silicone oil (2000 cS). Pollen counting was performed at a x400 magnification (bright field), with critical determinations at x1000 magnification using an oil-immersion objective. About 600 grains and spores were counted in each sample.

All pollen and spores of non-obligate aquatic taxa are included in the calculation sum (ΣP) and expressed as percentages of ΣP. Pollen and spores of obligate aquatic taxa, algae, *Sphagnum*, indeterminable and unknown grains, and microscopic charcoal particles are expressed as percentages of ΣP + Σ relevant category (see Birks, 1973).

Numerical analyses of the pollen-stratigraphical data were performed to answer the following questions. (1) How can the pollen stratigraphies from the two cores be correlated? (2) What is the appropriate zonation for the total stratigraphy, given the likelihood that part of the NAG30 core overlaps with part of the NAG27 sequence? (3) What are the major underlying gradients of variation in the pollen-stratigraphical data?

All numerical analyses were based on taxa included in the calculation sum. The percentages were transformed to their square roots to stabilise variances and to maximise the 'signal to noise' ratio. As the total compositional change in the combined stratigraphy is 0.97 standard deviations (as estimated by a detrended canonical correspondence analysis constrained by sample order with detrending by segments, non-linear rescaling, and downweighting of rare taxa), the linear-based ordination technique of principal components analysis (PCA) and sequence-slotting (Birks & Gordon, 1985) were used to answer question (1). Optimal sum-of-squares partitioning (Birks & Gordon, 1985) and comparison with the broken-stick model to assess the approximate statistical significance of the zones (Bennett, 1996a) were used to answer question (2). PCA was used, in conjunction with the broken-stick approach, to answer question (3). Computations were implemented using the computer programs CANOCO version 3.12a with strict convergence criteria, CANODRAW, ZONE, SLOTSEQ, and BSTICK.

3.5 AMS ^{14}C Dating

Terrestrial plant macrofossils were considered ideal for AMS ^{14}C dating however few were present in the Lochnagar sediment samples (S. Peglar, pers. comm.). Bulk samples of fine organic material (particulate fraction) were considered the best alternative and adopted for the Lochnagar samples. AMS ^{14}C Dates were obtained from the Dating Laboratory, University of Helsinki, Finland. Lake sediment samples from Lochnagar were stored in polythene bags in a fridge at 4°C. Samples for dating were transferred to sterilised glass bottles. Pre-preparation of all CHILL samples for dating was conducted at the dating laboratory.

3.6 Diatoms

Diatom samples were prepared using known volumes of wet sediment placed in polyethylene test-tubes and digested in a waterbath using the standard hydrogen peroxide (H_2O_2) method (Battarbee, 1986). The mixture was boiled in a fume cupboard for approximately 2 hours or until all the organics were removed. After adding a few drops of HCl to remove the remaining H_2O_2 the mixture was then allowed to cool and settle. The samples were then washed clean with distilled water, centrifuged and the supernatant discarded. Prior to the last wash 1% NH_3 was added to disperse the diatoms and prevent clumping. This diatom solution was subsampled at a suitable concentration and the aliquot placed on a microscope coverslip (ca. 18 mm x 18 mm). The coverslips were placed on a metal plate and allowed to dry slowly (1-2 days). The dried samples were subsequently inverted and placed onto a drop of a mounting medium Naphrax on a microscope slide. The mount was then made permanent by evaporating the Naphrax solvent with a hotplate temperature of 130 °C.

To determine diatom concentrations (cells g wwt^{-1}) a known number of microscopic markers were added to a known amount of sediment (Battarbee & Keen, 1982). Divinylbenzene (DVB) spheres are added to the diatom suspension prior to slide preparation.

Diatom accumulation rates (valves cm^{-2} year^{-1}) can be calculated for sediments that have been dated (radiometrically). Diatom accumulation rates (valves cm^{-2} year^{-1}) were calculated by multiplying the wet mass accumulation rate (cm^{-2} year^{-1}) and the diatom concentration (cells g wet wt^{-1}).

Diatoms were prepared at 2 mm intervals from NAG27 (1,262 samples) and have been counted at 1 cm interval (185 samples) to pick up trends. Samples at 1 cm intervals were prepared and are being counted for NAG30. Low sum diatom counting (c. 100 valves) was conducted on all samples (Renberg, 19XX).

Diatom counts were entered into the diatom database AMPHORA at University College London Data manipulation was performed using TRAN (Juggins, 1994) to create Cornell condensed format percentage data. TILIA and TILIAGRAPH (Grimm, 1991) and Microsoft EXCEL were used for storing, manipulating and plotting stratigraphic diatom data. The diatom data were are subjected to clustering and ordination techniques (indirect analysis). Zonation of stratigraphical fossil diatom data was achieved using ZONE. This programme uses a number of methods to analyse stratigraphic data (CONSLINK (using a Chord distance dissimilarity matrix), CONISS (using a Squared Chord distance dissimilarity matrix), SPLITLSQ, SPLITINF and Cluster analysis). Detrended correspondence analysis (DCA), a form of correspondence analysis, is a unimodal indirect ordination method. DCA incorporates the option detrending by segments (to smooth variation). The eigenvalues represent variation within the data and total variance is expressed as total inertia.

3.7 Chironomids

Samples at 4 cm intervals from core NAG28 were obtained by amalgamating material from four consecutive 2 mm sediment slices (40 samples). Samples from core NAG30 were taken directly from the 1 cm sediment slices at 5 cm intervals (14 samples).

3.8 Tephra

Tephra shards were extracted from lake sediments using H_2O_2 to remove organic matter, NaOH to remove biogenic silica and HCL to remove carbonates and bicarbonates, a procedure described by Rose et al., (1996). Known amounts (c. 0.1 g) of dried lake sediment are placed in glass test tubes and 2 ml of 30% H_2O_2 added. Cold over-night digestion is followed by the addition of 5 ml of H_2O_2 and digestion in a waterbath at 80°C for 3 hours. Samples are then allowed to cool centrifuged and the supernatant is discarded. Five ml of 0.3M NaOH is then added and heated in a waterbath for 3 hours. A final 5 ml of 3M HCL is then added and samples are digested in the waterbath for 1 hour. A known fraction of the final residue is evaporated on coverslips.

Tephra are counted under a light microscope with a rotating stage and cross polarised light. Shard concentrations are expressed in units of g DM^{-1}. All the shards present on the coverslip are counted.

4.   Results

4.1   Sediment Lithology

4.1.1   Loss on Ignition and Dry Weight - C. Dalton, University College London

The sediment lithology of Lochnagar is characterised by multiple peaks and troughs in organic matter and very sharp peaks in dry weight (in NAG27) (Figure 7). These variations are replicated in similar results for the parallel sediment core NAG28 (Figure 8). NAG30, on the other hand, collected closer to the perimeter of the lake has a less variable profile with lower levels of organic matter (Figure 9). This could be related to the lower resolution analysis (1 cm intervals) being less sensitive to sediment change or may be a factor of spatial variation within the lake sediment body. However, lower resolution analysis of NAG28 (1 cm) did not reduce the signal compared to NAG27 (2 mm), so this could not account for the results in NAG30. A peripheral lake sediment core closer to catchment peats should potentially have higher levels of catchment derived organic matter, therefore, the lower %LOI values for NAG30 was unexpected. Sediment bulk or wet density measurements varied between 1.01 and 1.14 g cm^3 (on NAG27). Little overall change in bulk density is apparent.

The hypothesis is that these peaks in loss on ignition represent phases of higher productivity at the site. The profiles for NAG27 and NAG28 may therefore represent oscillations in productivity over the 5,500 year period covered by the sequence. In the bottom half of the NAG27 core three major peaks and three toughs in organic matter are clearly identified. This corresponds to the period 5,500-3,000 yrs BP. The major troughs coincide approximately with uncalibrated dates of 5,000, 4,000 and 3,000 yrs BP. Periodicities pre-3,000 years, therefore, appear to be based on approximately 1,000 year cycles.

Post-3,000 yrs BP there is a 3-4-fold increase in oscillations with approximately 10 peaks in organic matter. These periodicities of 250-350 years represent a major change in the Lochnagar system post - 3,000 yrs BP.
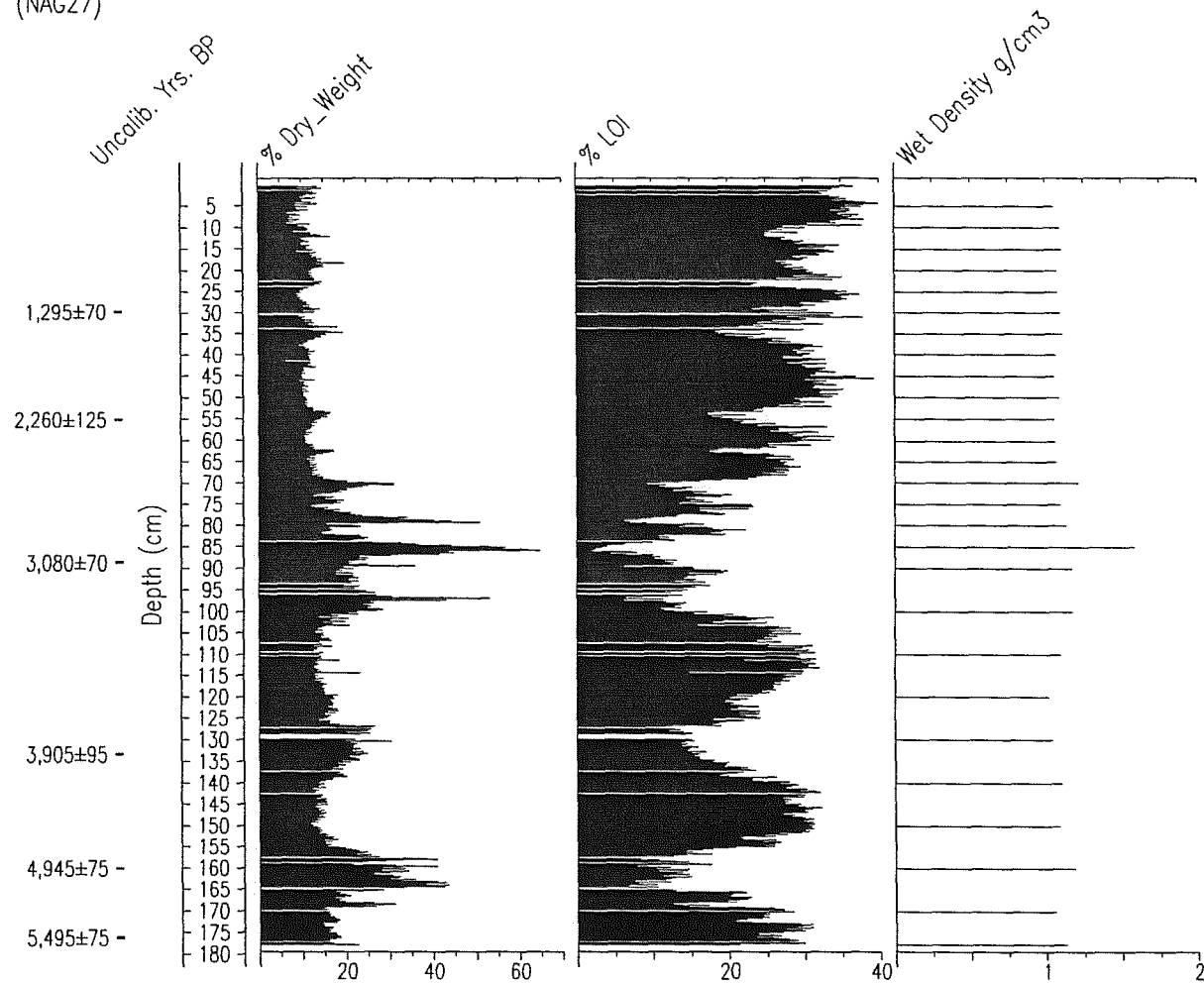
Figure 7: Lochnagar (NAG27) sediment lithology, including bulk density (wet density g m³), dry matter (% dry weight) and organic matter (% LOI)
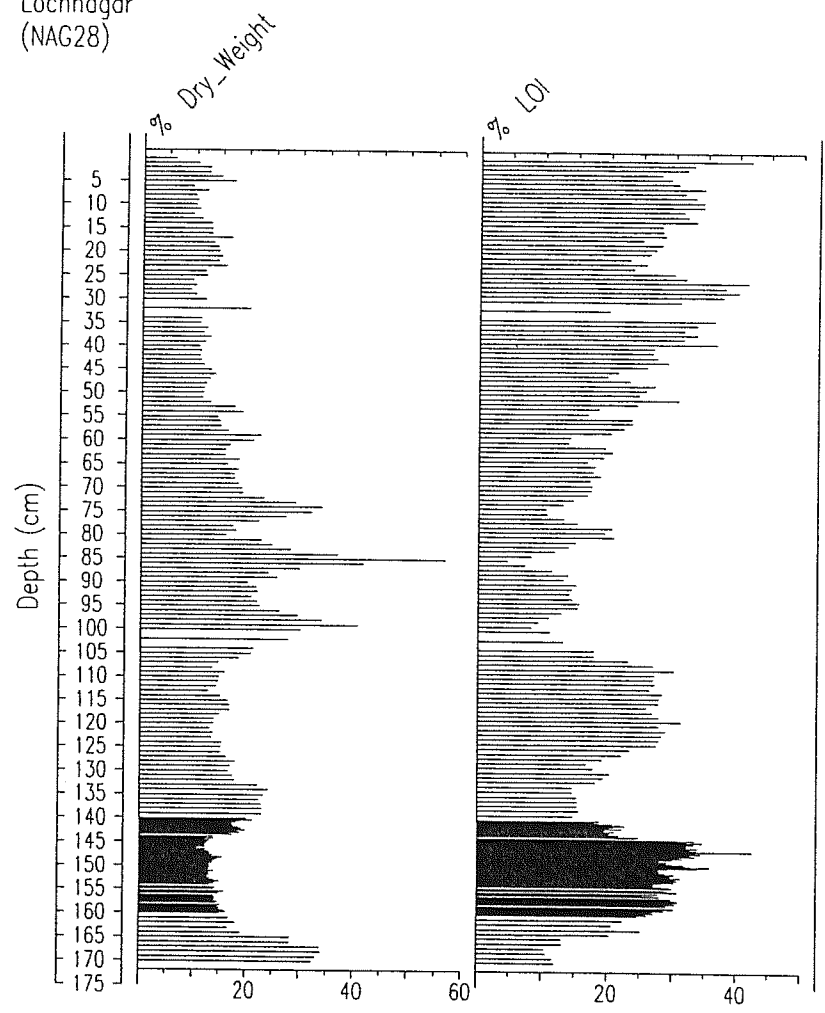
Figure 8: Lochnagar sediment lithology (NAG28), including dry matter (% dry weight) and organic matter (% LOI)
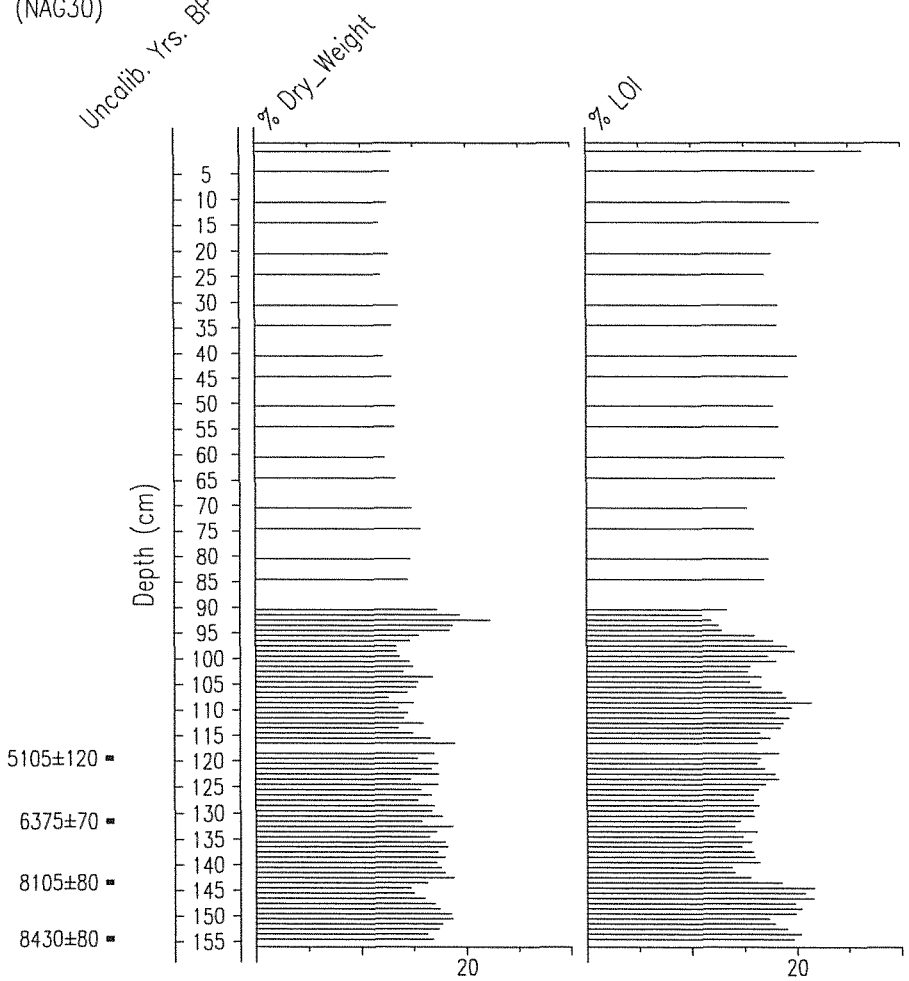
Figure 9: Lochnagar sediment lithology (NAG30), including dry matter (% dry weight) and organic matter (% LOI)

The sediment dry weight exhibits peaks and troughs in the profile and generally shows an inverse relationship with loss on ignition measurements (Figures 8, 9 and 10). Dry matter rarely drops below 15% in the lower half of the core (pre- 3,000 yrs BP) and 10 % in the upper half, post 3,000 yrs BP in NAG27 and NAG28. Of note are three peaks in dry matter between 100-75 cm. Peaks of 50-65% dry weight are recorded for NAG27 and up to 60% for the parallel core NAG28. These correspond to major troughs in LOI. These high DW levels suggest a major catchment minerogenic input around 3,000 yrs BP and may represent the first effects of anthropogenic disturbance in the catchment. The dry weight profile for NAG30 from shallower water show a more uniform record with maximum % DW levels of just 20% (Figure 9).

4.1.2 Particle size and magnetism - R. Thompson & S. Derrick, University of Edinburgh

4.1.2.1 Introduction

Lake bottoms are the depositional site of both minerogenic and organic matter that is transported to the lake from the surrounding drainage basin as well of as matter that forms within the lake itself. Thus lake sediments typically consist of accumulates of minerogenic particles (e.g. quartz or feldspar), plant fragments, diatom frustules and calcium carbonate precipitates. Mountain lakes, with small inflowing streams, can often contain bottom sediments dominated by diatoms. Following removal of the organic fraction, particle-size analysis forms a quantitative approach to characterising the non-organic component of lake sediments. A previous study at Lochan Uaine, a high corrie loch in Scotland, revealed a relationship between particle-size and the key stratigraphic parameter of loss-on-ignition. The cause of the relationship however was not discovered. Three potential controls on the particle-size distribution in remote mountain lakes are (i) changes in the importance of catchment erosion, (ii) changes in the preservation (e.g. breakage) of diatom frustules and (iii) changes to the diatom flora. One hundred and sixty samples of bottom sediment from Lochnagar spanning approximately the last 8,000 years, have been analysed to further investigate the particle-size distribution of remote mountain lake sediments and the relationship of particle-size and magnetism with biological proxies of climate change.

4.1.2.2 Results

Particle-size

The sediments of Lochnagar predominantly consist of silt sized particles with smaller percentages of clay and sand. Uni-modal, bi-modal and even tri-modal particle-size distributions are found (Figure 10). The average sediment size is about 40 μm in diameter. The middle section of core 28 contains significantly sandier horizons.

Magnetism

The magnetic properties of Lochnagar sediments are very weak, nevertheless a cryogenic magnetometer can, with care, be used for their measurement. The sediment typically only contains about one grain in one hundred thousand, which is magnetic. Magnetic concentration varies with sediment age. The highest magnetic concentrations are found in the sediments near the top of the sequence (Figure 11).

4.1.2.3 Discussion

Three types of material control the particle-size distribution of Lochnagar sediments. First, coarse (sand) sized particles produce the right hand peaks seen most clearly in the particle size plots of Figure 10 c, d and e. Secondly fine (clay) sized particles give the left-hand tail in Figures 10 a-f. Both the sand and clay fractions appear to be catchment derived. Both these materials can be attributed to catchment sources. Thirdly diatoms preserved in the sediment form the sharp silt sized peaks, seen most clearly in the particle size plots of Figure 10 b, c and f. Over time there have been large changes in the proportions of diatoms to catchment materials preserved in the Lochnagar sediment.

The cause of the changes in magnetic properties, particularly the increase of magnetic particles in the uppermost sediments, remains to be determined. It may have been caused by (i) an increase in atmospheric pollution particles or by (ii) dissolution effects or by (iii) a catchment erosion effect.
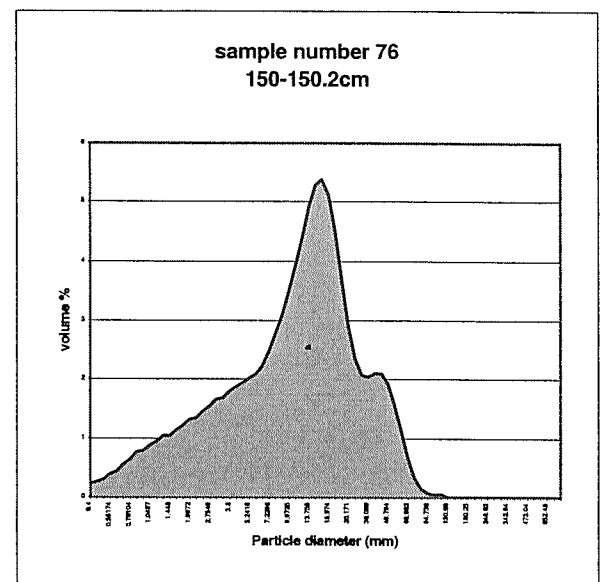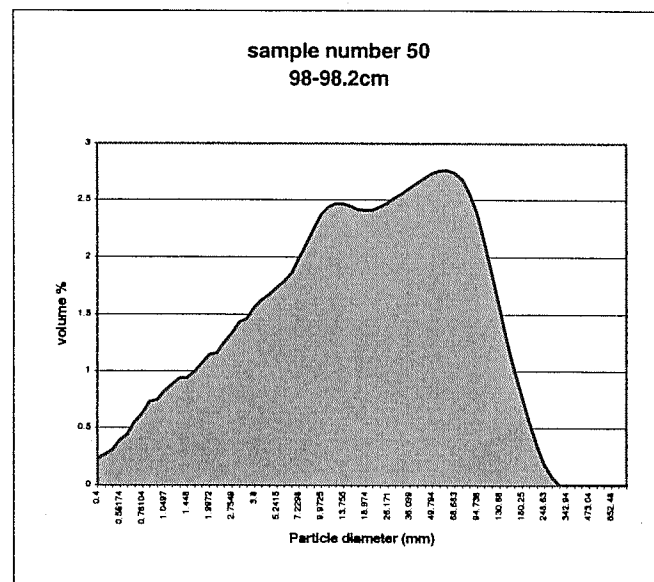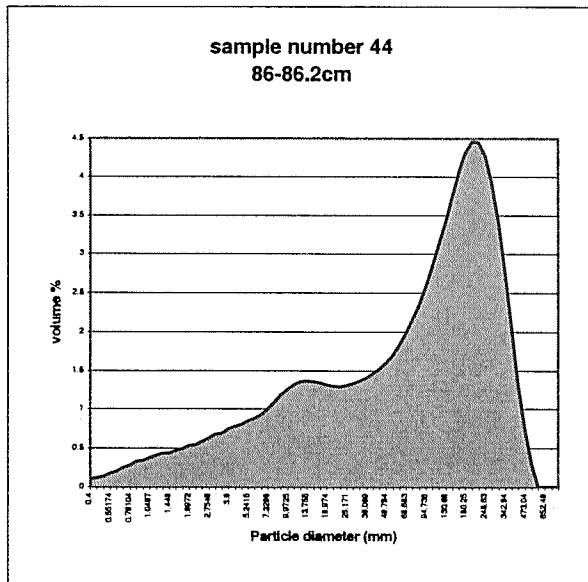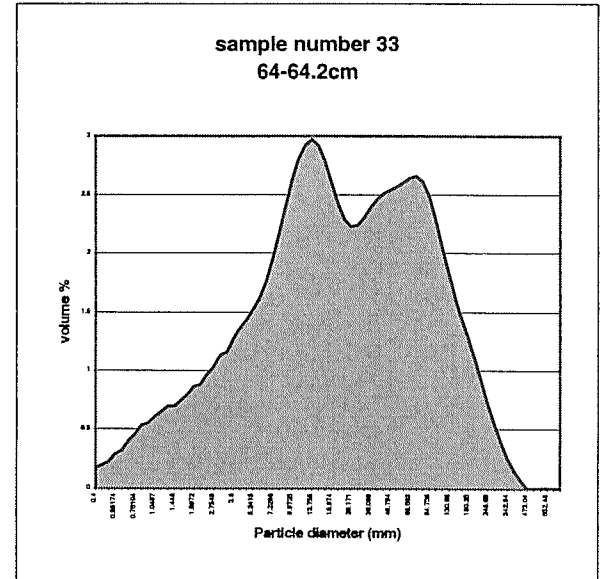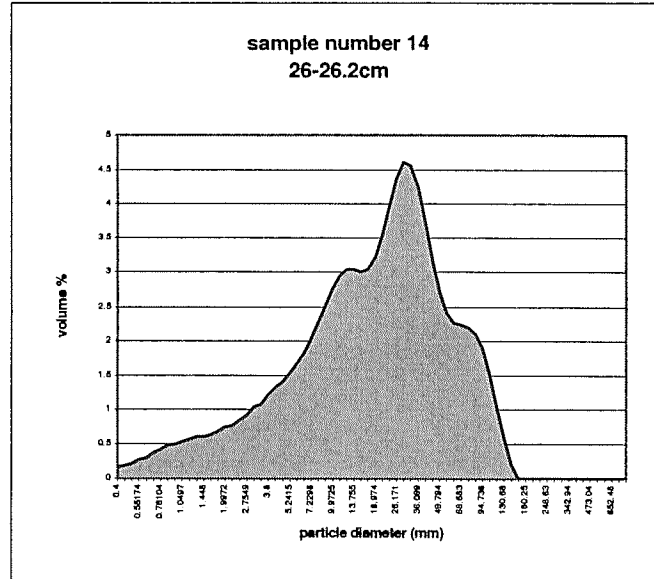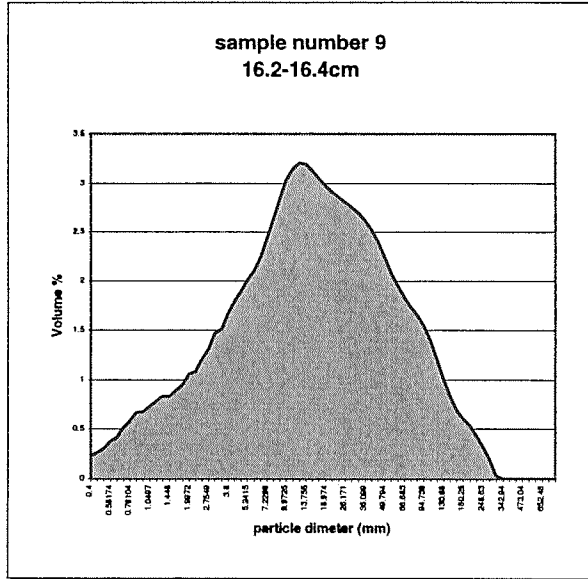
Figure 10: 6 samples representing the main particle size characteristics of Lochnagar (NAG28)
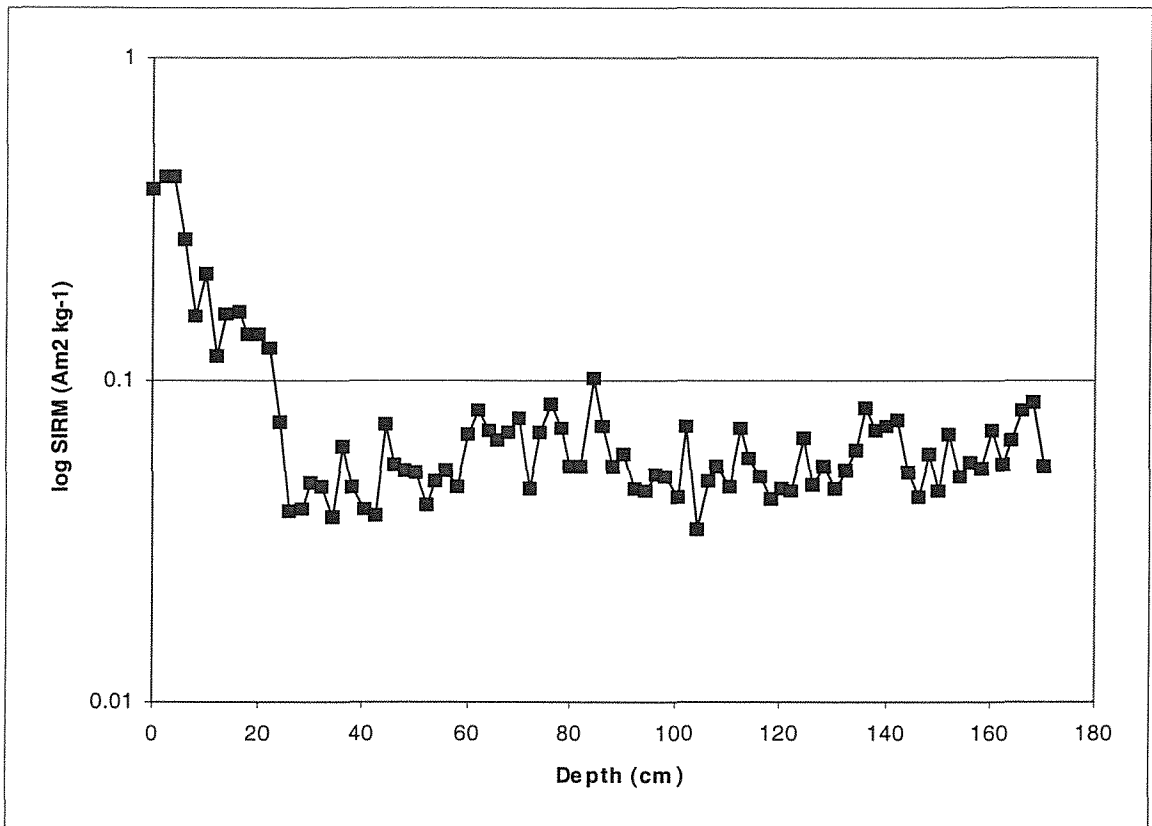
Figure 11: Magnetic and particle-size properties of Lochnagar core 28 sediment. Magnetic concentration of SIRM. The highest magnetic concentrations occur near the sediment surface.
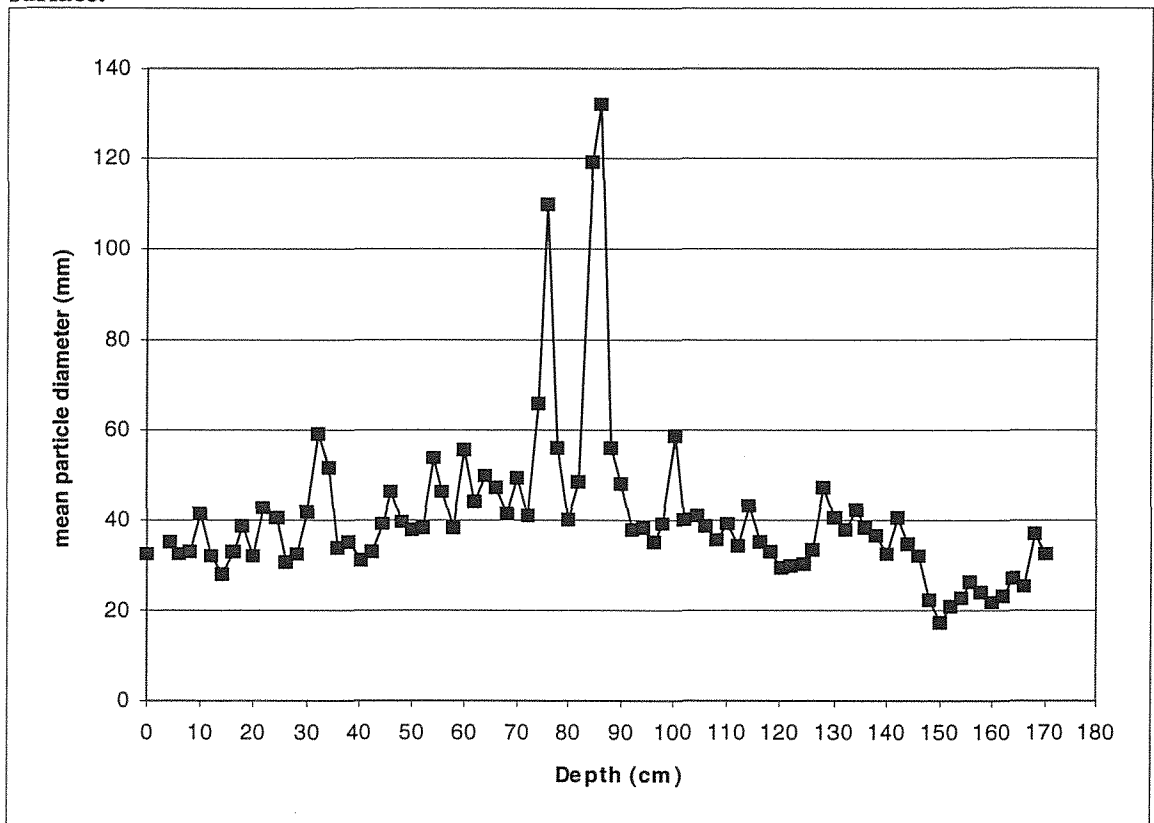
Figure 12: Particle-size properties of Lochnagar core 28 sediment. Mean particle size.

4.1.4 Sediment Geochemistry - J.A. Scott & R.P. Evershed, School of Chemistry, University of Bristol

4.1.4.1 Bulk Analyses

Total organic carbon content of the core (NAG28) varies between 1.2 and 17.6% with the lowest amount occurring between 70 and 100 cm depth (Figure 13). Nitrogen content tends to follow the trend of organic carbon (Figure 14), and indeed, both plots are similar to that for loss on ignition (Figure 8).

Carbon/nitrogen ratios show large variation in the uppermost sediment, however values below 20 cm are fairly constant with an average of about 15 (Figure 15). The sequence shows small variations in $\delta^{13}C_{TOC}$ with an amplitude of less than $3^0/_{00}$ (-26.3 to $-23.4^0/_{00}$) (Figure 16). The heaviest values occur around 80 to 100 cm and coincide with low organic carbon content.

4.1.4.2 Lipid Analyses

The distributions of n-alkanes and n-alkanols from nine and six samples (across the sequence) respectively, have been plotted as concentration of lipid (μg per gram total organic carbon) versus carbon number (Figure 17 and 18). The carbon number for the n-alkanes ranges from C_{19} to C_{33} with a maximum at C_{31}. The carbon preference index (CPI) values for C_{21} to C_{33} are in the range 8-13. The bacterial indicator, hop-17(21)-ene and the higher plant-derived triterpenoid, taraxast-20-ene, are present in the hydrocarbon fraction.

The n-alkanols do not show much variation with depth as do the n-alkanes (Figure 17). n-Alkanols range from C_{16} to C_{32} with a maximum at C_{30}, however C_{31} n-alkanol appears to be co-eluting with C_{30} 4-methyl stanol, which has been proposed as an indicator of dinoflagellate communities. Between C_{22} and C_{32}, the n-alkanols show a strong even-over-odd preference, however the concentrations of C_{17} to C_{21} alkanols are fairly similar. C_{14}, C_{16} and C_{18} mono-glycerols are also present in the alcohol fraction in low abundance.

4.1.4.3 Future Work

Samples for lipid extraction have been "bulked up" at 5 cm intervals. The remaining levels will be extracted, separated on a Bond Elut column and the fractions analysed by GC and SIM-GC-MS. Using mass spectral data for quantification assumes that the full scan peak area for any compound is proportional to it's concentration. SIM:full scan response factors are calculated by

Total Organic Carbon
%C
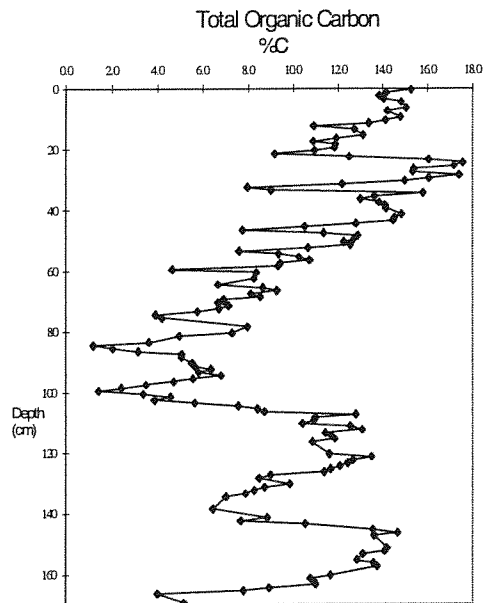
Figure 13: Total organic carbon (NAG28)

Total Nitrogen Content
%N
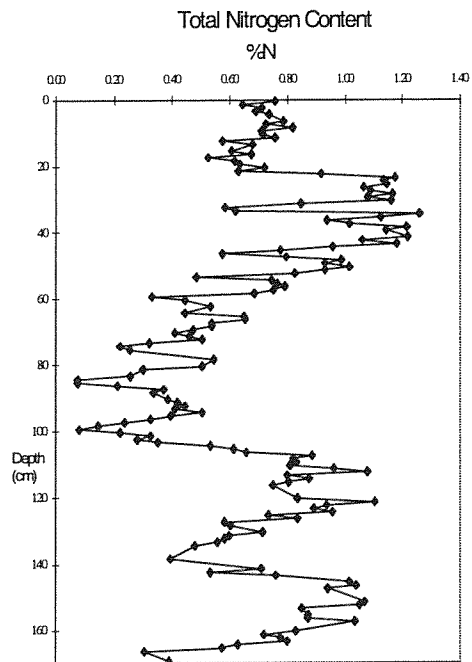
Figure 14: Total nitrogen (NAG28)

Carbon/ Nitrogen Ratio

%C:%N
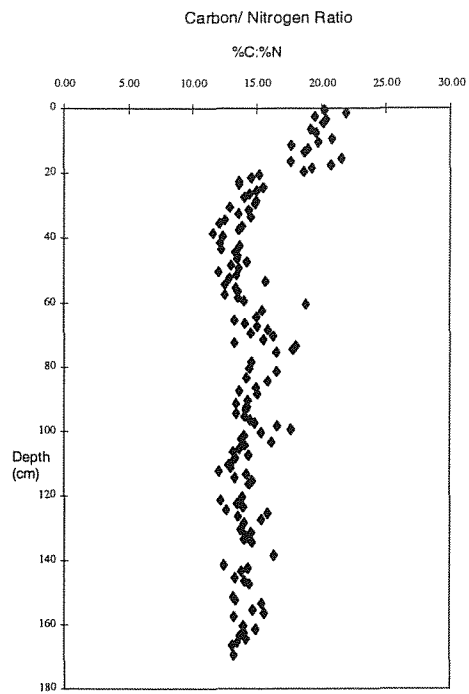
Figure 15: Carbon/nitrogen ratios (NAG28)

Bulk δ ^{13}C
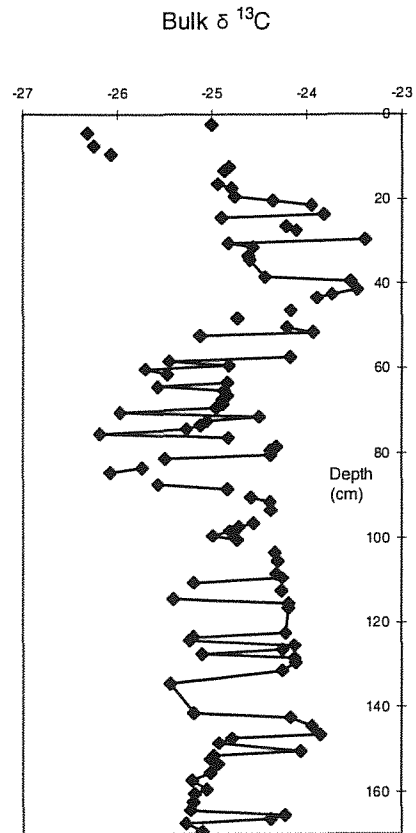
Figure 16: Bulk $\delta^{13}C_{TOC}$ (NAG28)
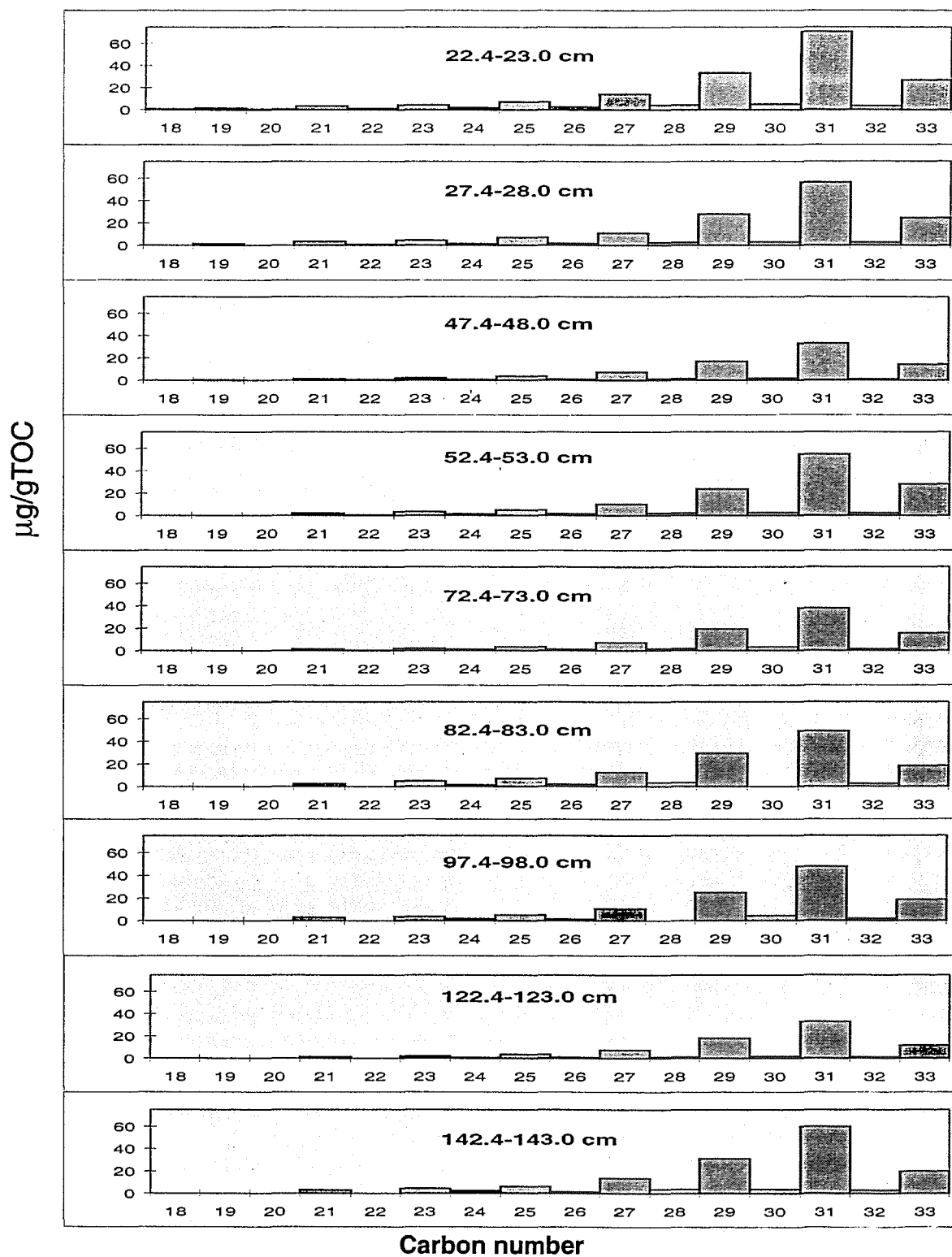
Figure 17: *n*-alkanes (NAG28)

NAG28 *n*-Alkanol Distribution
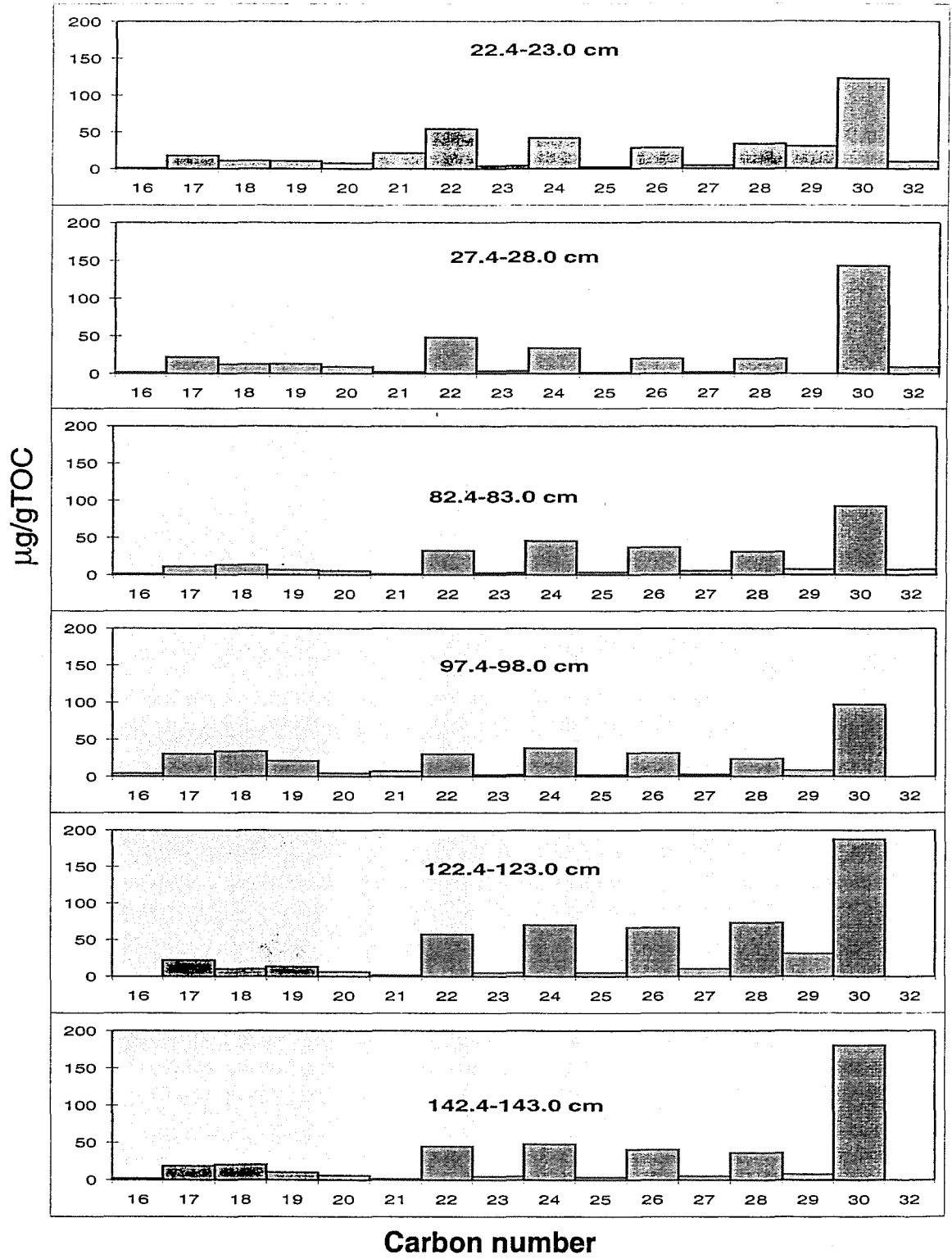
Figure 18: *n*-alkanols (NAG28)

comparing the ratio between a sample peak's area and a standard peak's area in full scan mode with the equivalent ratio in SIM mode. Concentrations and acquisition conditions must not be changed during this calibration.

Plant and peat samples have been crushed and freeze-dried: these will be extracted to determine their lipid composition and contribution to the sedimentary organic matter. Comparing the carbon isotope ratios ($\delta^{13}C$) of individual n-alkanes from the plants with those from the lake sediments will help to discriminate between the sources of the sedimentary carbon.

Determine compound specific $\delta^{13}C$ values by GC-combustion-IRMS.

Chlorin concentrations will be determined by UV/visible spectrophotometry and the compounds identified by LC-MS

4.2   Chronology

Three different methods were available to provide a sediment chronology for the Lochnagar core (NAG27). These were pollen stratigraphy, tephrachronology and AMS radiocarbon (^{14}C) dating.

4.2.1 Pollen - S.M. Peglar & H.J.B. Birks, University of Bergen, Norway

The pollen-stratigraphical data from cores NAG27 and NAG30 are plotted in Figure 19, along with the available radiocarbon dates and the pollen zonation. All stratigraphical plots were drawn using the computer program TILIA-GRAPH written by E.C. Grimm.

4.2.1.1 Numerical analyses

Principal components analysis (PCA) of the total pollen-stratigraphical data (Figure 20) shows that the stratigraphies of the two cores overlap in terms of pollen composition. In this plot of sample scores on PCA axes 1 and 2 with distance biplot scaling, samples of similar pollen composition are positioned close together, given the constraint that the plane formed by the two PCA axes captures 55.2% of the total variance in the data (axis 1 = 38.9%, axis 2 = 16.2%, axis 3 = 5.9%, axis 4 = 3.3%). There is clear overlap between samples from 93.5 - 129.5 cm in NAG30 and samples from 145.3 - 177.3 cm in NAG27. Sequence slotting of the two sequences suggests a close matching between 177.3 cm in

NAG27 and 121.5 cm in NAG30 with a psi value of sequence discordance of 1.87. These levels are marked in both cores by a decrease in *Ulmus* pollen values from 3-5% to 1%, the first occurrence of *Plantago lanceolata* pollen, and the first rise of Gramineae pollen to values of 4% or more.

Given that the uppermost 10 samples in NAG30 overlap in pollen composition with the lowest 5 or 6 samples in NAG27, these 10 samples in NAG30 were deleted in an initial optimal partitioning. They were then included in a second partitioning when the basal 6 samples of NAG27 were deleted. The resulting partitionings with the uppermost 10 NAG30 samples excluded or included and the lowermost 6 NAG27 samples included or excluded were then evaluated. In both partitionings the zonation for NAG27 and NAG30 combined was the same, but with a partition at 171.3 cm in NAG27 in analysis 1 and at 120.5 cm in NAG30 in analysis 2. Comparison with the broken-stick model suggests 4 statistically significant zone boundaries in the combined sequence with the same boundary (zone Lch-2/Lch-3) repeated in the two cores. The zonation into local pollen-assemblage zones is shown on Figures 19 and 22.

Principal components analysis of the combined data and comparison of the eigenvalues of the PCA axes with the broken-stick distribution (Legendre & Legendre 1998) indicates that only PCA axes 1 and 2 are statistically significant. These capture 55.2% of the total variance (468.9) in the pollen data. A correlation biplot (Figure 21) of all pollen and spore taxa with scores greater than $|0.4|$ on either PCA axis 1 or 2 illustrates the major correlation structure in the pollen data. A group of taxa have high positive correlations between themselves and with PCA axis 1 (e.g. Gramineae, *Plantago lanceolata, Calluna vulgaris, Carex*-type, *Vaccinium*-type, *Rumex acetosella*-type, Rubiaceae), all of which have pollen percentages increasing towards the top of NAG27. There is a group of taxa with high positive correlations between themselves and with PCA axis 2 (e.g. *Betula, Populus tremula, Salix* undiff., *Dryopteris filix-mas*-type). This group is largely uncorrelated to the previous group on PCA axis 1. *Corylus avellana, Juniperus communis* and *Ulmus* have high positive correlations between themselves and high negative correlations with PCA axis 1, whereas *Alnus glutinosa, Fraxinus excelsior* and, to a lesser extent, *Quercus* and *Pinus sylvestris* have a high internal covariance and are negatively correlated with PCA axis 2. This correlation structure summarises the major stratigraphical patterns in the pollen data (Figure 19) with taxa that increase together from the beginning of zone Lch-3 towards the present-day (e.g. *Calluna vulgaris*), widespread pollen and spore types with their highest values in zone Lch-1 (e.g. *Betula*), taxa with their maximal values in zone Lch-2 (e.g. *Pinus, Quercus*), and taxa with their highest values in zones Lch-1 and Lch-2 (e.g. *Corylus avellana*). These broad groupings of taxa based on their stratigraphical covariances also differ in their edaphic demands, shade tolerance, and abilities to withstand disturbance.

LOCHNAGAR

Pollen & spore percentages

Analysed by Sylvia M. Peglar, 1999-2000

Figure 19: Pollen diagram for Lochnagar based on cores NAG27 and NAG30. Pollen and spores included in the calculation sum are expressed as percentages of the calculation sum. Other microfossils are expressed as percentages of the calculation sum plus the relevant category. The unshaded curves are x10 exaggeration

LOCHNAGAR 27

43

LOCHNAGAR 30

% total land pollen & spores

^{14}C yrs BP

1295 ± 70
2260 ± 125
3080 ± 70
3905 ± 95
4945 ± 75
8430 ± 80

Depth (cm): 0, 25, 50, 75, 100, 125, 150, 175, 100, 125, 150

Trees & Shrubs · Dwarf Shrubs · Herbs · Pteridophytes · Alnus glutinosa · Betula · Betula/Corylus/Myrica · Carpinus betulus · Corylus avellana · Fagus sylvatica · Fraxinus excelsior · Hedera helix · Juniperus communis · Myrica gale · Picea · Pinus sylvestris · Populus · Prunus padus · Quercus · Rubus fruticosus-type · Salix · Taxus baccata · Tilia · Ulex-type · Ulmus · Viburnum opulus · cf. Sorbus aucuparia · Arctostaphylos · Calluna vulgaris · Empetrum nigrum · Erica tetralix-type · Ericaceae-type · Rubus chamaemorus · Salix herbaceo-type · Vaccinium-type · Zone

Lch-5
Lch-4
Lch-3
Lch-2
Lch-3
Lch-2
Lch-1

20 40 60 80 100   20   20   20 40   20   20   20

44

LOCHNAGAR 27

% total land pollen & spores

(c)

LOCHNAGAR 27

% total land pollen & spores

(d)

LOCHNAGAR 27

46

% total land pollen & spores (ΣP)

Σ = ΣP + Σ relevant category

Figure 20: Plot of samples from NAG27 and NAG30 on principal component analysis axes 1 and 2. The samples are joined in stratigraphical sequence. Scaling is distance biplot scaling.
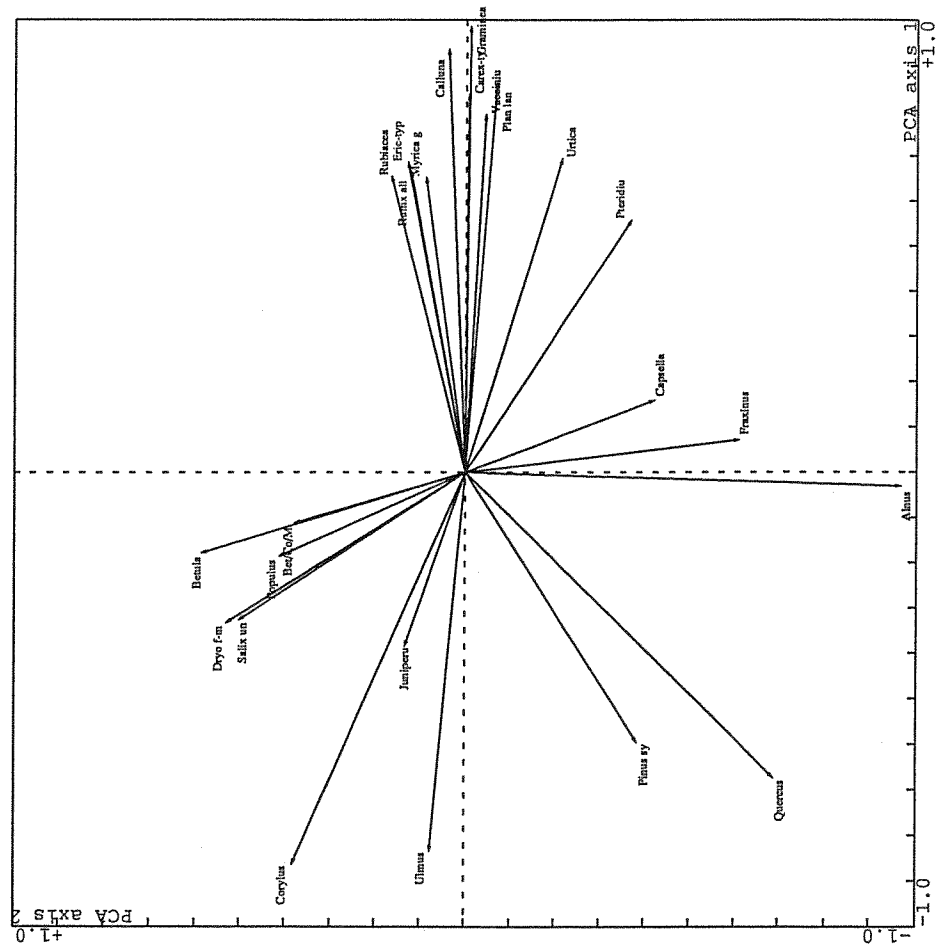
Figure 21: Plot of major pollen and spore taxa on principal component analysis axes 1 and 2. Scaling is correlation biplot scaling.

Figure 22: Plot of sample scores on principal component analysis axes 1 and 2 plotted stratigraphically. Sample scores are scaled for distance biplots and have been multiplied by x100. The scores for axis 1 have also been reflected.

The individual sample scores are plotted on Figure 22, along with the local pollen zonation. The scores are scaled to reflect the relative magnitude of PCA axes 1 and 2. PCA axis 1 (38.9%) parallels the total tree and shrub pollen curve in Figure 19 and reflects the progressive decline in tree and shrub cover in the pollen-source area of the loch over the last 8400 radiocarbon years. PCA axis 2 (16.2%), with high positive scores for taxa such as *Betula, Dryopteris filix-mas*-type, *Salix* undiff., *Populus tremula,* and *Corylus avellana* may reflect the long-term change in soil-type within the loch's catchment, from moderately fertile brown-earth soils in zone Lch-1, a change to less fertile podsols with moder or mor humus in zone Lch-2, and the development of acid podsols and shallow peat in zone Lch-3. Soil erosion, burning, and grazing during zones Lch-4 and Lch-5 may have favoured some plants of more open mineral soils with a slightly higher base-demand. The two major underlying gradients of variation in the pollen-stratigraphical data are thus a gradient of decreasing tree and shrub cover and associated change in light and shade conditions and a gradient of changing soil fertility from brown earths to podsols and shallow peat to more open soils in the last 1300 radiocarbon years.

4.2.1.2 Vegetational history

4.2.1.2.1 Botanical background

Lochnagar lies within an impressive corrie at 785 m altitude with steep, often vertical back-walls (up to 240 m high) consisting of acid granite. The corrie faces north-east and today supports a mosaic of sparse vegetation (*ca.* 60% cover) dominated by dwarf, prostrate *Calluna vulgaris* and stunted *Vaccinium myrtillus*, with some *V.vitis-idaea, V.uliginosum, Empetrum nigrum* spp. *hermaphroditum,* and *Arctostaphylos uva-ursi* on well-drained skeletal, ranker, or thin podsolic soils, alternating with areas dominated by *Scirpus cespitosus, Eriophorum vaginatum, Molinia caerulea,* and *Nardus stricta* on shallow peat. In wind-exposed areas *Loiseleuria procumbens, Juncus trifidus,* and *Carex bigelowii* are locally common. Extensive areas of stable block-scree below the cliffs support ferns such as *Athyrium distentifolium, Cryptogramma crispa, Blechnum spicant, Dryopteris assimilis,* and *D.abbreviata,* often growing with *Luzula sylvatica* and shaggy *Calluna vulgaris.* On some of the broader ledges on the cliffs, ungrazed vegetation dominated by tall herbs such as *Filipendula ulmaria, Rumex acetosa, Silene dioica, Luzula sylvatica, Trollius europaeus, Cirsium heterophyllum, Oxalis acetosella, Cochlearia officinalis, Geranium sylvaticum, Sedum rosea, Angelica sylvestris, Geum rivale, Oxyria digyna,* and *Saussurea alpina* occurs locally. *Cicerbita alpina, Saxifraga rivularis,* and *Gnaphalium norvegicum* are national rarities that occur on ledges and gullies near the Black Spout. The flora and vegetation of the corrie surrounding the loch are strongly montane in character, with affinities to the sub-alpine and low-alpine zones of western Norway today. Lochnagar lies above the known natural tree-limit in this part of Scotland today (*ca.* 650 m), although

seedlings of pine and birch can very rarely be found as high as 850 m on crags and sheltered rock outcrops and fossil stumps occur as high as 790 m in the area.

In their reconstruction of the potential vegetation of the Scottish Highlands, McVean and Ratcliffe (1962) proposed that Lochnagar itself was at or near the tree-line and that the valleys to the south and east were dominated by *Betula* to about 650 m, by *Pinus sylvestris* to about 550 m, and by *Quercus* spp. to about 400 m.

The status of *Quercus* spp. in this part of Scotland is obscure. There are several small oak woods on Deeside, for example at Craigendarroch at Ballater at *ca.* 250 - 350 m, at Crathie at *ca.* 350 m, and at Dinnet at *ca.* 200 m. These woods have tall, well-grown trees over 100 years old and although they have been coppiced, they have the appearance of being semi-natural, with a 'typical' associated flora of shrubs, dwarf-shrubs, herbs, grasses, bryophytes, and lichens.

4.2.1.2.2 Inferred vegetational history

Even though there are no trees in the catchment of the loch today, the modern pollen deposition contains about 40% tree and shrub pollen (mainly *Betula* but with surprisingly low *Pinus* values and high values of *Corylus avellana* and *Alnus glutinosa*). It is many kilometres to the nearest *Corylus* bushes. *Alnus glutinosa* occurs locally in the valleys near Lochnagar at about 300 m, for example in Deeside, Glen Esk, and Glen Clova. The modern pollen assemblage suggests that the relevant pollen-source area of the loch is very large, and much greater than the theoretic expectation based on Sugita's (1994) pollen-representation model that would predict a source area with a radius of about 500 - 800 m from the loch's margin. It seems that today (and one presumes in the past too) the relevant pollen-source area is likely to have a radius of several km. If this is correct, then interpretations of the pollen stratigraphy at Lochnagar in terms of the vegetational history of the corrie are very difficult and are largely conjectural, and are likely to be erroneous.

The lowest pollen zone (Lch-1) with a basal date of 8430 ± 80 radiocarbon years BP may reflect the local occurrence of fern-rich *Betula* and *Corylus* scrub with some *Populus tremula, Sorbus aucuparia*, and *Salix* growing on fertile brown-earth soils in or near the corrie. Tall-herbs such as *Angelica, Filipendula, Urtica*, and *Rumex acetosa* may have grown in such stands, as they do today in high-altitude birch woods in Glen Clova and on Deeside.

Pinus sylvestris and, a little later, *Alnus glutinosa* pollen values rise in Lch-2 (the age of the Lch-1/Lch-2 boundary is not yet known). These rises reflect the arrival and expansion of these trees in this

part of Scotland from about 7500 radiocarbon years BP (Birks, 1996; Bennett, 1996b). Pine certainly grew near the loch during the Holocene as pine stumps occur in eroding peat near the outflow and along the Lochnagar Burn at about 700 m. Rapson (1985) obtained a radiocarbon date of 6080 ± 50 radiocarbon years BP for a pine stump near the eastern shore of the loch. It is possible that during zone Lch-2 the corrie was lightly wooded with sub-alpine birch scrub associated with *Salix* spp., *Populus tremula, Sorbus aucuparia,* and *Juniperus communis*, abundant ferns, and some tall-herbs on the slopes and block-screes below the cliffs. Small stands of stunted pine may have occurred locally, including the peaty areas near the loch. It is unclear if *Alnus glutinosa, Quercus* spp., *Ulmus*, or *Fraxinus excelsior* grew near the loch at this time. Overall on ecological grounds it seems unlikely. These trees may have extended their altitudinal ranges by about 200 m if early- and mid-Holocene mean summer temperatures were about 1.5 - 2°C higher than today. Given such an elevational rise, their upper altitudinal limits may have been 500 - 600 m, about 200 m lower than the loch.

The zone Lch-2/Lch-3 transition is marked by the decline in *Ulmus* pollen percentages. This decline presumably reflects the widespread decrease of *Ulmus* pollen regionally that occurred throughout much of the British Isles and parts of north-west Europe between about 4800 - 5200 radiocarbon years BP.

Zones Lch-3, Lch-4, and Lch-5 show progressively increasing values of Gramineae, *Carex*-type, *Calluna vulgaris,* and *Vaccinium*-type pollen and correspondingly decreasing percentages of tree pollen, especially *Pinus, Quercus,* and *Corylus avellana*. These changes are interpreted as reflecting the progressive loss of woodland and scrub in the pollen-source area of the loch and the local and regional expansion of grassland, moorland, heath, and blanket bog, with plants such as *Arctostaphylos, Empetrum nigrum, Rubus chamaemorus, Vaccinium, Melampyrum, Narthecium ossifragum, Ranunculus acris, Rumex acetosa, R. acetosella, Urtica, Huperzia selago,* and *Sphagnum*. The increase in microscopic charcoal particles in the top 25 cm may reflect 'muir-burning' and the management of grouse moor, as the charcoal values are closely paralleled by changes in *Calluna vulgaris* pollen values.

The scattered occurrences of pollen or spores of 'alpine' and montane taxa, all of which persist today in the corrie or on the cliff ledges or in the gullies of the surrounding cliffs, indicate their persistence locally during the Holocene. These include *Huperzia selago, Lycopodium annotinum, Diphasiastrum alpinum, Cryptogramma crispa, Selaginella selaginoides, Trollius europaeus, Saxifraga oppositifolia*-type, *S.stellaris*-type, *S. cernua/S.rivularis, Sedum* (? *S.rosea), Rubus chamaemorus, Cerastium cerastioides*-type, and *Salix herbacea*-type.

The aquatic macrophyte flora of the loch today is sparse, consisting of *Isoetes lacustris* and *Juncus bulbosus* forma *fluitans*. The pollen straigraphy suggests that the macrophyte flora has been similarly impoverished throughout the Holocene, but with the former presence of *Potamogeton* (*Eupotamogeton*) (? *P.natans*), *Ranunculus trichophyllus*-type (? *R.flammula*), and *Sparganium emersum*-type (? *S.angustifolium*). *Isoetes lacustris* may have been commoner in the loch during Lch-1 and part of Lch-2, possibly because of greater water clarity, higher base-status, or warmer temperatures. Lochnagar today is one of the highest known localities for *I.lacustris* in Scotland.

4.2.1.3 Conclusions

The pollen stratigraphy of Lochnagar covers the last 8400 radiocarbon years. It has many unexpected features, nearly all of which are interpretable on the assumption that the relevant pollen-source area of the loch is about two orders of magnitude larger than the theoretical predictions of Sugita's (1994) model. Such a difference is theoretically possible if the local and extra-local pollen deposition is very low at Lochnagar. As a result regional and extra-regional pollen deposition dominates the pollen record at Lochnagar.

The major patterns of long-term change have been progressive loss of woodland cover and soil deterioration from brown-earths to podsols and shallow peat. The pollen stratigraphy, as interpreted here as reflecting primarily regional and extra-regional pollen deposition, provides no unambiguous evidence for climatic change in the Holocene.

4.2.2 ^{14}C AMS Dates

Six ^{14}C AMS dates were initially allocated under the CHILL protocol and an additional four dates were obtained to confirm the pollen inferred chronology. Table 4 lists the samples selected for dating from NAG27 and NAG30.

The samples were chosen as follows: First, three samples (median, 1st quartile, 2nd quartile) were selected from NAG27. The median sample corresponded to pollen zone Lch-4 and Chironomid zone Nag-ch2 (see sections 4.2.1 and 4.4). The second quartile sample corresponded to zone Nag-ch1 and Lch-3. The first quartile sample was altered from 44 cm to 30 cm to correspond to zone Lch-5 and Nag-ch3 (see below). Two more samples were selected from NAG27 at 55 cm and 160 cm based on changes in the diatom assemblages. Basal sample were

selected from both NAG27 and NAG30 to confirm the full age of the sequences as well as dates to confirm the expansion of *Pinus*, the expansion of *Alnus* and the decline of *Ulmus* in NAG30.

Table 4: Lochnagar bulk sediment samples sent for ^{14}C AMS dates

Sample No.	Core	Sample Interval (cm)	Notes
1.	NAG27	29.6 - 30.0	
2.	NAG27	55.0 - 55.4	
3.	NAG27	88.6 - 89.0	Median sample
4.	NAG27	133.2 - 133.6	2nd Quartile sample
5.	NAG27	160.0 - 160.4	
6.	NAG27	176.0 - 176.6	Basal sample
1.	NAG30	119.0 - 120.0	
2.	NAG30	131.0 - 132.0	
3.	NAG30	143.0 - 144.0	
4.	NAG30	154.0 - 155.0	Basal sample

Table 5: Dating results (Dating Laboratory University Of Helsinki)

Lab. no.	Sample	$\delta^{13}C$	AGE (BP)
Hela-398	NAG27, 29.6 - 30.0 cm	-26.2	1295 ± 70
Hela-399	NAG27, 55.0 - 55.4 cm	-26.6	2260 ± 125
Hela-400	NAG27, 88.6 - 89.0 cm	-27.2	3080 ± 70
Hela-401	NAG27, 133.2 - 133.6 cm	-26.7	3905 ± 95
Hela-402	NAG27, 160.0 - 160.4 cm	-26.6	4945 ± 75
Hela-415	NAG27, 176.0 - 176.6 cm	-26.5	5495 ± 75
Hela-414	NAG30, 119.0 - 120.0 cm	-26.1	5105 ± 120
Hela-413	NAG30, 131.0 - 132.0 cm	-26.6	6375 ± 70
Hela-414	NAG30, 143.0 - 144.0 cm	-27.1	8105 ± 80
Hela-403	NAG30, 154.0 - 155.0 cm	-27.2	8430 ± 80

Table 6: Sediment accumulation rates derived from ^{14}C AMS radiocarbon dates (NAG27)

Time Period Yrs BP	Depth (cm)	No. of Years	Rate of Sediment accumulation cm yr^{-1}	Rate of Sediment accumulation yr cm^{-1}
5495-4945	16.2	550	0.029	33.95
4945-3905	26.8	1040	0.026	38.81
3905-3080	44.6	825	0.054	18.50
3080-2260	33.6	820	0.041	24.40
2260-1295	25.4	965	0.026	37.99
1295-0	30.0	1295	0.023	43.17

The six ^{14}C AMS dates reveal a c. 5,500 year chronology for Lochnagar in NAG27 and an older basal sediment date of c. 8,500 years for NAG30 (Table 5). The chronology for NAG27 has a small average age error of approximately 85 years. These results confirm the estimated dates based on pollen analysis. The expansion of *Pinus* starts at c. 8,100 yrs BP, expansion of *Alnus* at c. 6,400 yrs BP while the *Ulmus* decline is AMS dated at c. 5,100 yrs BP.

Uncalibrated ^{14}C AMS radiocarbon years BP are used to calculate sediment accumulation rates for NAG27 (Table 6). Linear extrapolation is used to interpolate ages between dates and extrapolate to the top and bottom of the sediment core in TILIA (Grimm, 1991). This constrains interpretation for intervening levels and determination of changes does not account for deviations in accumulation rate. The age-depth profile (Figure 23) for Lochnagar (NAG27) is consistent with a slow sedimentation rate throughout the sequence. The average accumulation rate is approximately 0.033 cm yr^{-1} (or 32.8 yr cm^{-1}). Fastest sediment accumulation rates are found around 4000 yrs BP with declining rates in sediments post 3000 yrs BP.
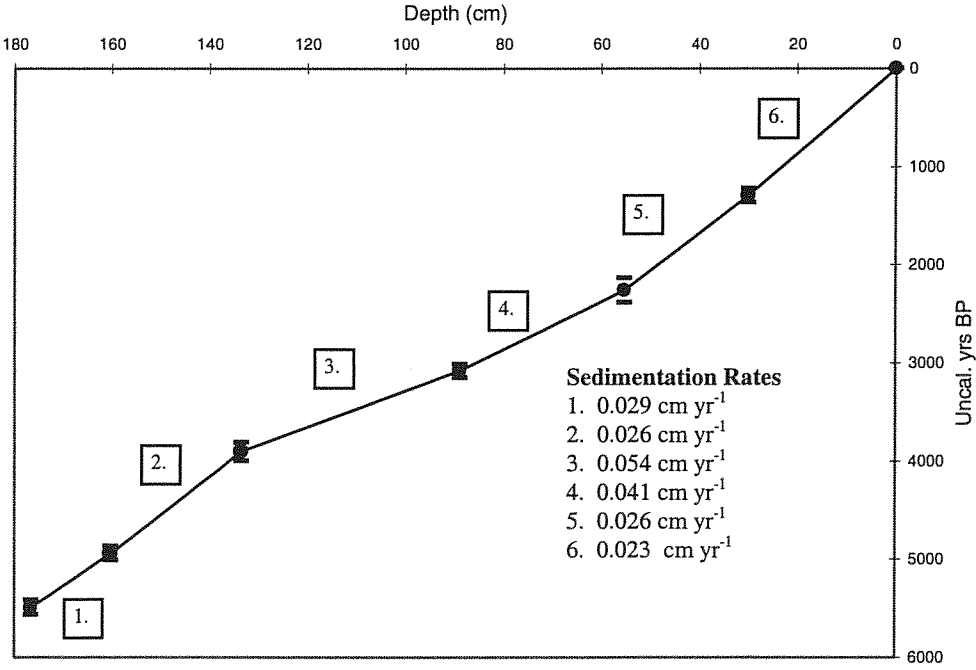
Figure 23: Composite age/depth curve for Lochnagar (NAG27)

4.2.3   Tephra - C.Dalton & N. Cameron, University College

Tephra shards still to be counted for NAG27.

A total of 221 diatom species were identified in 185 samples selected from the Lochnagar core. Diatom counts were transformed to percentages and taxa with a maximum occurrence of less than 1% and not found in more than two samples were eliminated using TRAN (Juggins, 1994). This reduced the working data-set to 102 taxa. A summary diatom diagram is presented in Figure 24.

The number of diatom taxa found in each sample typically varies between 22 and 44, and the sample heterogeneity (Hill's diversity index - N2 (Hill, 1973)) for different core depths ranges from 20-40 through the core (Figure 25). A polynomial trend line (order 6) has been added (Figure 25). Generally the pattern of taxa numbers reflects sample heterogeneity through the core, with declines in both in the top 20 cm.   High levels of sample heterogeneity are maintained throughout the majority of the core (average N2 = 34). The diversity declines slightly for the most recent sediments (average N2 = 28).

Diatom analysis of the Lochnagar NAG27 core reveals multiple floristic changes (Figure 24). *Achnanthes scotica, Tabellaria flocculosa, Achnanthes detha* are present throughout the sequence with fluctuating levels. Species such as *Fragilaria vaucheriae, Aulacoseira lirata* var *alpigena, Navicula schassmannii, Navicula seminuloides* are also present throughout most of the core but are absent in the top 10 cm. These species declines are paralleled with increases in *Achnanthes marginulata, A. [marginulata] f. major* and *Eunotia incisa*. Other changes of note include high levels of *Fragilaria virescens* var *exigua* between 150 and 30 cm, and notable expansions of *Eunotia pectinalis* var *undulata* and declines in *A. [marginulata] f. major* above 90 cm.

4.3.1 Floristic Zones

The fossil assemblages were zoned stratigraphically using the programme ZONE. Multiple zonation methods are used to identify major zones common to all programmes. From comparison of the results six zones were identified in the fossil diatom data.

Zone 1 (176-154 cm)

Zone 1 reflects high levels of *Tabellaria flocculosa, Achnanthes detha, Fragilaria vaucheriae, Navicula schassmannii*. This zone is also characterised by low levels of *Fragilaria virescens* var *exigua*, and increases in *Aulacoseira distans* var *nivalis* and *Fragilaria virescens*.

Zone 2 (153-93 cm)

Zone 2 is delineated with high levels of *Fragilaria virescens* var *exigua* and *Aulacoseira perglabra*.

Zone 3 (92-46 cm)

Zone 3 differs from zone 2 with declines in *Aulacoseira lirata* var *alpigena, A. distans* var *nivalis, Navicula schassmannii, Fragilaria capucina* var *gracilis* and large expansions in *Eunotia pectinalis* var *undulata, A. [marginulata] f. major*.

Zone 4 (45-28 cm)

Zone 4 reflects a decline in *Fragilaria virescens* var *exigua, Aulacoseira lirata* var *alpigena, Navicula schassmannii* and increases in *Achnanthes marginulata, A. minutissima* var *scotica*.

Zone 5 (27-10 cm)

Zone 5 is delineated with major expansions in *Achnanthes [marginulata] f. major, A. marginulata, Eunotia incisa* and *Navicula krasskei, Fragilaria vaucheriae* while declines are apparent in *Fragilaria virescens* var *exigua*.

Zone 6 (9-0 cm)

The uppermost zone (6) is characterised by the virtual disappearance of *Fragilaria vaucheriae, Aulacoseira lirata* var *alpigena, Navicula schassmannii, Navicula seminuloides, Navicula cocconeiformis* and *major increases* in *Achnanthes marginulata* spp. and *Eunotia incisa*.

The floristic changes described in zones 1-5 are not reflected in changes in the diversity index (N2). However, between zone 5 and 6 the sharp decline in N2 is clearly a reflection of the notable declines in important species including *Fragilaria virescens* var *exigua, F. vaucheriae, Aulacoseira lirata* var *alpigena, Navicula schassmannii, Navicula seminuloides* and *Navicula cocconeiformis*.

Figure 24: Summary Diatom profile (NAG27)
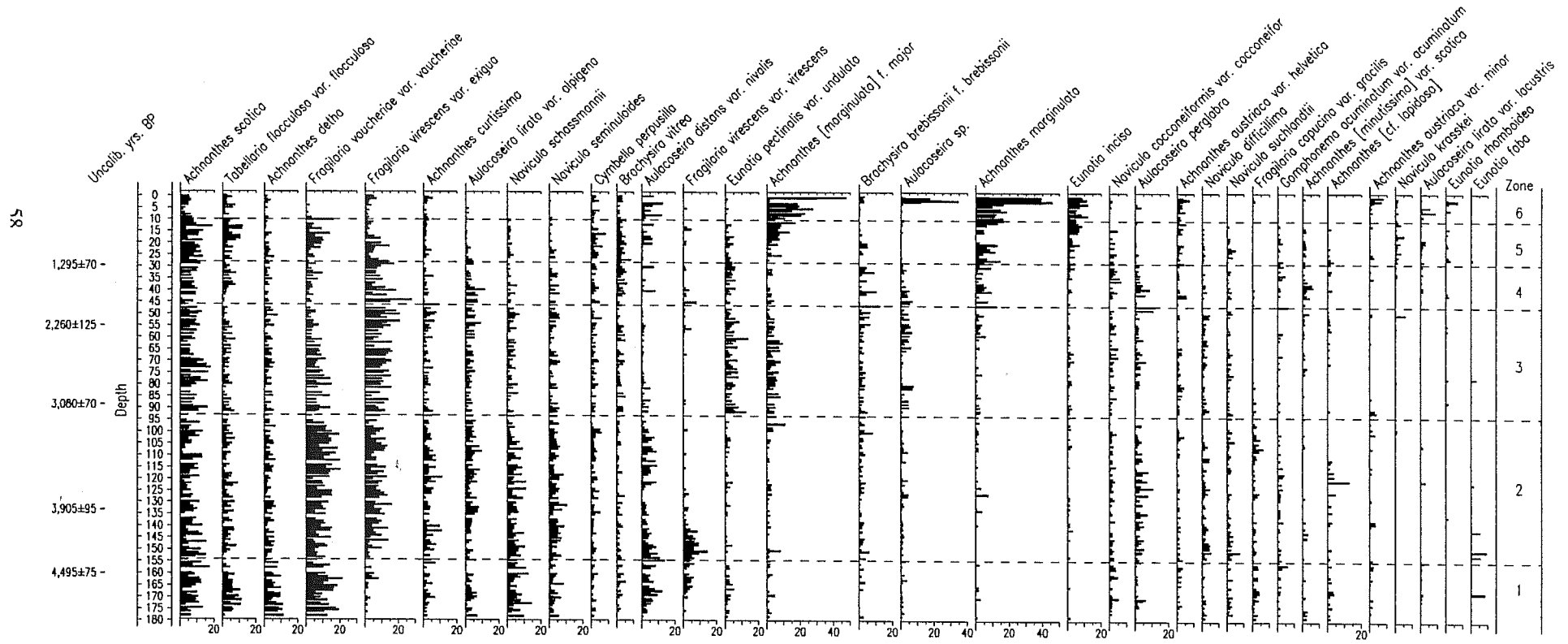
4.3.2 Diatom Concentrations

Diatom concentrations for NAG27 were calculated using the microsphere method (Battarbee & Keen, 1982). The concentration of diatom valves per gram of wet sediment is illustrated in Figure 25. Valve concentrations are variable up the core profile. Concentrations are highest at the base of the core with peaks of up to 30×10^8 valves g WS^{-1}). A polynomial trendline (order 6) indicates an average valve concentration maximum of 21×10^8 valves g WS^{-1} at approximately 140 cm. Above 140 cm the valve concentrations decline steadily toward the top of the core. Valve concentrations are maintained around 10×10^8 valves g WS^{-1} between 80-40 cm and decline again toward the top of the core. Highest diatom concentrations are found in zone 2 but these decline at the top of the zone. Zone 3 and half of zone 4 corresponds to the period of steady valve concentrations while zone 5 and 6 have the lowest concentrations of the core. The diatom concentration profile is not reflected closely in the profile of any one species.

4.3.3 Diatom Accumulation Rates

Diatom valve concentrations are only indirect proxies for diatom productivity as sediment accumulation rates will not be constant. In order to correct for sediment accumulation rates diatom accumulation rates (DAR cm^{-2} $year^{-1}$) were calculated by multiplying the wet mass accumulation rate (cm^{-2} $year^{-1}$) and the diatom concentration (cells g wet wt^{-1}). The DAR profile (Figure 25) is similar to the diatom concentration profile with higher rates at the base of the core and declines toward the top. The DAR rates are highest, suggesting greatest diatom productivity, for the period of highest sediment accumulation in zone 2.

4.3.4 Ordination Analysis

Ordination analysis is used to illustrate the floristic signal in the core by reducing the species variation to a few ordination axes. Changes in ordination sample scores represent variation in species assemblages with depth and thus through time. Ordination of the fossil diatom assemblages using detrended correspondence analysis (DCA) gave an axis 1 and axis 2 gradient of 2.4 and 2.3 SD units respectively, so the data were subjected to unimodal ordination analysis (DCA) (Table 7). The DCA biplot of axes 1 and 2 is represented in Figure 26. Zone 6 (10-0 cm) has the most dissimilar assemblages while zones 5-1 have many species in common. DCA axis scores are also represented as TILIAGRAPH profiles in Figure 27. DCA axis 1 captures 17.3 % of the variation in the diatom assemblages while axis 2 adds just an additional 3.6%. This highlights the dominance of the first ordination gradient (possibly a pH gradient) in the fossil diatom data.
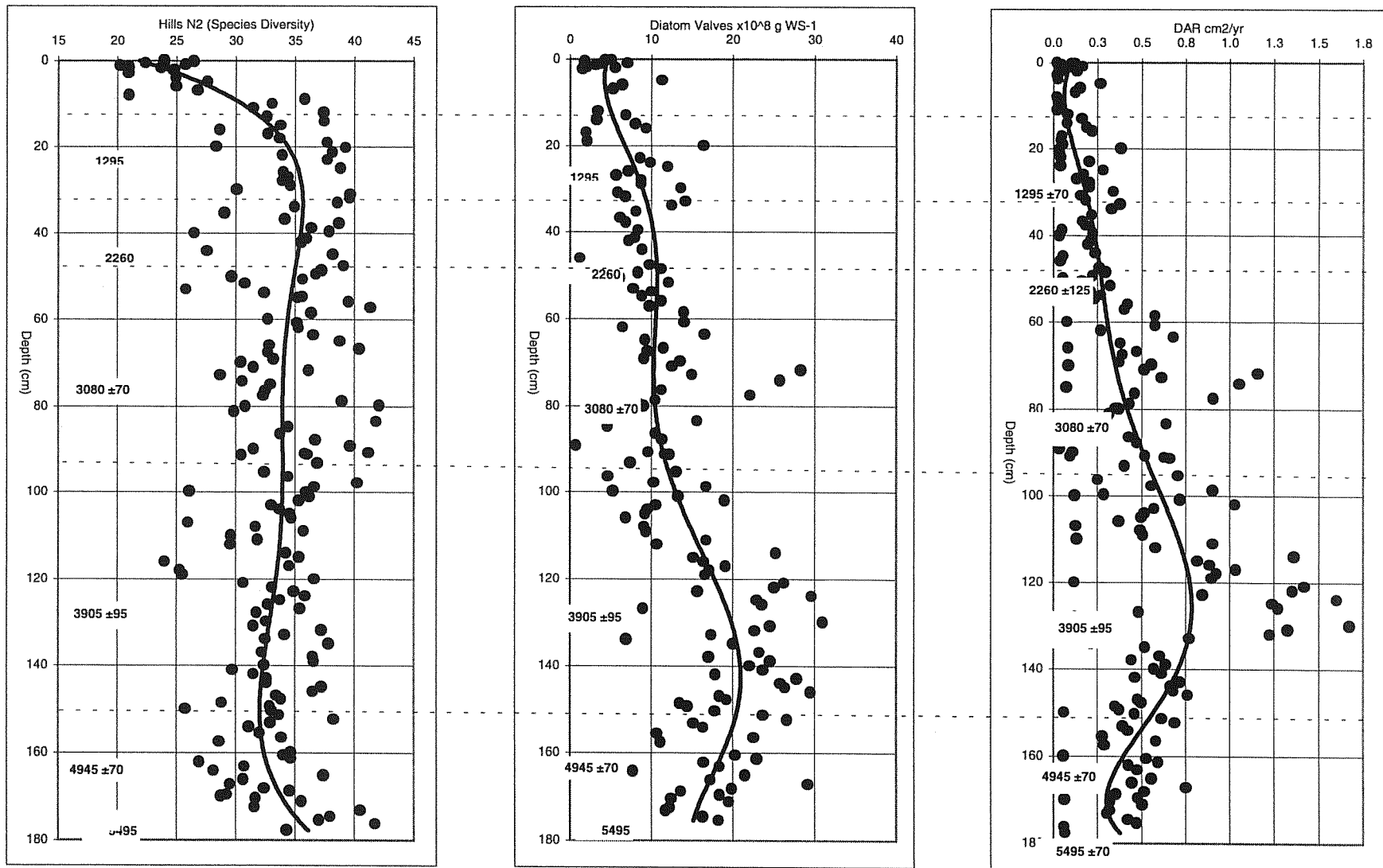
Figure 25: Hills diversity Index (N2), Diatom valve concentrations (valves g WS^{-1}) and Diatom accumulation rates (DAR cm^{-2} year^{-1}) (NAG27)
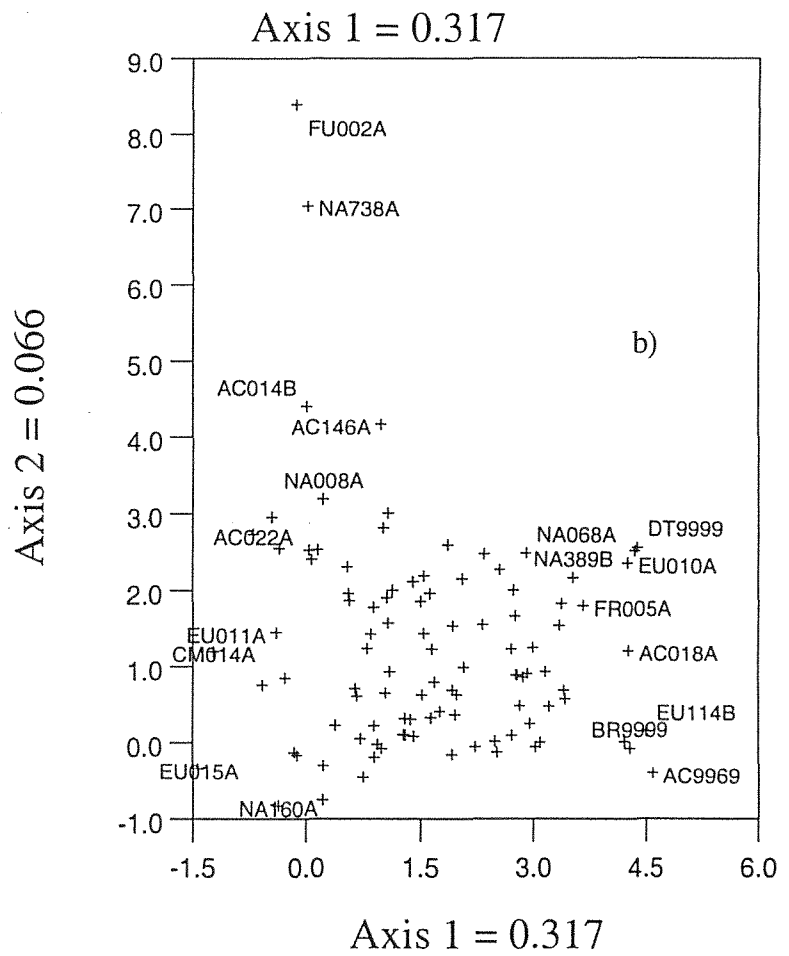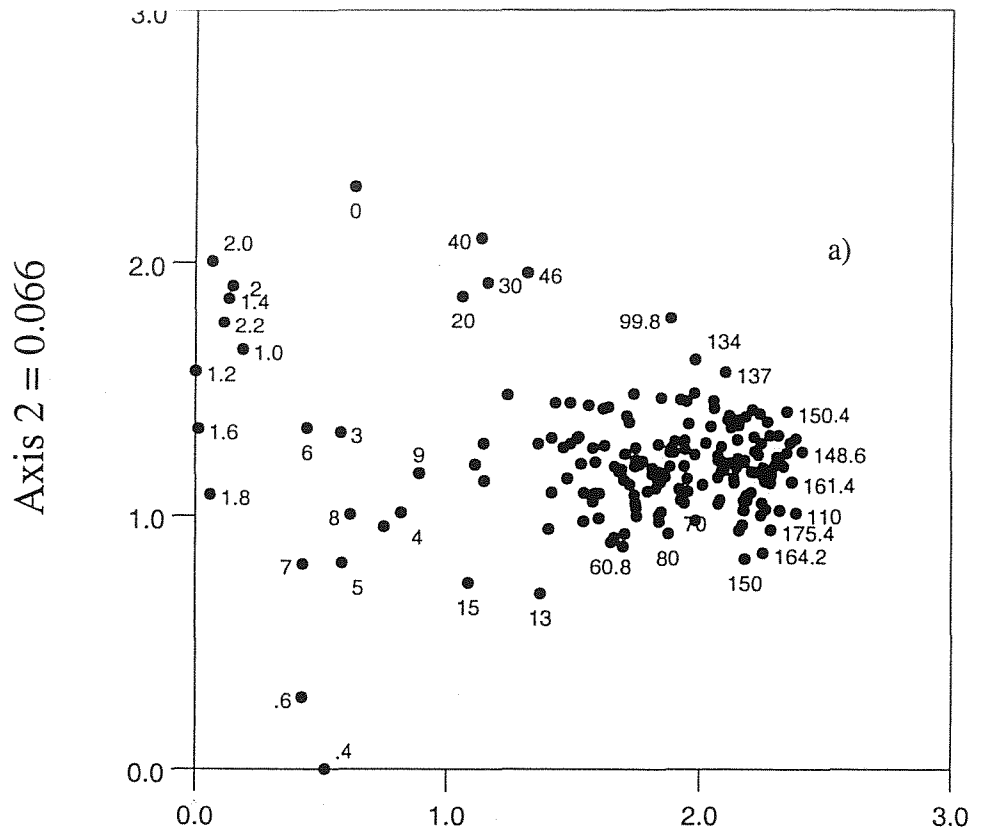
Figure 26: DCA biplot of axes 1 and 2 a) sediment samples, b) species (NAG27)

61
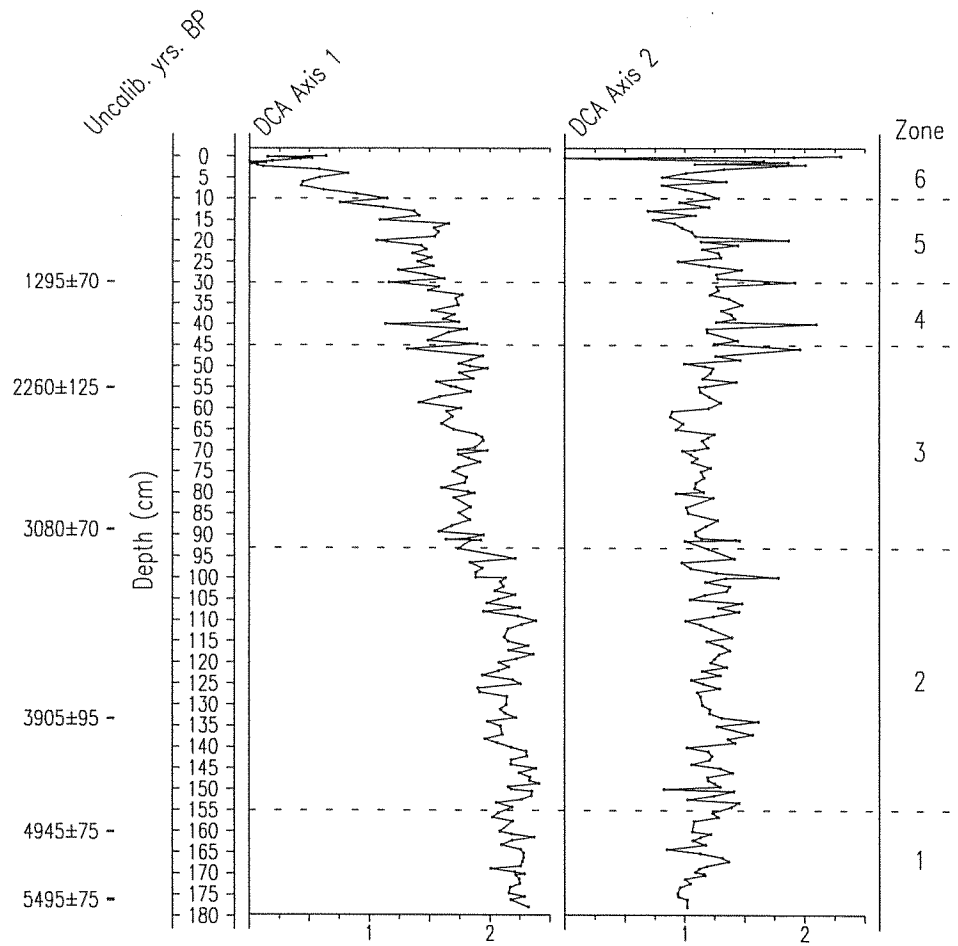
Figure 27: DCA axis scores 1 & 2 for NAG27 represented as TILIAGRAPH profiles

Table 7: Summary statistics for DCA of NAG27 fossil diatom data (n = 185 samples)

Axes	1	2	3	4	Total inertia
Eigenvalues	0.317	0.066	0.055	0.049	1.834
Lengths of gradient	2.408	2.301	1.485	1.462	
Cumulative percentage variance of species data	17.3	20.9	23.9	26.6	
Sum of all unconstrained eigenvalues					1.834

4.3.5 pH Reconstruction

The WA-PLS diatom-pH transfer function derived for the AL:PE training set (Cameron *et al.,* 1999) was applied to the fossil assemblages from the Lochnagar core (NAG27) using WA-PLS Version 1.1 (Juggins & ter Braak, 1996). Inferences for historical pH were obtained by adding core fossil diatom counts from different sediment depths as passive samples to the AL:PE surface sediment calibration samples using the WA-PLS (2) model. The WA-PLS model with two components has an r^2 of 0.80 and RMSEP of 0.34. The optimal number of WA-PLS components to use is based on RMSEP. The modelled relationship between diatoms and pH was used to infer pH levels for the fossil assemblages at different depths in the core. The diatom-pH reconstruction (with polynomial trendline) is illustrated in Figure 28. Jack-knifed inferred pH for each core sample and their error terms (as determined from the RMSEP of the training-set) are presented in Appendix 1.

Diatom inferred pH for the fossil samples gives a fluctuating range between 5.5 and 6.6 throughout the history of the core (Figure 28). Zone 1, pre 5,000 yrs BP, was a period of increasing diatom-inferred pH ranging from a basal-low of 6.2. Zone 1 has an average diatom-inferred pH of 6.2/6.3. Increasing inferred pH levels at the top of zone 1 reflect increases in *Aulacoseira distans* var *nivalis* and *Fragilaria virescens*. Inferred pH estimates for zone 2 are the highest for the core (approximately 6.6 pH units) and reflect the presence of high levels of *Fragilaria virescens* var *exigua* and *Aulacoseira perglabra*. This period of high pH is AMS dated to 4,000 yrs BP. Diatom-inferred pH values decline at the top of zone 2 in response to declines in *Aulacoseira distans* var *nivalis, A. perglabra* and *Navicula schassmannii.* Zone 3 reflects steady levels in diatom inferred pH around 6.2/6.3. Sharp pH declines from c. 6.2 to 5.7 are apparent above 40 cm (c. 1,500 yrs BP). At no other point in the core is there such an obvious change in diatom-reconstructed pH. This earlier than expected pH decline may be an artefact of data smoothing and dating error. This decrease of diatom-inferred pH is associated with decreases in *Fragilaria virescens* var *exigua, Eunotia pectinalis* var *undulata, Aulacoseira*
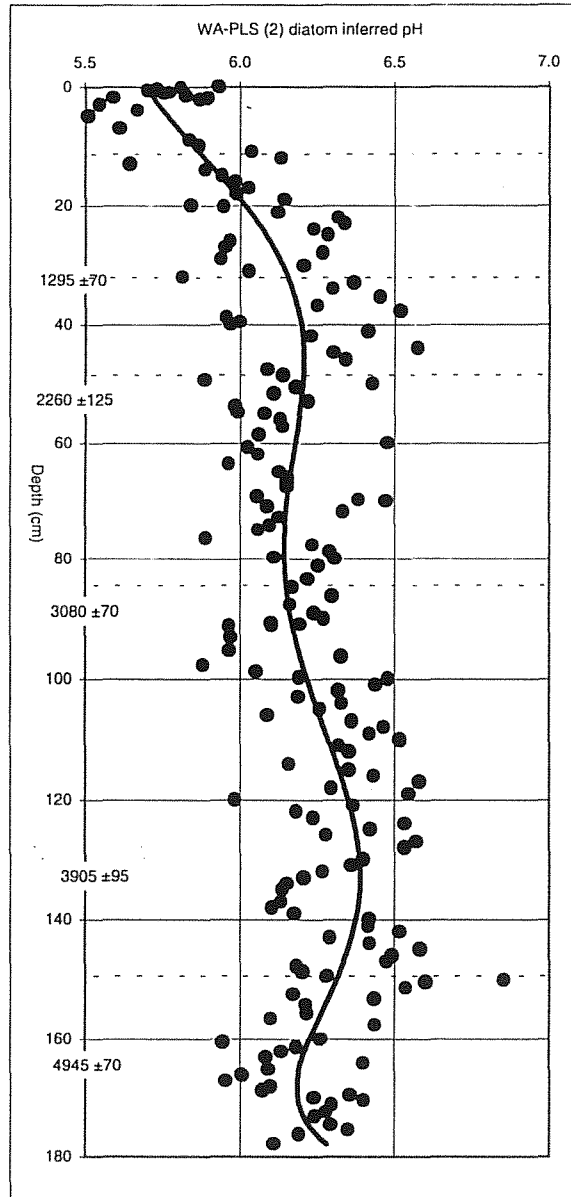
Figure 28: Diatom-inferred pH for NAG27 using the AL:PE WA-PLS(2) model

lirata var *alpigena, Navicula schassmannii* and increases in *Achnanthes marginulata, A. minutissima* var *scotica.* Major increases in acidophilous taxa in the most recent sediments correspond to other studies showing a reduction in pH in the last few hundred years.

In summary, pre-industrialisation diatom analyses show shifts in assemblages that may correspond to cold/warm phases. A more productive phase is indicated around 4,000 yrs BP with highest diatom concentrations and diatom accumulation rates. This is also reflected in high levels of diatom inferred pH. In contrast, the diatom reconstructed pH for Lochan Uaine is very low around this time, sediment Ca values are high and a tephra peak is apparent. Large declines species diversity and in diatom inferred pH are evident in the last 1,500 years.

4.3.6 Further Work

Diatom counts from NAG30

Integration of NAG27 and NAG30 diatom records.

4. 4   Chironomidae analysis - S. Brooks, Department of Entomology, The Natural History Museum

Samples were taken at 4 cm intervals since this resolution was considered sufficient to pick up major trends. From NAG28, 44 samples were received via UCL in May 1999, and a further 14 samples from core NAG30 in February 2000. To date, chironomid analysis has been completed on 41 samples from NAG28. Sampling resolution can be increased to focus on critical depths if sufficient resources are available following completion of coarse resolution analysis. Four grams of wet sediment were necessary to provide enough material and samples were therefore bulked over 1 cm.

Chironomid head capsules were in good condition and abundant in NAG28. Preliminary results from 41 samples are presented in Figure 29. Four stratigraphic zones were identified using CONISS to group the chironomid taxa.

Zone NAG-ch1 (170-156 cm)

This zone has a low abundance of *Dicrotendipes, Microtendipes* and *Heterotrissocladius marcidus*, however, an ecological interpretation is difficult since the zone appears to be truncated

and comprises just the four lowest samples of the core. Once more results are available from core NAG30 the characteristics of the zone might become more apparent.

Zone NAG-ch2 (156-98 cm)

This zone is characterised by high concentrations of *Microtendipes* and *Dicrotendipes*. The presence of these taxa suggests prevailing temperate climatic conditions.

Zone NAG-ch3 (98-30 cm)

This zone is delineated by declines in *Microtendipes* and *Dicrotendipes* and increased abundance of *Zavrelia, Protanypus, Psectrocladius septentrionalis*-group and *Stictochironomus*. This suggests that the climate was probably cooler than in the previous zone.

Zone NAG-ch4 (30-0 cm)

This zone is marked by declines in *Microtendipes, Mesopsectrocladius, Procladius, Micropsectra insignilobus*-group and increases in *Heterotrissocladius grimshawi, Psectrocladius sordidellus*-group, *Corynoneura scutellata*-group, *Ablabesmyia*, and *Heterotrissocladius marcidus*. These faunal changes suggest a response to natural acidification of the catchment. The increase in *Sergentia, Heterotanytarsus apicalis, Heterotrissocladius marcidus* and *Psectrocladius sordidellus*-group in the uppermost sample may be in response to post-industrial acidification.

The chironomid stratigraphy shows similar zonation to the pollen data (see Figure 19).

4.4.1 Further Work

The 18 remaining samples in NAG28 and NAG30 will be counted by the end of June 2000. If resources permit, further samples at 1 cm resolution will also be counted to establish the precise position of zone boundaries and allow rates of change to be compared with other proxies.

In summary, major changes in the chironomid stratigraphy coincide with the pollen zones. A response to temperature change moving from warm to cool is indicated in zones NAG ch1-2. NAG ch3 reflects a response to acidification following catchment changes. In zone NAG ch4 a response to post-industrial acidification is detectable. Pre-industrialisation diatom analyses show no major shifts in assemblages, however, variation in diatom species composition may correspond to cold/warm phases.
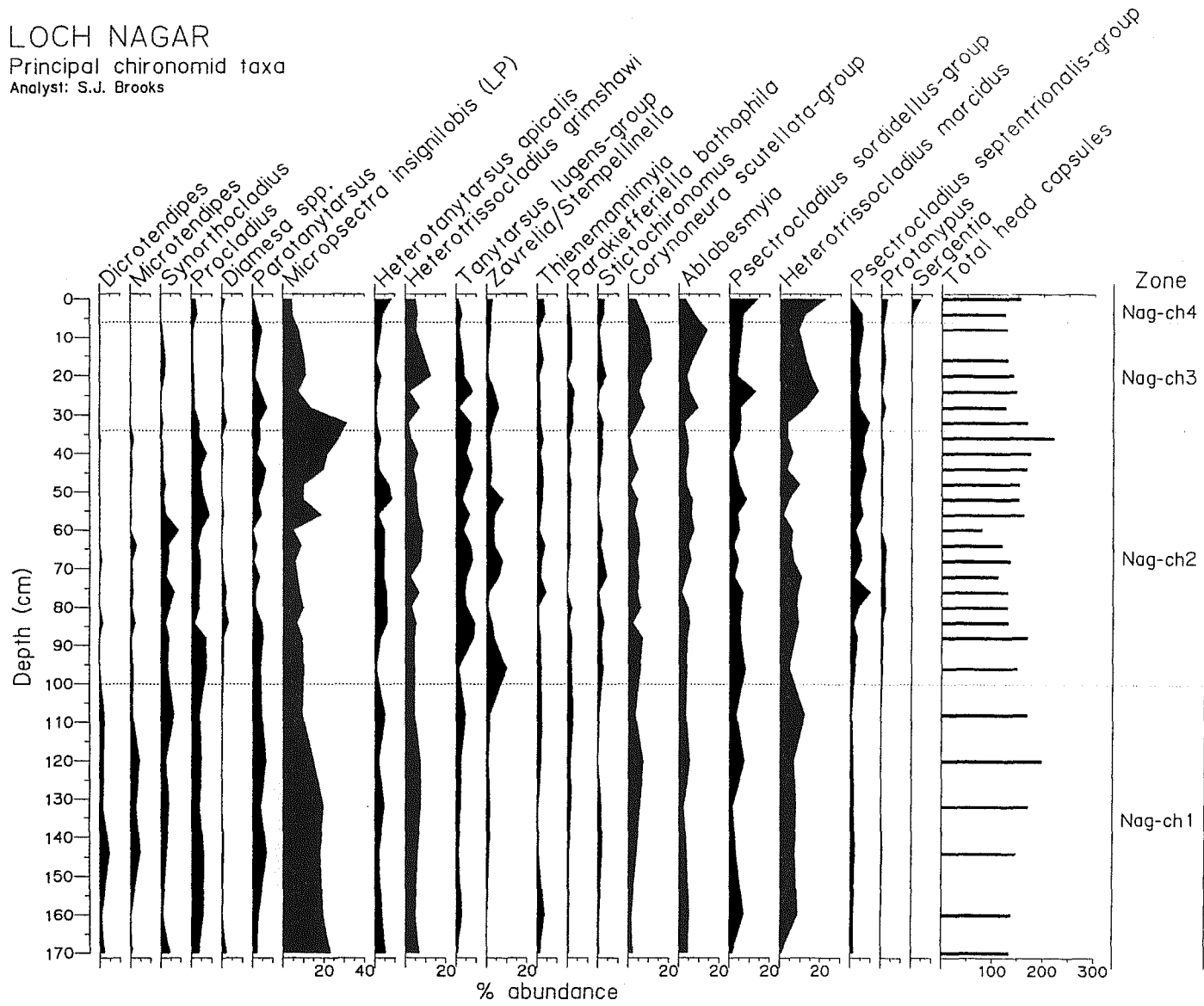
Figure 29: Chironomid profile for NAG28

## 5.	Preliminary Discussion

A preliminary discussion of the results to date is contained in this section. This discussion is based on the three biological proxies and the sediment lithology for NAG27 only and represents approximately 5,500 radiocarbon years. Zonation of the biological data revels three main areas of environmental change common to all palaelimnological signals. The zones coincide approximately with 176-100 cm (c 5,500-3,000 yrs BP), 100-30 cm (c. 3,000-1,300 yrs BP) and 30-0 cm (c. 1,300-present day).

5.1 176-100 cm (c. 5,500-3,000 yrs BP)

This first period represents pollen zone Lch-3, diatom zones 1 and 2 and chironomid zone NAG-ch1.

Shortly after the base of NAG27 elm declines. Rises in Gramineae, *Urtica, Plantago lanceolata* and other herbs indicate human influence. Increasing Ericaceous dwarf shrubs including *Calluna* and *Vaccinium* and a decrease in woodland indicate the development of grassland and heath with some grazing.

The diatom assemblages for this part of the core have high levels of *Tabellaria flocculosa, Achnanthes detha, Fragilaria vaucheriae, Navicula schassmannii.* This is followed subsequently by increases in more circumneutral taxa *Fragilaria virescens* var *exigua* and *Aulacoseira perglabra.* A fluctuating trend in diatom inferred pH is notable for this period, starting at levels of 6.2 rising by almost 0.5 pH units and then falling again to original levels. This high diatom inferred pH coincides with highest diatom valve concentration and diatom accumulation rates suggesting higher lake productivity for the period. The high pH levels appear to be associated with declines in *Fragilaria virescens* and *Aulacoseira distans* var *nivalis* rather than increases in more alkaliphilous species. What is uncertain at this point is whether this maximum in inferred pH is representative of warmer climate conditions c. 4,000 yrs BP. The answer to this question will be clarified with further analysis of temperature proxy data.

The results of chironomid analyses show low abundance of chironomidae *Dicrotendipes, Microtendipes* and *Heterotrissocladius marcidus* for this period. The presence of these taxa suggests prevailing warm temperate climatic conditions and thus supports a link between higher diatom inferred pH and warmer temperatures.

The core sediment lithology for this period shows three major peaks and three toughs in organic matter with periodicities based on approximately 1,000 year cycles. However, there is no evidence for systematic variation in the biological proxies or inferred pH linked to peaks and troughs in DW and LOI. The period of high diatom-inferred pH (and possibly warmer temperature) c. 4,000 yrs BP corresponds to a trough in organic matter and a peak in dry weight. This may be coincidental or result from a minerogenic inwash from the catchment. A positive relationship between warmer conditions and increases in organic matter could be explained by longer growing seasons. In contrast, results from other lakes (Monteith unpublished) and Lochan Uaine suggest that lake productivity may be enhanced by colder rather than warmer conditions. No direct link with Holocene climate change can be inferred at this point.

Nitrogen and organic carbon content tends to follow the trend of that for loss on ignition. Carbon/nitrogen ratios are constant for the period with an average of about 15. The sequence shows small variations in $\delta^{13}C_{TOC}$ with an amplitude of less than $3^0/_{00}$ (-26.3 to $-23.4^0/_{00}$).

5.2 100-30 cm (c. 3,000-1,300 yrs BP)

The second period represents pollen zone Lch-4/Lch-3, diatom zones 3 and 4 and chironomid zone NAG-ch 2.

Further increases in herbs, dwarf shrubs and *Pteridium* in conjunction with decreases in land pollen and spores of tree and shrub taxa to less than 50% of total land pollen and spores - indicate loss of woodland and scrub and local and regional expansion of grassland, moorland and blanket bog. Peat is local at high altitudes today in the Cairngorms (max. elevation c. 1,000 m) and many are extensively eroded.

Changes in diatoms include declines in *Aulacoseira lirata* var *alpigena*, *Fragilaria capucina* var *gracilis* and large expansions in *Eunotia pectinalis* var *undulata* and *A. [marginulata] f. major*. Towards the top of this section there is also a decline in *Fragilaria virescens* var *exigua* and *Aulacoseira lirata* var *alpigena*. However, a period of steady diatom inferred pH levels is indicated for this period. Diatom accumulation rates decline but diatom concentrations are maintained.

The chironomidae profile is delineated by declines in *Microtendipes* and *Dicrotendipes* and increased abundance of *Zavrelia, Protanypus, Psectrocladius septentrionalis*-group and *Stictochironomus*. This suggests that the climate was probably cooler than in the previous zone. A response to temperature change moving from warm to cool is indicated in chironomid zones 1-2.

Highest levels of dry matter, coincident with the lowest levels of organic matter suggest a major catchment minerogenic input around 3,000 yrs BP. The heaviest $\delta^{13}C_{TOC}$ values occur around 80 to 100 cm and coincide with low organic carbon content. Once again these major lithological changes are not reflected in the biological proxy data or in diatom-inferred pH levels. No links between diatom proxy signals sedimentological proxies were found for Lochan Uaine (Barber *et al.*, 1999). Declines in diatom valve concentrations and accumulation rates are apparent but these do not recover with increases in organic input for the remainder of the sequence. This major peak in DW probably represents the first effects of anthropogenic disturbance (deforestation) in the catchment. The increase in organic matter post-3,000 yrs BP and increase in the frequency of oscillations (with approximately 10 peaks in organic matter) coincides with paludification of soils and local and regional development of blanket peat. The question that needs to be clarified is if these oscillations are associated with catchment disturbance or with climate induced periodicities. The evidence to date provides no unambiguous support for either of these hypotheses.

5.3 30-0 cm (c. 1,300-present day)

The final period of major environmental change is represented by pollen zones Lch-5, diatom zones 5 and 6 and chironomid zone NAG-ch-3 and NAG-ch-4.

In the pollen profile further increases in Calluna pollen and also *Sphagnum* represent the development of heath on drier soils and bogs in wetter parts of the Lochnagar catchment area.

This section of the core is delineated with expansions in acidophilous species *Achnanthes [marginulata]* f. *major, A. marginulata, Eunotia incisa, Navicula krasskei, Fragilaria vaucheriae* and declines in circumneutral *Fragilaria virescens* var *exigua*. The uppermost 10 cm is characterised by the virtual disappearance of indifferent taxa *Fragilaria vaucheriae, Aulacoseira lirata* var *alpigena, Navicula schassmannii, Navicula seminuloides, Navicula cocconeiformis* and major increases in acidophilous *Achnanthes marginulata* spp. and *Eunotia incisa*. A major decline in pH of up to 1 unit is inferred for the top 30 centimetres. This coincides with further declines in diatom concentrations and N2 (Hills diversity index). The

earlier than expected timing of this decline may be a factor of data smoothing and error associated with uncalibrated and extrapolated radiocarbon AMS dates. This decline in diatom inferred pH is, however, coincident with an increase in magnetic particles in the uppermost sediments. Possible causes of changes in the magnetic properties include an increase in atmospheric pollution particles, dissolution effects or a catchment erosion effect.

This period is marked by declines in chironomid genera *Microtendipes*, *Mesopsectrocladius*, *Procladius*, *Micropsectra insignilobus*-group and increases in *Heterotrissocladius grimshawi*, *Psectrocladius sordidellus*-group, *Corynoneura scutellata*-group, *Ablabesmyia*, and *Heterotrissocladius marcidus*. These faunal changes suggest a response to natural acidification of the catchment. An increase in *Sergentia, Heterotanytarsus apicalis, Heterotrissocladius marcidus* and *Psectrocladius sordidellus*-group in the uppermost sample may be in response to post-industrial acidification.

Further periodicities in organic matter of 250-350 years appear in the top 30 cm and are similar to trends found at other Cairngorm sites. Carbon/nitrogen ratios also show large variation in the uppermost sediment.

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Appendix 1: Results for Lochnagar fossil samples: no. taxa per sample; N2; WA-PLS (2) diatom inferred pH reconstruction (estimated mean values and standard errors of prediction

Sample Level	No. Taxa	N2	Lower est. error	WA-PLS(2) inferrd pH	Upper est. error
0.0	25	23.87	5.57	5.93	6.28
0.2	28	26.37	5.45	5.80	5.93
0.4	26	23.86	5.36	5.73	5.93
0.6	24	22.29	5.34	5.70	5.93
1.0	28	25.71	5.41	5.76	5.93
1.2	22	20.11	5.39	5.74	5.93
1.4	22	20.85	5.47	5.82	5.93
1.6	26	23.64	5.47	5.82	5.93
1.8	23	20.90	5.23	5.59	5.93
2.0	27	24.75	5.54	5.89	5.93
2.2	27	24.62	5.51	5.86	5.93
3.0	22	20.85	5.18	5.54	5.93
4.0	26	24.88	5.29	5.66	5.93
5.0	29	27.55	5.14	5.51	5.93
6.0	26	24.92	5.02	5.41	5.93
7.0	29	26.74	5.22	5.61	5.93
8.0	22	20.92	5.03	5.39	5.93
9.0	37	35.74	5.47	5.83	5.93
10.0	35	32.98	5.51	5.86	5.93
11.0	33	31.36	5.63	6.03	5.93
12.0	39	37.34	5.71	6.13	5.93
13.0	34	32.54	5.26	5.64	5.93
14.0	39	37.39	5.52	5.88	5.93
15.0	35	33.72	5.58	5.94	5.93
16.0	30	28.56	5.62	5.98	5.93
17.0	34	32.62	5.67	6.02	5.93
18.0	35	33.63	5.62	5.99	5.93
19.0	39	37.62	5.75	6.14	5.93
20.0	30	28.29	5.47	5.84	5.93
20.2	41	39.18	5.55	5.94	5.93
21.2	40	38.06	5.72	6.12	5.93
22.0	35	33.82	5.91	6.31	5.93
23.0	39	37.65	5.93	6.33	5.93
24.0			5.86	6.23	5.93
25.0	40	38.75	5.86	6.28	5.93
26.0	35	33.94	5.61	5.96	5.93
27.0	36	34.30	5.58	5.95	5.93
28.0	35	33.83	5.82	6.26	5.93
29.0	36	34.54	5.56	5.93	5.93
30.0	31	29.99	5.84	6.20	5.93
31.0	41	39.56	5.67	6.03	5.93
32.0	41	39.51	5.45	5.81	5.93
33.0	40	38.49	5.98	6.37	5.93
34.0	36	34.87	5.94	6.30	5.93
35.4	30	28.95	6.01	6.45	5.93
36.8	35	34.04	5.82	6.25	5.93
37.8	40	38.61	6.12	6.52	5.93
38.8	38	36.30	5.59	5.95	5.93
39.6	39	37.80	5.62	5.99	5.93
40.0	28	26.43	5.60	5.96	5.93
41.2	37	35.85	6.05	6.41	5.93
42.0	37	35.43	5.87	6.22	5.93
44.0	29	27.50	6.13	6.57	5.93
44.8	40	38.10	5.94	6.30	5.93
46.0			5.98	6.34	5.93
47.6	41	38.99	5.72	6.09	5.93
48.6	39	37.15	5.76	6.13	5.93
49.4	39	36.70	5.51	5.88	5.93

50.0	31	29.58	6.01	6.43	5.93
50.6	37	35.57	5.82	6.18	5.93
51.6	32	30.69	5.75	6.11	5.93
53.0	27	25.74	5.83	6.22	5.93
53.8	34	32.31	5.63	5.98	5.93
54.8	37	35.50	5.62	5.99	5.93
55.0	37	35.12	5.70	6.08	5.93
56.0	41	39.42	5.76	6.12	5.93
57.2	43	41.28	5.78	6.13	5.93
58.6	38	36.29	5.69	6.06	5.93
60.0	34	32.64	6.08	6.47	5.93
60.8	37	35.08	5.66	6.02	5.93
62.0	37	35.20	5.69	6.06	5.93
63.6	38	36.45	5.60	5.96	5.93
65.0	41	38.70	5.76	6.12	5.93
66.0	34	32.75	5.77	6.15	5.93
66.8	42	40.35	5.78	6.15	5.93
67.6	34	32.64	5.79	6.15	5.93
69.2	35	33.09	5.67	6.05	5.93
69.8	32	30.38	6.02	6.38	5.93
70.0	32	30.33	6.02	6.47	5.93
71.0	33	31.42	5.72	6.09	5.93
71.8	38	36.08	5.96	6.33	5.93
72.8	30	28.60	5.73	6.12	5.93
74.2	32	30.48	5.70	6.09	5.93
75.0	34	32.85	5.69	6.05	5.93
76.4	34	32.42	5.50	5.88	5.93
77.6	34	32.22	5.82	6.23	5.93
78.8	41	38.88	5.87	6.29	5.93
79.8	44	42.01	5.74	6.11	5.93
80.0	32	30.73	5.94	6.30	5.93
81.2	31	29.80	5.88	6.25	5.93
83.4	44	41.76	5.86	6.22	5.93
84.8	36	34.37	5.80	6.16	5.93
86.4	35	33.68	5.93	6.29	5.93
87.8	38	36.62	5.79	6.16	5.93
89.2	41	39.56	5.87	6.24	5.93
90.0	33	31.43	5.91	6.27	5.93
90.8	43	41.11	5.71	6.10	5.93
91.0	37	35.73	5.80	6.19	5.93
91.2	38	35.94	5.70	6.10	5.93
91.4	32	30.38	5.54	5.96	5.93
93.2	38	36.80	5.58	5.96	5.93
95.4	35	32.32	5.52	5.96	5.93
96.4	36	34.36	5.96	6.32	5.93
97.8	42	40.17	5.50	5.88	5.93
98.8	38	36.54	5.68	6.05	5.93
99.8	27	26.03	5.78	6.19	5.93
100.0	38	35.86	6.12	6.48	5.93
101.0	38	36.12	6.08	6.44	5.93
102.0	37	35.25	5.96	6.32	5.93
103.0	35	32.94	5.82	6.19	5.93
104.0	35	33.62	5.96	6.33	5.93
105.0	36	34.48	5.89	6.25	5.93
106.0	36	34.61	5.73	6.09	5.93
107.0	27	25.91	5.99	6.36	5.93
108.0	33	31.60	6.07	6.46	5.93
109.0	37	35.66	5.97	6.42	5.93
110.0	31	29.54	6.15	6.51	5.93
111.0	33	31.76	5.96	6.32	5.93
112.0	31	29.50	5.95	6.35	5.93
114.0	36	34.14	5.78	6.16	5.93
115.0	37	35.26	5.95	6.35	5.93
116.0	25	23.91	6.00	6.43	5.93

117.0	36	34.44	6.17	6.58	5.93
118.0	26	25.22	5.93	6.29	5.93
119.0	27	25.44	6.19	6.54	5.93
120.0	38	36.55	5.62	5.98	5.93
121.0	32	30.57	6.00	6.36	5.93
122.0	34	32.96	5.79	6.18	5.93
123.0	36	34.84	5.87	6.23	5.93
124.0	37	35.79	6.13	6.53	5.93
125.0	35	33.66	6.01	6.42	5.93
126.0	34	32.61	5.91	6.27	5.93
127.0	37	35.33	6.16	6.57	5.93
128.0	33	31.67	6.12	6.53	5.93
130.0	34	32.49	5.99	6.39	5.93
131.0	33	31.41	6.00	6.36	5.93
132.0	39	37.16	5.90	6.26	5.93
133.0	36	34.05	5.85	6.20	5.93
134.0	34	32.41	5.77	6.15	5.93
135.0	39	37.75	5.76	6.13	5.93
137.0	33	32.11	5.73	6.13	5.93
138.0	38	36.44	5.74	6.10	5.93
139.0	38	36.50	5.81	6.17	5.93
140.0	34	32.33	6.06	6.41	5.93
141.0	31	29.67	6.03	6.41	5.93
142.0	33	31.42	6.06	6.51	5.93
143.0	34	32.54	5.93	6.29	5.93
144.0	34	32.54	6.05	6.42	5.93
145.0	39	37.16	6.18	6.58	5.93
146.0	38	36.44	6.09	6.49	5.93
147.0	35	33.36	6.06	6.47	5.93
147.8	35	33.77	5.79	6.18	5.93
148.6	30	28.74	5.83	6.20	5.93
149.4	34	32.79	5.92	6.28	5.93
150.0	27	25.71	6.37	6.85	5.93
150.4	34	32.93	6.17	6.60	5.93
151.4	35	33.57	6.09	6.53	5.93
152.4	40	38.17	5.80	6.17	5.93
153.2	34	32.85	6.00	6.43	5.93
154.2	32	31.04	5.85	6.21	5.93
155.6	33	31.94	5.85	6.21	5.93
156.6	35	33.80	5.74	6.10	5.93
157.6	30	28.54	6.07	6.43	5.93
160.0	36	34.58	5.83	6.26	5.93
160.6	35	33.95	5.58	5.94	5.93
161.4	36	34.57	5.81	6.18	5.93
162.2	28	26.86	5.77	6.13	5.93
163.2	32	30.65	5.69	6.08	5.93
164.2	29	28.05	6.00	6.40	5.93
165.2	39	37.31	5.72	6.09	5.93
166.2	32	30.57	5.64	6.00	5.93
167.2	31	29.42	5.55	5.95	5.93
168.2	34	32.32	5.72	6.09	5.93
168.8	36	34.48	5.71	6.07	5.93
169.6	30	29.13	5.97	6.35	5.93
170.0	30	28.66	5.84	6.24	5.93
170.4	33	31.59	6.03	6.40	5.93
171.2	37	35.48	5.93	6.29	5.93
172.4	33	31.53	5.87	6.27	5.93
173.2	42	40.44	5.87	6.24	5.93
174.6	40	37.87	5.91	6.29	5.93
175.4	39	36.93	5.98	6.35	5.93
176.2	43	41.66	5.82	6.19	5.93
177.8	36	34.24	5.75	6.11	5.93