DISPLAY ONLY

ISSN 1366-7300

ENVIRONMENTAL CHANGE RESEARCH CENTRE

University College London

RESEARCH REPORT

No. 10

Studies of water quality change at black-throated diver sites

T.E.H. Allott, P.G. Golding & P.G. Appleby

A Progress Report to the R.S.P.B.

December 1994

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

Table of Contents

Table of Contents

1. Introduction
2. Current Work Programme
3. Fieldwork Progress
4. Sediment Cores: Lithostratigraphic Analysis
5. Sediment Cores: Carbonaceous Particle Analysis
6. Sediment Cores: Diatom Analysis
7. Sediment Cores: Radiometric Dating
8. Critical Loads Assessments of Black-throated Diver Lochs
9. Classification of Black-throated Diver Lochs
10. Publications
11. Acknowledgements
12. References

Appendix 1 Lithostratigraphic analyses of sediment cores from Loch an Eion and Loch Kemp

Appendix 2 Carbonaceous particle analyses of sediment cores from Loch an Eion and Loch Kemp

Appendix 3 Reports on the radiometric dating of sediment cores from Loch Clair and Loch nam Brac

1. Introduction

This report provides an update on recent research activities at the Environmental Change Research Centre relating to the Royal Society for the Protection of Birds' (RSPB) project on Black-throated divers in Scotland. These research activities are ongoing, with the analytical work programme due to be completed by February 1995. This document therefore presents additional data available since the previous report (Allott & Rose 1993), and describes progress on outstanding analyses. Detailed discussion and interpretation of results are therefore not included.

Current work is focused on two principal areas:

- The assessment of water quality changes at lochs with populations of Black-throated divers.

- The classification of Black-throated diver lochs using a variety of physical, chemical and biological data.

Allott and Rose (1983) used palaeolimnological techniques to study water quality changes at a number of diver lochs, and finding clear evidence of acidification at one loch and nutrient enrichment at a second site. These results are being substantiated by further analyses of existing sites and by the application of palaeolimnological techniques to additional diver sites sensitive to either acidification or nutrient enrichment.

The RSPB project has generated a substantial amount of data relevant to the ecology of Black-throated divers. Multivariate statistical methods are being used to integrate these data and generate classifications suitable for characterising the diver sites. Such classification will allow diver behaviour and ecology to be objectively related to environmental variables, and thereby greatly aid interpretation of the environmental factors important to diver ecology.

2. Current Work Programme

The current work programme consists of the following analyses.

1) Radiometric dating of sediment cores from Loch Clair and Loch nam Brac. Previous results indicated that these lochs have been impacted by acidification and nutrient enrichment respectively. Dating will allow the timing and causes of these changes to be evaluated.

2) Palaeolimnological evaluation of water quality change at Loch an Eion, a site susceptible to acidification. The analyses include lithostatigraphy, carbonaceous particles, diatom assemblages and diatom-inferred pH change.

3) Palaeolimnological evaluation of water quality change at Loch Kemp, a site susceptible to nutrient enrichment. The analyses include lithostatigraphy, carbonaceous particles, diatom assemblages, diatom-inferred pH change and radiometric dating.

4) Assessment of the extent of acidification at Black-throated diver lochs by the application of critical loads models. These assessments are complimentary to the more detailed palaeolimnological evaluations, allowing the acidification status of a larger number of sites to be established.

5) Analysis of epilithic diatom samples from selected diver lochs for loch classification purposes.

6) Classification of Black-throated diver sites using physical, chemical and biological data (e.g. lake and catchment details, water chemistry, diatoms, invertebrates, fish).

3. Fieldwork Progress

Sediment cores were obtained from three additional diver sites in April 1994; Loch an Eion, Loch Kemp and Loch Ba. The cores from Loch an Eion and Loch Kemp have been incorporated into the current studies. The core from Loch Ba has been stored pending possible future analyses.

4. Sediment Cores: Lithostratigraphic Analysis

Results of lithostratigraphic analyses of the cores from Loch an Eion and Loch Kemp are presented in Appendix 1.

The core from Loch an Eion shows relatively low % loss-on-ignition (LOI) in the lower section (20-37 cm). There is a sharp increase in LOI at 20 cm to c.50%, indicative of a shift to highly organic sediment. Similar features have been recorded in cores from lakes in many upland areas of Britain, and are often interpreted as evidence of peat erosion within the lake catchment (Stevenson *et al.* 1990). The uppermost section of the Loch an Eion core shows a pattern of gradually declining LOI, suggesting that any peat erosion within the catchment has stabilised.

The core from Loch Kemp shows relatively stable dry weight and LOI profiles, although there is a slight trend of increasing LOI from 18 cm upwards. These results indicate a generally stable depositional environment at the loch throughout the period represented by the core.

5. Sediment Cores: Carbonaceous Particle Analysis

Carbonaceous particles (SCPs) have been analysed from the Loch an Eion and Loch Kemp cores using the methods of Rose (1990). The resulting carbonaceous particle profiles are presented in Appendix 2, and can be used to provide evidence of atmospheric contamination and an approximate chronology for each core (see Allott & Rose 1993).

The SCP profile from Loch an Eion indicates that the core contains significant concentrations of carbonaceous particles above 8 cm. A provisional chronology based on this profile would date 10 cm as c.1860 AD and 5 cm as c.1950 AD. Carbonaceous particle concentrations fluctuate within the top 4 cm of the core, and the sub-surface peak which occurs in many Scottish cores at c.1978 is not readily apparent within the profile.

The SCP profile from the Loch Kemp core indicates significant concentrations above 15 cm. A provisional chronology would date 18 cm as c.1860, 10 cm as c.1950 and 2.5 cm as c.1978. The profile clearly shows the sub-surface peak corresponding to c.1978, above which there is a marked decline in concentrations.

The provisional chronologies indicate that the Loch an Eion core has a relatively low mean sediment accumulation rate (c.0.8 mm yr^{-1}) compared to Loch Kemp (c.1.4 mm yr^{-1}). These rates are within the range typical of nutrient-poor Scottish lochs (cf Battarbee *et al.* 1988), and the particularly low accumulation rate from Loch an Eion is consistent for a high-altitude upland loch.

6. Sediment Cores: Diatom Analysis

Diatom analyses are currently being completed on the cores from Loch an Eion and Loch Kemp. Although the diatom counts have not yet been entered onto the computer data-base and fully analysed, provisional results indicate that floristic change has taken place at both lochs.

Lower levels in the Loch an Eion core are dominated by the planktonic taxon *Cyclotella rossii* with *Brachysira vitrea* and *Achnanthes minutissima* also common. In the uppermost levels of the core *Cyclotella rossii* disappears to be replaced by *Tabellaria flocculosa*, indicative of more acid conditions. This change could be interpreted as an acidification signal, but may also be the result of the loss of plankton due to increased water turbidity following peat erosion. Full computation of the data will allow these interpretations to be evaluated.

The lower levels of the Loch Kemp core are characterised by planktonic *Cyclotella* species. The uppermost levels of the core contain higher abundances of *Asterionella formosa* and *Tabellaria flocculosa* var. III, planktonic taxa associated with more mesotrophic conditions. This floristic change indicates that the loch may have been affected by nutrient enrichment. Full computation of the diatom data combined with catchment land-use information, particularly data on fish farming at the site, will allow the timing and cause of this change to be evaluated.

7. Sediment Cores: Radiometric Dating

Cores from three lochs were selected for radiometric dating using ^{210}Pb, ^{137}Cs and ^{241}Am; Loch Clair, Loch nam Brac and Loch Kemp. The core from Loch Clair contains clear evidence of acidification, and the cores from the latter two lakes contain evidence of nutrient enrichment, possibly related to the setting of fish cages. Cores are being dated at the University of Liverpool by Dr P.G. Appleby.

Reports on the radiometric dating of sediment cores from Loch Clair and Loch nam Brac are presented in Appendix 3. Chronologies for both cores have been successfully established from these radiometric dates. The core from Loch Kemp is currently being dated and a chronology should be available at the beginning of January 1995.

The ^{210}Pb chronology for the Loch Clair core generally confirms the provisional chronology for the core generated from the carbonaceous particle profile (Allott and Rose 1993). Diatom-based pH reconstruction from the core revealed a marked trend of steadily declining pH above approximately 15 cm (Allott & Rose 1993). The ^{210}Pb chronology indicates that this acidification started at around 1880 AD. This date is consistent with the timing of lake acidification from other regions of Scotland (e.g. Galloway, Trossachs, Cairngorms). It is clear that despite its remote location in the north-west of Scotland, Loch

Clair has acidified due to atmospheric contamination and that the acidification has taken place over approximately the last 120 years.

The ^{210}Pb chronology generated for the upper section of the core from Loch nam Brac corresponds with the provisional chronology derived from the carbonaceous particle profile (Allott & Rose 1993). However, the chronology suggests a more rapid accumulation rate in the lower section of the core than estimated from the provisional SCP chronology. Diatom analysis of the core revealed substantial floristic changes above 2 cm indicative of nutrient enrichment of the loch. According to the ^{210}Pb chronology this floristic change took place after 1981 AD. In order to evaluate the cause of the nutrient enrichment comparisons are being made with timing of recent land-use changes within the loch catchment, particularly the setting of fish cages on the loch itself.

8. Critical Loads Assessments of Black-throated Diver Lochs

Water chemistry data collected from Black-throated diver lochs and analysed by Ron Harriman at the Freshwaters Fisheries Laboratory, Pitlochry, are being used to calculate critical loads. There are various definitions for critical loads, but the most commonly used is that of Nilsson and Grennfelt (1988):

> "A critical load for acid deposition is the highest deposition of acidifying compounds that will not cause chemical changes leading to long- term harmful effects on ecosystem structure and function"

Critical loads essentially define the sensitivity of an ecosystem to acid deposition. In combination with data on current levels of acid deposition they can be used to calculate critical load exceedances, predictions of acidification status.

Two models are available for calculating critical loads for freshwaters: the steady-state water chemistry model of Henriksen (Henriksen *et al.* 1992, Harriman & Christie 1994) and the diatom model (Battarbee *et al.* 1994). The Henriksen model provides critical loads relating to the maintenance of a pre-selected level of acid neutralising capacity (ANC). In the UK critical loads are calculated relating to a critical ANC level of zero, a value chosen because of its relationship with the probability of brown trout populations being present (Battarbee 1994). The Henriksen model therefore provides critical loads specific to species or species groups. Alternatively the diatom model can be used to provide the 'baseline' critical load for a site. Critical loads calculated using the diatom model effectively predict the deposition loading before response of diatom communities to acidification. As diatoms are amongst the most sensitive indicators of acidification, this represents the first ecological response to acid deposition.

Critical loads have been calculated for 99 Black-throated diver sites using both the diatom and Henriksen models. Critical loads exceedances have been calculated using sulphur deposition data from the United Kingdom Review Group on Acid Rain (1990) to provide an assessment of current acidification status (Tables 1 and 2).

Table 1
Number of Black-throated diver lochs within each critical loads exceedances class according to the Diatom model

Class	Keq S ha^{-1} yr^{-1}	Number of sites
1	<= 0.0 (not exceeded)	71
2	>0.0 & <=0.2	15
3	>0.2 & <=0.5	7
4	>0.5 & <=1.0	4
5	>1.0	2

Table 2
Number of Black-throated diver lochs within each critical loads exceedances class according to the Henriksen model

Class	Keq S ha^{-1} yr^{-1}	Number of sites
1	<= 0.0 (not exceeded)	83
2	>0.0 & <=0.2	11
3	>0.2 & <=0.5	3
4	>0.5 & <=1.0	2
5	>1.0	0

The results indicate that although the majority of sites are not currently exceeded, a significant proportion of the sites are predicted to have acidified. Using the diatom model, for example, 28 of the sites currently exceed their critical load. The lochs with exceedances greater than 0.5 Keq S ha^{-1} yr^{-1} are generally located in southern areas of the Black-throated diver range (e.g. Galloway, Rannoch Moor). In these areas the extent and impacts of lake acidification has been well documented (e.g. Battarbee *et al.* 1988). However, it is important to note that the model predicts critical loads exceedances of diver lochs in areas such as Wester Ross, Sutherland and the Outer Hebrides, although the degree of exceedance at these sites is lower (typically <0.5 Keq S ha^{-1} yr^{-1}). These are areas with little previous evidence of the impact of acid deposition.

The significance of acidification at sites across the whole Black-throated diver range can be evaluated using the palaeolimnological data obtained during this study from selected lochs (e.g. Loch Clair, Loch an Eion, Loch Tollaidh). The palaeolimnological data is therefore being used to both validate the critical loads predictions and to enumerate historical pH changes. Provisional results suggest that relatively severe acidification has taken place at several diver sites in southern Scotland. However, within the core area of the diver range in north-west Scotland, although some acidification has taken place at sensitive sites the degree of this acidification is slight.

9. Classification of Black-throated Diver Lochs

As part of the programme of research on Black-throated divers the RSPB have collated a range of data for a series of lochs. These data include basic catchment and lake information, water chemistry, littoral macroinvertebrates and fish. In addition to providing basic environmental data for direct comparison with observed diver ecology, the data provide a basis for more objective classification of the Black-throated diver lochs. Such classification will allow characterisation of the diver lochs, provide a basis for effective analysis of the influence of environment factors on diver ecology, and allow the comparison of lochs with and without diver populations. The Environmental Change Research Centre is contributing to this research in three ways:

1) Enumeration of epilithic diatom samples from selected diver lochs. These data will be used to provide basic information on the algal flora of the lochs, and in conjunction with direct water chemistry measurement can be used to classify the sites. The epilithic diatom samples have been counted, and are currently being computed. Results and analyses will be available in January 1995.

2) Provision of advice for data formatting and the construction of an integrated, relational data-base containing the data generated during the research. The database provides a rapid and flexible mechanism for retrieving blocks or different combinations of data.

3) Collaboration with RSPB staff in the multi-variate analysis of data to construct classifications of the diver sites. These classifications will be based on different combinations of the physical, chemical and biological data available.

This work is ongoing, and will be completed in February 1994.

10. Publications

A number of collaborative papers have been planned in consultation with RSPB staff. Given RSPB endorsement, it is intended that these will be published in refereed scientific journals.

A paper on the impact of acid deposition on Black-throated diver lochs is currently in draft form, and will be circulated in December 1994. This paper presents critical loads and palaeolimnological assessments of the acidification status of the lochs, and evaluates the biological significance of the observed acidification.

A paper on the palaeolimnological evaluation of nutrient enrichment at selected sites is in first draft stage. A more complete draft of this paper will be circulated in January 1995.

The classification work on the diver sites is ongoing. This research could be published as one major paper, or as several smaller papers. A decision on publication strategy will be made after consultation with RSPB staff in January 1995, when classification results will be available.

11. Acknowledgements

We are grateful to Ron Harriman for providing water chemistry data, Chris Curtis for calculation of critical loads values, and Digger Jackson for fieldwork support.

12. References

Allott, T.E.H. & Rose, N.L. (1993). A palaeolimnological study of recent water quality changes in lochs with Black-throated diver populations: a report to the Royal Society for the Protection of Birds. Research Report No. 6, Environmental Change Research Centre, University College London, 65 pp.

Battarbee, R.W. (ed) (1994). *Critical Loads of Acidity for UK Freshwaters.* in press

Battarbee, R.W., Allott, T.E.H., Juggins, S. & Kreiser, A.M. (1994). Estimating the base critical load: the diatom model. In **Battarbee, R.W. (ed) (1994).** *Critical Loads of Acidity for UK Freshwaters.* in press

Battarbee, R.W., Anderson, N.J., Appleby, P.G, Flower, R.J., Fritz, S.C., Haworth, E.Y., Higgit, S., Jones, V.J., Kreiser, A., Munro, M.A.R., Natkanski, J., Oldfield, F., Patrick, S.T., Richardson, N.G., Rippey, B. & Stevenson, A.C. (1988). *Lake Acidification in the United Kingdom 1800-1986.* ENSIS Publishing, London, 68pp.

Harriman, R. & Christie, A.E.G. (1994). Estimating critical loads for biota: the steady-state water chemistry (Henriksen) model. In **Battarbee, R.W.** (ed) **(1994).** *Critical Loads of Acidity for UK Freshwaters.* in press

Henriksen, A.J., Kamari, M., Posch, M. & Wilander, A. (1992). Critical loads of acidity: Nordic surface waters. *Ambio* 21, 356-363.

Nilsson, J. & Grennfelt, P. (eds) (1988). *Critical loads for sulphur and nitrogen.* UNECE/Nordic Council workshop report, Skokloster, Sweden. March 1988. Nordic Council of Ministers: Copenhagen.

Rose, N.L. (1990). A method for the extraction of carbonaceous particles from lake sediments. *J. Palaeolimnology* 3, 45-53.

Stevenson, A.C., Jones, V.J. & Battarbee, R.W. (1990). The cause of peat erosion: a palaeolimnological approach. *New Phytologist* 114, 727-735.

United Kingdom Review Group on Acid Rain (1990). *Acid Deposition in the United Kingdom 1986-1988.* Third report of the United Kingdom Review Group on Acid Rain. Warren Springs Laboratory, Stevenage, 124pp.

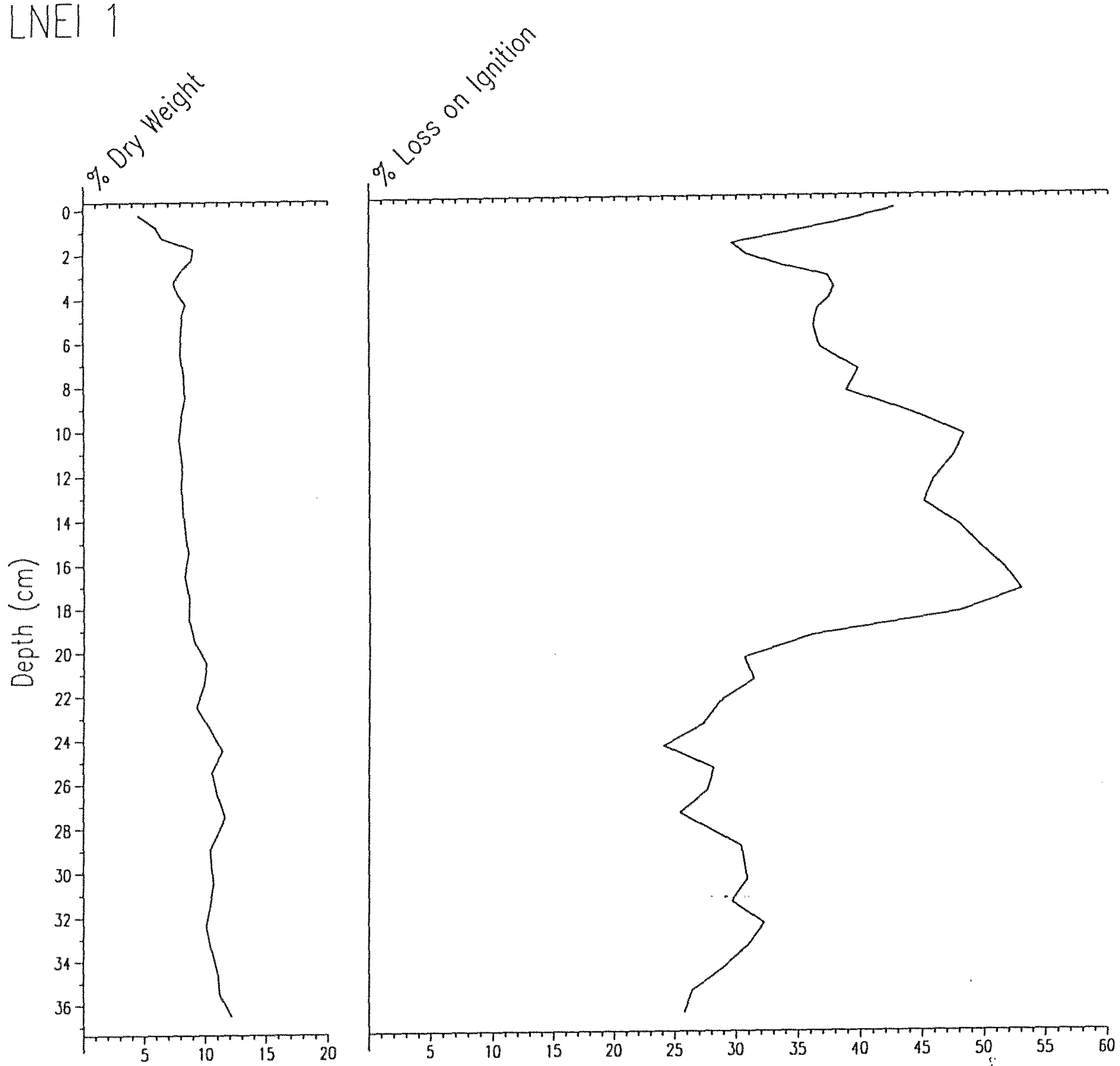
Appendix 1

Lithostratigraphic analyses of sediment cores from Loch nan Eoin and Loch Kemp

LOCH NAN EION	(LNEI 1)					
Mean Depth	Crucible Empty	Cruc Wet Weight	Cruc Dry Weight	Cruc LOI Weight	% Dry Weight	% LOI
0.25	5.6718	6.8494	5.7248	5.7022	4.500	42.64
0.75	5.6881	6.8731	5.7586	5.7312	5.949	38.86
1.25	5.7555	6.9824	5.8347	5.8074	6.455	34.46
1.75	5.7064	7.0615	5.8289	5.7926	9.039	29.63
2.25	5.9012	6.9293	5.9928	5.9646	8.909	30.78
2.75	4.9930	6.2901	5.0961	5.0614	7.948	33.65
3.25	5.7885	6.9003	5.8713	5.8404	7.447	37.31
3.75	5.4625	6.6325	5.5533	5.5189	7.760	37.88
4.25	5.7811	7.2565	5.9048	5.8585	8.384	37.42
4.75	5.4262	6.6406	5.5248	5.4888	8.119	36.51
5.50	5.6856	7.1780	5.8057	5.7623	8.047	36.13
6.50	6.2785	7.6783	6.3900	6.3491	7.965	36.68
7.50	5.9971	7.0466	6.0836	6.0492	8.242	39.76
8.50	5.5757	6.9604	5.6910	5.6462	8.326	38.85
9.50	5.9213	7.2706	6.0294	5.9818	8.011	44.03
10.5	5.9487	7.1694	6.0444	5.9982	7.839	48.27
11.5	5.8572	7.2164	5.9673	5.9151	8.100	47.41
12.5	5.7368	7.3517	5.8667	5.8072	8.043	45.80
13.5	5.9434	7.1784	6.0442	5.9988	8.161	45.03
14.5	5.4537	6.6738	5.5556	5.5068	8.351	47.89
15.5	5.9340	7.1354	6.0374	5.9861	8.606	49.61
16.5	5.0585	6.5590	5.1829	5.1188	8.290	51.52
17.5	5.7811	7.3128	5.9135	5.8434	8.643	52.94
18.5	5.9025	7.3966	6.0317	5.9698	8.647	47.91
19.5	5.8547	7.4379	5.9985	5.9466	9.082	36.09
20.5	5.7991	7.3697	5.9573	5.9089	10.07	30.59
21.5	5.7469	7.1443	5.8852	5.8418	9.896	31.38

LOCH NAN EION	(LNEI 1)					
Mean Depth	Crucible Empty	Cruc Wet Weight	Cruc Dry Weight	Cruc LOI Weight	% Dry Weight	% LOI
22.5	5.7070	6.8311	5.8115	5.7816	9.296	28.61
23.5	5.8197	7.1235	5.9551	5.9181	10.38	27.32
24.5	5.6532	7.0476	5.8123	5.7740	11.40	24.07
25.5	5.1022	6.4078	5.2403	5.2014	10.57	28.16
26.5	5.6471	6.8521	5.7795	5.7429	10.98	27.64
27.5	5.7802	6.9818	5.9200	5.8845	11.63	25.39
29	5.7848	7.1897	5.9312	5.8867	10.42	30.39
30.5	5.6897	7.2323	5.8548	5.8038	10.70	30.89
31.5	5.0604	6.3397	5.1934	5.1540	10.39	29.62
32.5	5.2316	6.4501	5.3543	5.3147	10.06	32.27
33.5	5.7715	7.0510	5.9059	5.8643	10.50	30.95
34.5	5.7441	7.1254	5.8961	5.8521	11.00	28.94
35.5	5.2604	6.5655	5.4065	5.3679	11.19	26.42
36.5	5.1897	6.5891	5.3602	5.3162	12.18	25.80

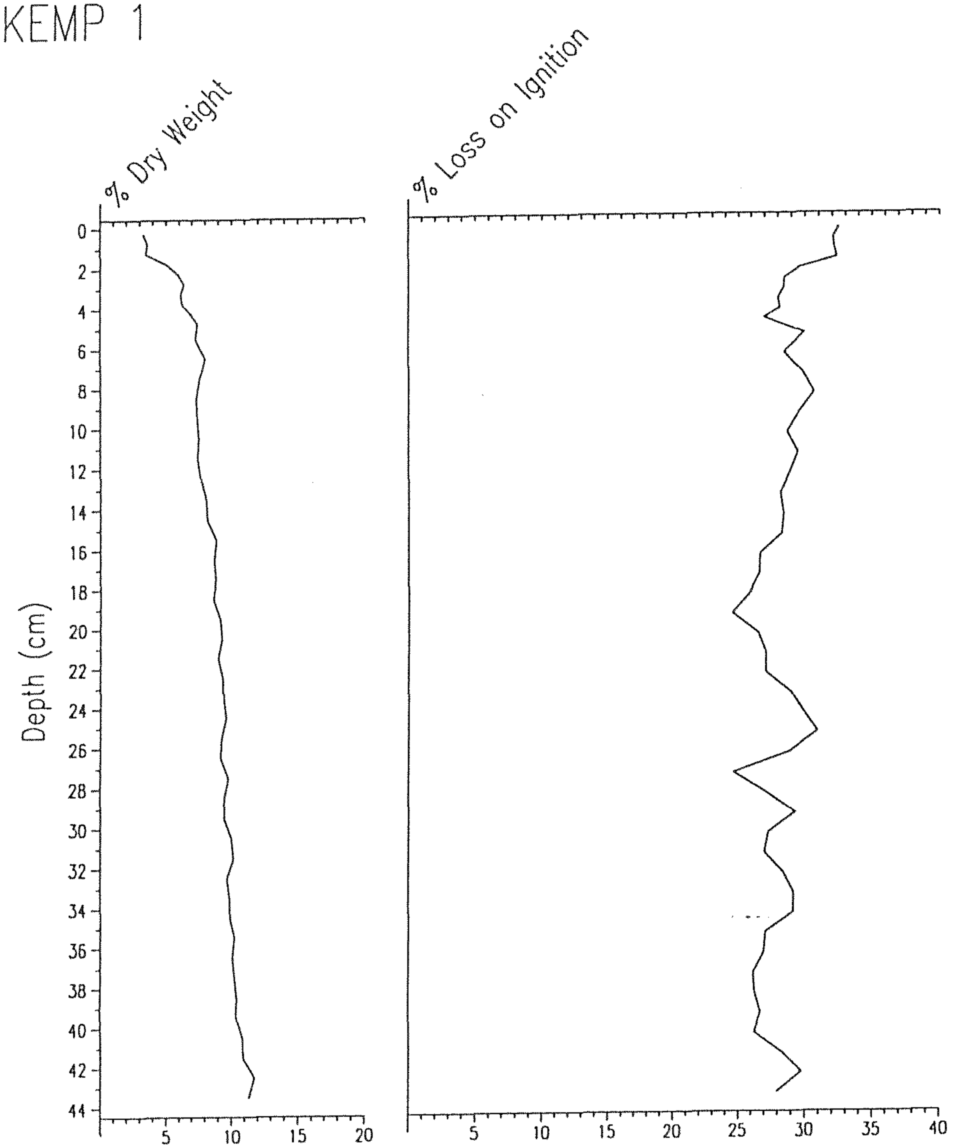
Loch Nan Eion
LNEI 1



LOCH KEMP	(KEMP 1)					
Mean Depth	Cruc Empty	Cruc Wet Weight	Cruc Dry Weight	Cruc LOI Weight	% Dry Weight	% LOI
0.25	5.1789	6.4104	5.2192	5.2061	3.272	32.50
0.75	4.9345	6.0274	4.9741	4.9614	3.623	32.07
1.25	5.8490	6.9996	5.8891	5.8762	3.485	32.16
1.75	5.7632	6.8753	5.8194	5.8012	5.053	32.38
2.25	5.7315	7.0267	5.8082	5.7855	5.921	29.59
2.75	5.9072	6.9931	5.9764	5.9567	6.372	28.46
3.25	5.2432	6.2891	5.3072	5.2890	6.119	28.43
3.75	5.6789	6.8560	5.7525	5.7319	6.252	27.98
4.25	5.7789	7.0046	5.8634	5.8396	6.894	28.16
4.75	5.7514	6.9378	5.8394	5.8157	7.417	26.93
5.50	5.8874	7.1072	5.9762	5.9496	7.279	29.95
6.50	6.0658	7.1749	6.1550	6.1296	8.042	28.47
7.50	5.7645	7.2637	5.8776	5.8439	7.544	29.79
8.50	6.2741	7.4557	6.3606	6.3341	7.320	30.63
9.50	5.7794	6.8985	5.8619	5.8375	7.371	29.57
10.5	4.9620	6.2201	5.0562	5.0292	7.487	28.66
11.5	5.8690	7.1239	5.9620	5.9346	7.410	29.46
12.5	5.7762	7.0171	5.8714	5.8439	7.671	28.88
13.5	5.5577	6.9594	5.6710	5.6391	8.083	28.15
14.5	5.9048	7.1434	6.0059	5.9772	8.162	28.38
15.5	5.6861	7.0791	5.8092	5.7744	8.837	28.26
16.5	5.5498	6.8912	5.6662	5.6352	8.677	26.63
17.5	5.8603	7.1257	5.9716	5.9420	8.795	26.59
18.5	5.7403	6.8267	5.8336	5.8095	8.587	25.83
19.5	5.7453	6.9142	5.8518	5.8257	9.111	24.50
20.5	5.5858	6.7140	5.6898	5.6623	9.218	26.44
21.5	5.8116	7.1390	5.9306	5.8984	8.964	27.05
22.5	5.9428	7.1111	6.0518	6.0223	9.329	27.06

LOCH KEMP	(KEMP 1)					
Mean Depth	Cruc Empty	Cruc Wet Weight	Cruc Dry Weight	Cruc LOI Weight	% Dry Weight	% LOI
23.5	5.5780	6.9740	5.7083	5.6706	9.333	28.93
24.5	5.6356	6.9358	5.7596	5.7226	9.536	29.83
25.5	5.7447	7.0979	5.8694	5.8309	9.215	30.87
26.5	5.7759	7.1659	5.9033	5.8665	9.165	28.88
27.5	5.5978	6.7495	5.7103	5.6826	9.768	24.62
28.5	5.7676	7.1042	5.8943	5.8600	9.479	27.07
29.5	5.9007	6.9711	6.0018	5.9722	9.445	29.27
30.5	5.6047	6.9310	5.7374	5.7012	10.00	27.27
31.5	5.1199	6.4500	5.2552	5.2187	10.17	26.97
32.5	5.0972	6.2317	5.2071	5.1759	9.687	28.38
33.5	5.3058	6.5692	5.4306	5.3942	9.878	29.16
34.5	5.1527	6.6277	5.2984	5.2559	9.877	29.16
35.5	5.7100	7.1934	5.8618	5.8207	10.23	27.07
36.5	5.8843	6.9518	5.9920	5.9630	10.08	26.92
37.5	5.2349	6.6607	5.3810	5.3428	10.24	26.14
38.5	5.8461	7.1065	5.9770	5.9426	10.38	26.27
39.5	5.7985	6.8297	5.9052	5.8767	10.34	26.71
40.5	5.7605	7.1366	5.9096	5.8705	10.83	26.22
41.5	5.6838	6.9430	5.8208	5.7820	10.87	28.32
42.5	5.8551	7.2055	6.0141	5.9668	11.77	29.74
43.5	4.9536	6.0456	5.0778	5.0431	11.37	27.93

Loch Kemp
KEMP 1

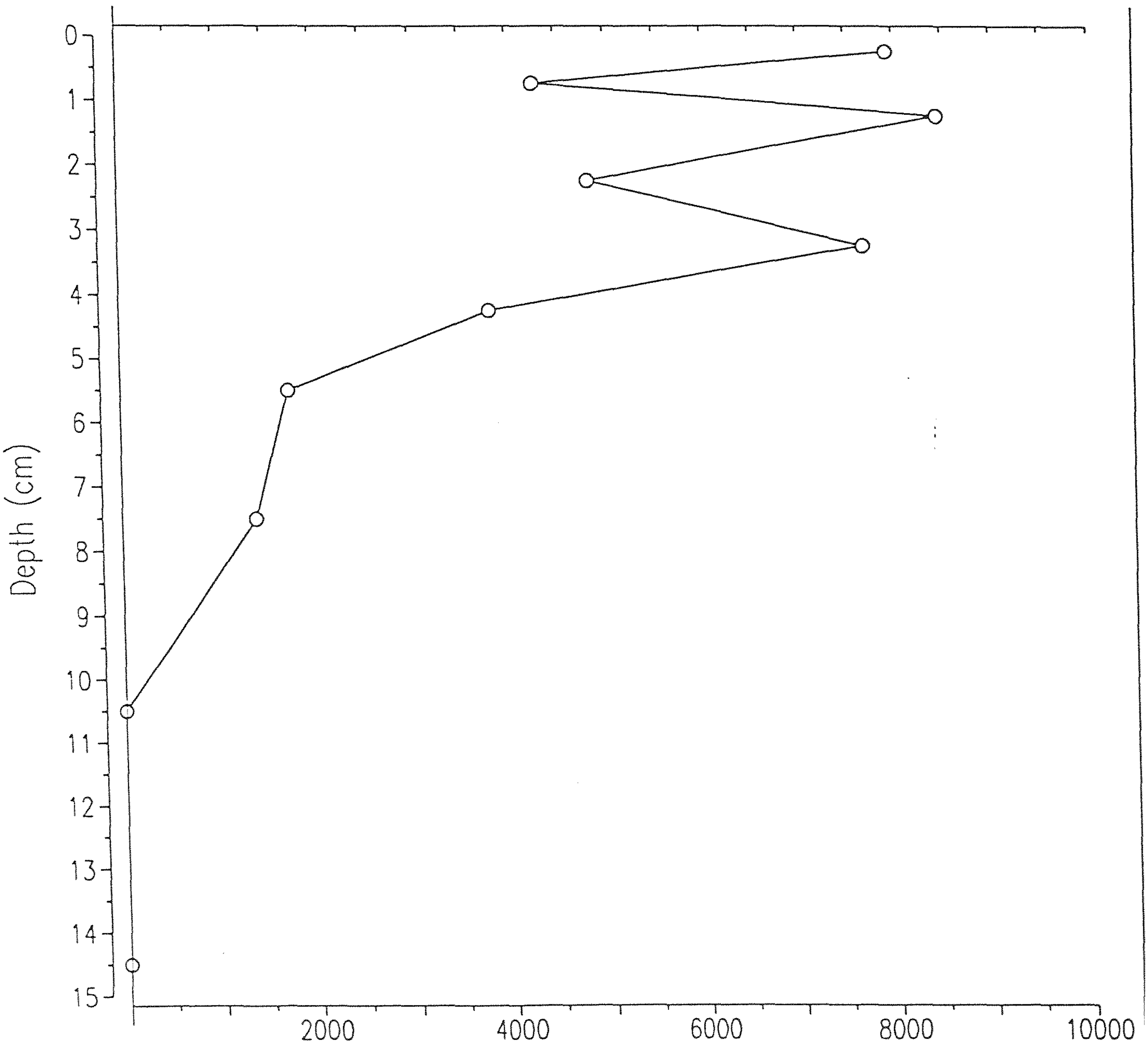


Appendix 2

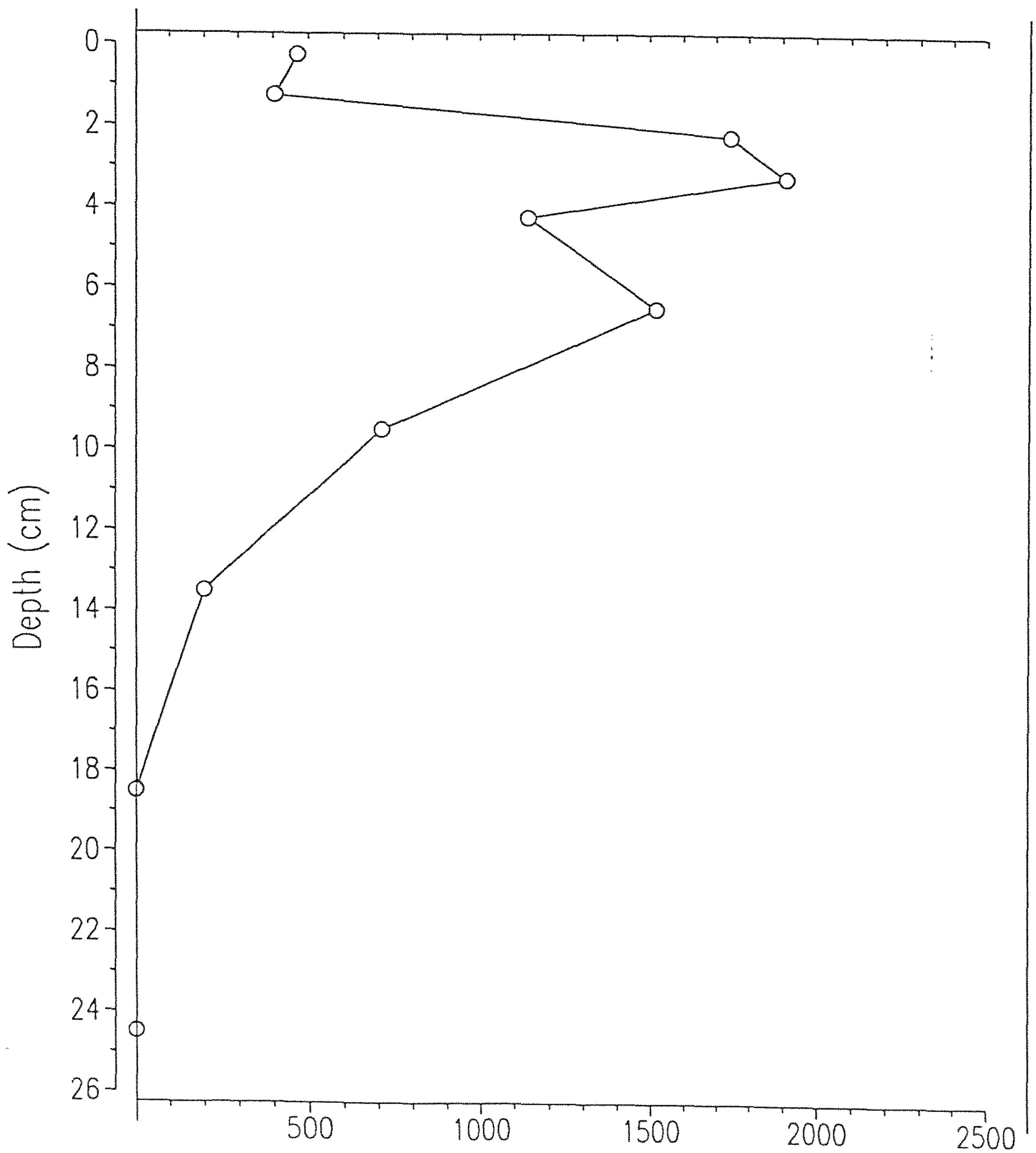
Carbonaceous particle analyses of sediment cores from Loch nan Eoin and Loch Kemp

Loch nan Eion (LNEI 1)

Carbonaceous Particle Concentration Profile



Loch Kemp (KEMP 1)
Carbonaceous Particle Concentration Profile



Appendix 3

Reports on the radiometric dating of sediment cores from Loch Clair and Loch nam Brac

Radiometric Dating of Loch Clair Core CLAI1

Sediment samples from core CLAI1 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using a well-type coaxial low background intrinsic germanium detector fitted with a sodium iodide (NaI(Tl)) escape suppression shield (Appleby *et al.* 1986). The ^{210}Pb and ^{226}Ra results are given in Table 1 and shown graphically in Fig.1 The ^{137}Cs and ^{241}Am results are given in Table 2 and Fig.2.

^{210}Pb dates have been calculated using both the CRS and CIC dating models (Appleby & Oldfield 1978) and the results are shown in Fig.3. Both models indicate significant fluctuations in the accumulation rate over the past 100 years, though both give a similar mean value for this period of 0.025±0.002 $gcm^{-2}y^{-1}$. The most prominent of these fluctuations occurs at a depth of 12.5 cm and appears to be associated with a layer of relatively dense sediment. This feature is interpreted by the ^{210}Pb as a brief episode of accelerated sediment and is dated ca.1900.

Fig.2 shows that the ^{137}Cs activity versus depth profile has a well defined peak at 4.25 cm. The ^{241}Am activity, also a product of weapons test fallout (Appleby *et al.* 1991), peaks at the slightly deeper level of 5.5 cm. Since the location of these peaks is partly a function of sample selection, it would seem reasonable to place the 1963 level recording maximum fallout from the atmospheric testing of nuclear weapons in the depth range 4.25-5.5 cm. Fig.3 shows that this inference is in good agreement with the CRS model ^{210}Pb chronology, which puts 1963 at a depth of 5.5 cm, in contrast to the CIC model which puts 1963 at a depth of more than 6.5cm. The CRS model dates would thus seem to be more appropriate for this core, and these form the basis of the chronology given in Table 3.

References

Appleby,P.G. and Oldfield,F., 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena*, 5:1-8.

Appleby,P.G., Nolan,P.J., Gifford,D.W., Godfrey,M.J., Oldfield,F., Anderson,N.J. and Battarbee,R.W., 1986. ^{210}Pb dating by low-background gamma counting. *Hydrobiologia*, **143**:21-27.

Appleby,P.G., Richardson,N. and P.J.Nolan, 1991. ^{241}Am dating of lake sediments. *Hydrobiologia*, **214**:35-42.

Table 1. Loch Clair: ^{210}Pb Data Core CLAI1

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Concentration	
		Total		Unsupp			
cm	$g cm^{-2}$	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±
0.25	0.01	921.7	55.2	831.5	56.3	90.2	11.0
1.25	0.08	853.9	50.8	800.9	51.6	53.0	8.9
3.25	0.33	883.2	28.1	829.1	28.4	54.1	4.1
4.25	0.47	785.5	29.1	720.3	29.5	65.2	4.6
5.50	0.68	586.9	12.1	530.0	12.2	56.9	1.9
6.50	0.86	362.0	15.8	311.1	15.9	50.9	2.1
8.50	1.31	222.8	10.8	169.1	11.0	53.7	2.0
10.50	1.81	175.8	10.0	118.2	10.2	57.6	2.0
11.50	2.06	119.8	7.5	68.8	7.7	51.0	1.5
12.50	2.35	73.9	7.0	30.1	7.1	43.8	1.2
14.50	3.00	79.3	6.5	29.3	6.6	50.0	1.6
16.50	3.59	72.0	7.1	21.2	7.3	50.8	1.8
18.50	4.18	62.6	5.0	10.5	5.2	52.1	1.4
20.50	4.75	57.4	6.7	11.0	6.8	46.4	1.3

Unsupported ^{210}Pb inventory: 8447±226 Bq m^{-2}

^{210}Pb flux: 263±7 Bq $m^{-2}y^{-1}$

Table 2. Loch Clair: ^{137}Cs and ^{241}Am Data Core CLAI1

Depth	^{137}Cs Conc		^{241}Am Conc	
cm	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±
0.25	457.88	36.63	0.00	0.00
1.25	434.83	18.41	0.00	0.00
3.25	798.79	12.41	4.40	1.31
4.25	840.49	13.46	2.93	1.16
5.50	695.33	5.58	7.78	0.77
6.50	331.31	4.86	1.28	0.63
8.50	64.53	2.25	0.00	0.00
10.50	34.11	1.90	0.00	0.00
11.50	11.25	1.10	0.00	0.00
12.50	11.42	0.75	0.00	0.00
14.50	11.76	1.53	0.00	0.00
16.50	14.25	1.44	0.00	0.00
16.50	0.00	0.00	0.00	0.00
16.50	1.13	0.82	0.00	0.00
Inventories:	7017±152 Bqm^{-2}		33±4 Bqm^{-2}	

Table 3. Loch Clair: ^{210}Pb chronology for Coré CLAI1

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	gcm^{-2}	AD	y	±	$gcm^{-2}y^{-1}$	cmy^{-1}	± (%)
0.00	0.00	1992	0				
0.50	0.03	1991	1	2	0.031	0.43	7.2
1.00	0.06	1990	2	2	0.031	0.33	7.0
1.50	0.11	1988	4	2	0.029	0.27	6.6
2.00	0.17	1986	6	2	0.027	0.24	6.0
2.50	0.24	1983	9	2	0.025	0.21	5.4
3.00	0.30	1981	11	2	0.023	0.18	4.8
3.50	0.36	1978	14	2	0.021	0.16	4.7
4.00	0.44	1975	17	2	0.021	0.14	5.1
4.50	0.52	1971	21	2	0.020	0.13	5.2
5.00	0.60	1967	25	2	0.020	0.12	4.9
5.50	0.68	1963	29	2	0.020	0.12	4.7
6.00	0.77	1958	34	2	0.023	0.12	5.9
6.50	0.86	1954	38	2	0.026	0.12	7.0
7.00	0.97	1950	42	2	0.027	0.12	7.5
7.50	1.09	1946	46	2	0.028	0.12	8.0
8.00	1.20	1942	50	2	0.028	0.12	8.6
8.50	1.31	1938	54	2	0.029	0.12	9.1
9.00	1.44	1933	59	3	0.027	0.12	10.0
9.50	1.56	1928	64	3	0.026	0.11	11.0
10.00	1.68	1924	68	3	0.024	0.10	12.0
10.50	1.81	1919	73	4	0.023	0.09	12.9
11.00	1.94	1914	78	4	0.026	0.10	14.8
11.50	2.08	1909	83	5	0.029	0.11	16.8
12.00	2.21	1905	87	5	0.040	0.14	22.2
12.50	2.35	1901	91	5	0.052	0.17	27.7
13.00	2.51	1897	95	6	0.047	0.15	28.2
13.50	2.68	1893	99	7	0.042	0.14	28.8
14.00	2.84	1889	103	7	0.037	0.12	29.3
14.50	3.00	1886	106	8	0.033	0.11	29.8
15.00	3.15	1880	112	7	0.030	0.10	33.2
15.50	3.30	1875	117	8	0.028	0.09	36.6
16.00	3.44	1870	122	9	0.026	0.09	40.0
16.50	3.59	1864	128	9	0.023	0.08	43.3
17.00	3.74	1858	134	10	0.023	0.08	48.3
17.50	3.88	1851	141	12	0.022	0.08	53.2
18.00	4.03	1845	147	13	0.021	0.07	58.1

Fig.1a

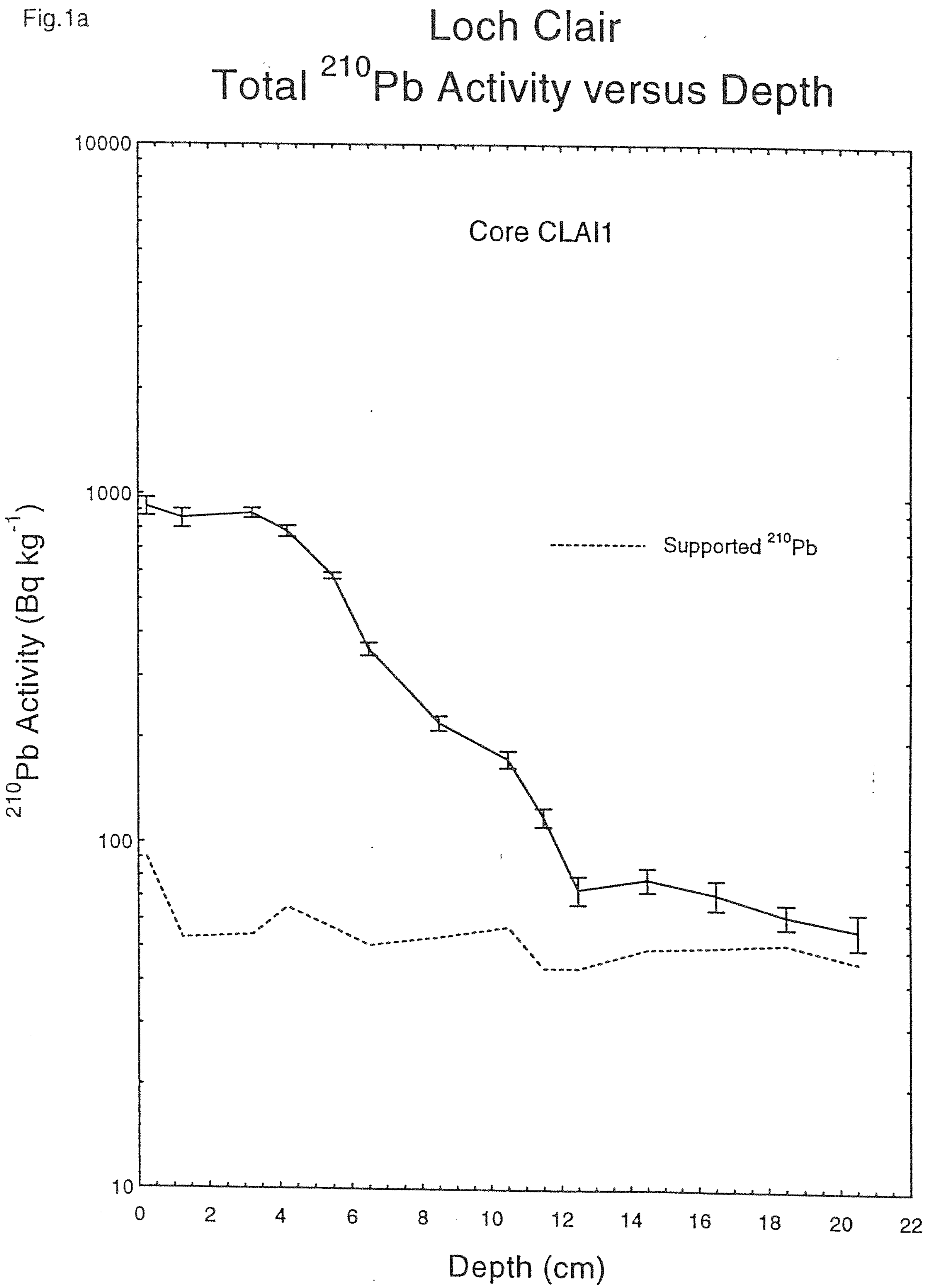

Loch Clair
Total ²¹⁰Pb Activity versus Depth
Core CLAI1
Supported ²¹⁰Pb
10000
1000
100
10
0
2
4
6
8
10
12
14
16
18
20
22
Depth (cm)
²¹⁰Pb Activity (Bq kg⁻¹)

Fig.1b

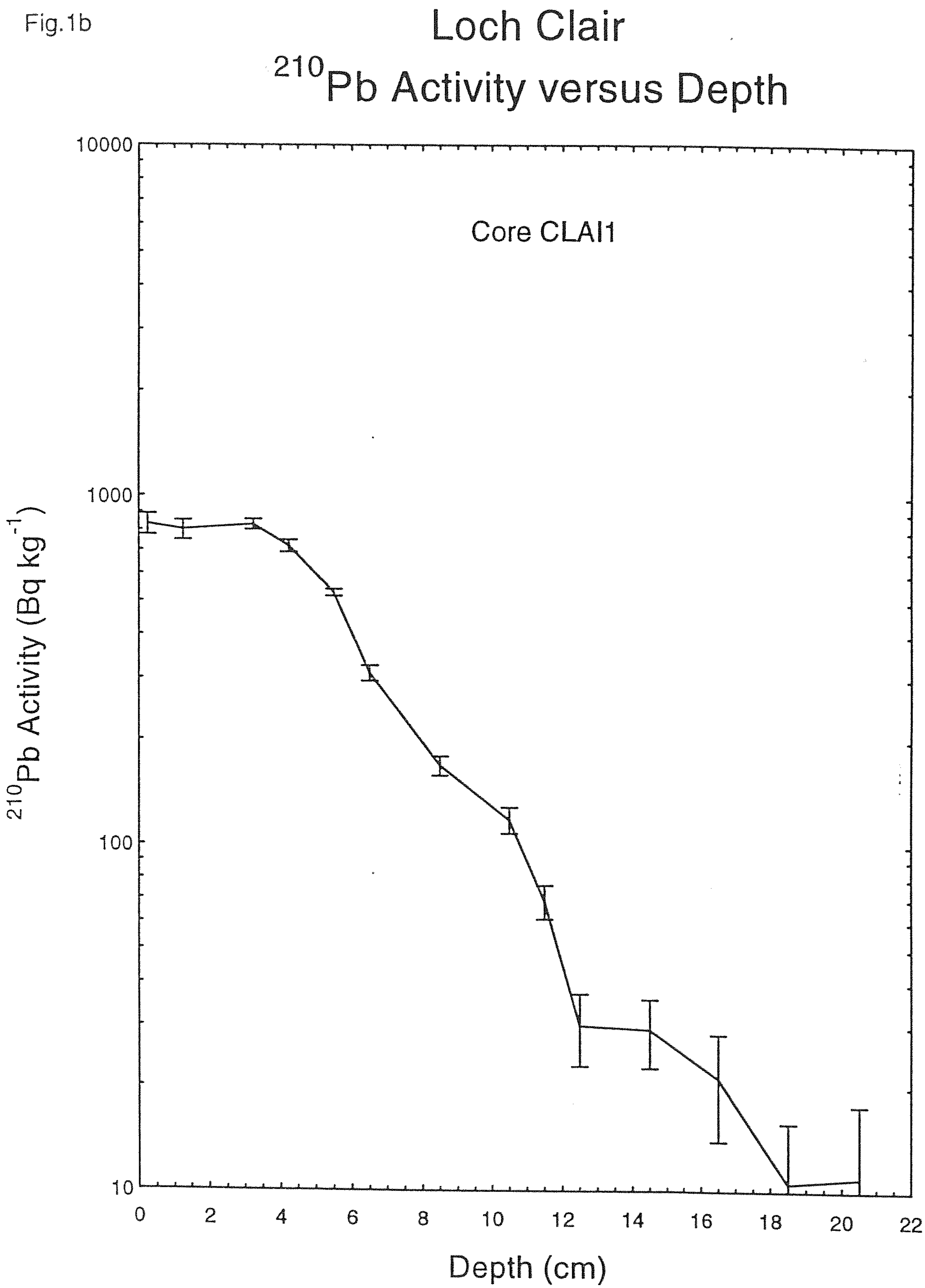

Loch Clair
210Pb Activity versus Depth
Core CLAI1
10000
1000
100
10
210Pb Activity (Bq kg-1)
0
2
4
6
8
10
12
14
16
18
20
22
Depth (cm)

Fig.2

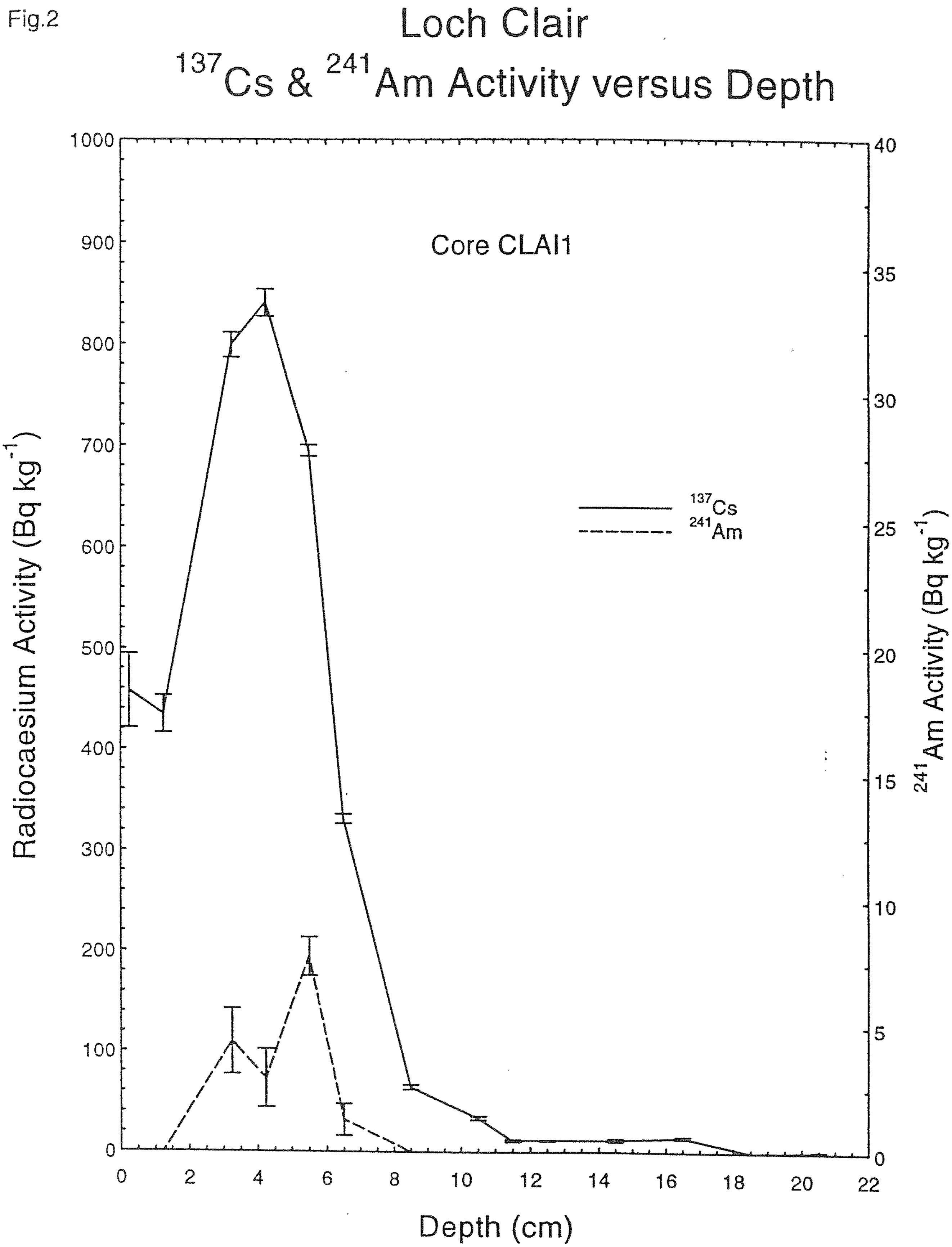
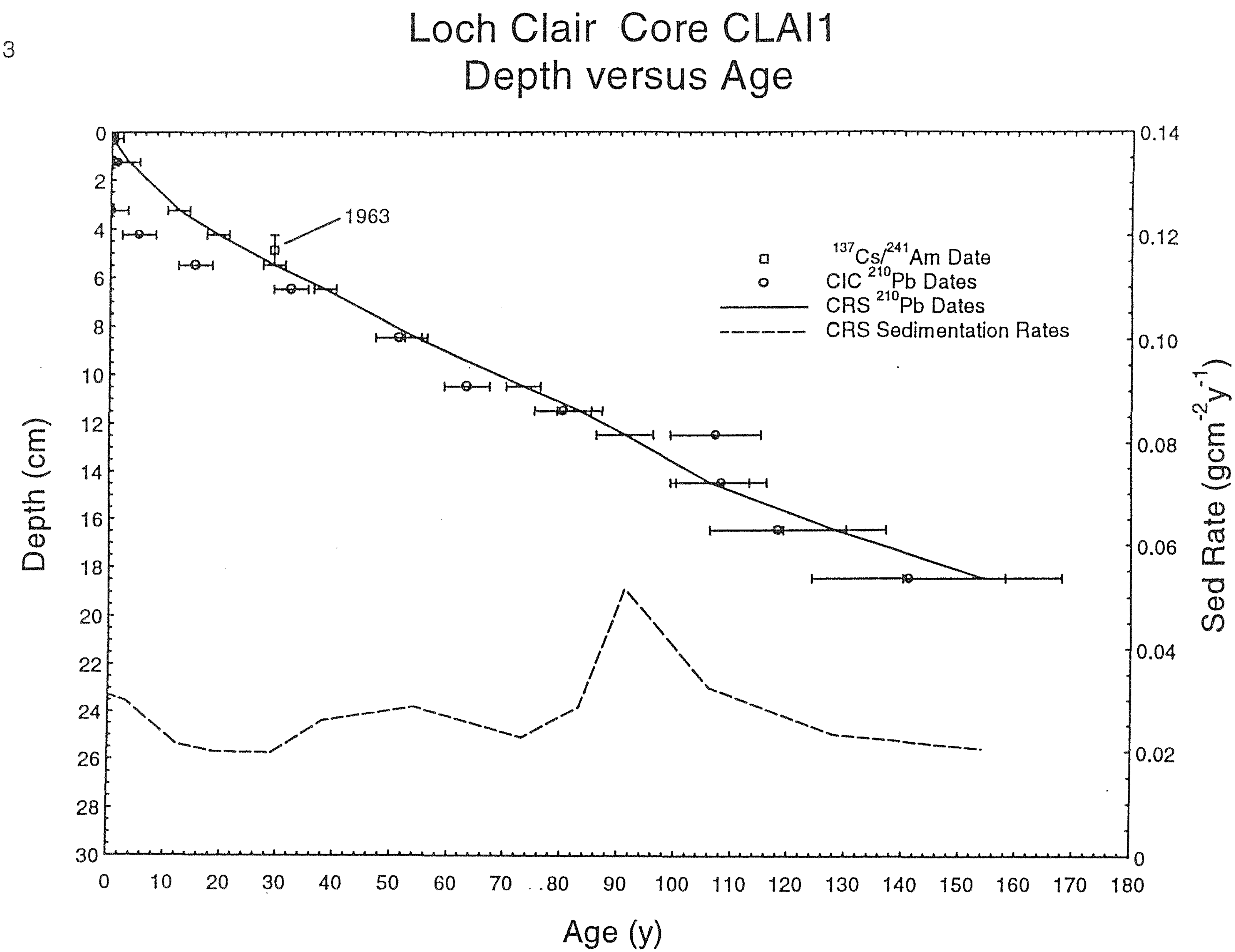

Loch Clair
137Cs & 241Am Activity versus Depth
Core CLAI1
137Cs
241Am
Radiocaesium Activity (Bq kg-1)
241Am Activity (Bq kg-1)
Depth (cm)
0
100
200
300
400
500
600
700
800
900
1000
5
10
15
20
25
30
35
40
2
4
6
8
10
12
14
16
18
20
22

Fig.3



Loch Clair Core CLAI1
Depth versus Age
1963
137Cs/241Am Date
CIC 210Pb Dates
CRS 210Pb Dates
CRS Sedimentation Rates
Depth (cm)
Sed Rate (gcm-2y-1)
Age (y)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

Radiometric Dating of Loch Nam Brac Core BRAC1

Sediment samples from core BRAC1 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using a well-type coaxial low background intrinsic germanium detector fitted with a sodium iodide (NaI(Tl)) escape suppression shield (Appleby *et al.* 1986). The ^{210}Pb and ^{226}Ra results are given in Table 1 and shown graphically in Fig.1 The ^{137}Cs and ^{241}Am results are given in Table 2 and Fig.2.

^{210}Pb dates have been calculated using both the CRS and CIC dating models (Appleby & Oldfield 1978) and the results are shown in Fig.3. Both models suggest a more or less constant sedimentation rate throughout the mid 19th century of 0.0064±0.0007 $gcm^{-2}y^{-1}$, a period of accelerating sedimentation during the late 19th century, and then a further period of stable sedimentation prevailing up to the present day. The mean sedimentation rate for the post-1900 period is calculated to be 0.0110±0.0006 $gcm^{-2}y^{-1}$. The CRS model suggests that the late 19th century increase took place gradually over a period of about 30 years. The CIC model indicates a more abrupt change around the turn of the century, and gives 19th century dates that are ca.15-20 years younger than the corresponding CRS model dates. The CIC model dates would imply a sustained increase in the ^{210}Pb flux of about 170%. Since there are no obvious factors that would cause such an increase, the CRS model dates are preferred, and these form the basis of the detailed chronology given in Table 3.

^{137}Cs activity in the core has its maximum value in the surficial sediments. The ^{210}Pb chronology places 1963 at a depth of 4cm, but there is no obvious record of the 1963 fallout peak at this level. There is however a well defined peak in ^{241}Am activity at 3.75±0.5 cm that would appear to give excellent support to the ^{210}Pb chronology (Appleby *et al.* 1991), as indicated in Fig.3.

The most likely reason for the absence of a subsurface ^{137}Cs peak is post-depositional mobility in the porewaters. Remobilisation of ^{137}Cs from the sediments to the water column may be indicated by the very low $^{137}Cs/^{210}Pb$ inventory ratio in the core compared to that expected from atmospheric fallout. Further contributing factors could be the presence of traces of Chernobyl fallout in the top 2-3cm, and a small amount of physical mixing of the surficial sediments, as evidenced by the uniformity of the ^{137}Cs and ^{210}Pb activity in the top 1cm.

References

Appleby, P.G. and Oldfield, F., 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena*, **5**: 1-8.

Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J. and Battarbee, R.W., 1986. ^{210}Pb dating by low-background gamma counting. *Hydrobiologia*, **143**: 21-27.

Appleby, P.G., Richardson, N. and P.J. Nolan, 1991. ^{241}Am dating of lake sediments. *Hydrobiologia*, **214**: 35-42.

Table 1. Loch Nam Brac: ^{210}Pb Data Core BRAC1

Depth	Dry Mass	^{210}Pb Concentration Total		Unsupp		^{226}Ra Concentration	
cm	gcm^{-2}	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±
0.25	0.01	2297.1	68.9	2181.3	69.6	115.8	10.1
1.25	0.07	2384.0	83.6	2286.2	84.4	97.8	12.2
2.25	0.16	1786.8	62.0	1652.9	62.8	133.9	10.1
3.25	0.26	1607.7	39.5	1499.8	39.9	107.9	5.9
4.25	0.36	1315.0	44.2	1223.3	44.8	91.7	7.2
6.50	0.57	673.6	19.2	593.1	19.4	80.5	3.1
8.50	0.76	418.9	18.4	350.6	18.6	68.3	2.7
10.50	0.95	305.9	13.7	214.9	14.0	91.0	3.0
12.50	1.13	237.7	10.4	156.5	10.7	81.2	2.3
14.50	1.33	175.2	13.2	80.8	13.6	94.4	3.3
16.50	1.53	103.8	9.1	22.9	9.3	80.9	1.8
20.50	1.91	85.9	7.3	7.6	7.6	78.3	1.9

Unsupported ^{210}Pb inventory: 10139±235 Bq m^{-2}

^{210}Pb flux: 316±7 Bq $m^{-2}y^{-1}$

Table 2. Loch Nam Brac ^{137}Cs and ^{241}Am Data Core BRAC1

Depth	^{137}Cs Conc		^{241}Am Conc	
cm	$Bq\ kg^{-1}$	±	$Bq\ kg^{-1}$	±
0.25	607.82	48.63	0.00	0.00
1.25	606.85	24.18	19.94	4.38
2.25	542.95	18.99	22.54	3.50
3.25	466.83	11.47	30.52	2.57
4.25	291.57	12.10	28.46	3.01
6.50	112.52	3.96	2.61	0.90
8.50	66.14	2.88	0.00	0.00
10.50	49.25	2.77	0.00	0.00
12.50	33.72	1.95	0.00	0.00
14.50	26.27	2.58	0.00	0.00
16.50	14.96	0.99	0.00	0.00
20.50	3.35	1.17	0.00	0.00
Inventories:	2724±64 Bqm^{-2}		116±8 Bqm^{-2}	

Table 3. Loch Nam Brac: ^{210}Pb chronology for Core BRAC1

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	gcm^{-2}	AD	y	±	$gcm^{-2}y^{-1}$	cmy^{-1}	± (%)
0.00	0.00	1992	0				
0.50	0.02	1990	2	2		0.228	
1.00	0.06	1988	4	2		0.173	
1.50	0.09	1985	7	2		0.142	
2.00	0.14	1981	11	2		0.135	
2.50	0.19	1977	15	2		0.127	
3.00	0.23	1973	19	2		0.120	
3.50	0.28	1968	24	2			
4.00	0.33	1964	28	2			
4.50	0.38	1959	33	2	0.0110		5.5
5.00	0.43	1954	38	2			
5.50	0.47	1950	42	2			
6.00	0.52	1946	46	2		0.114	
6.50	0.57	1941	51	2			
7.00	0.62	1937	55	2			
7.50	0.66	1932	60	2			
8.00	0.71	1928	64	2			
8.50	0.76	1924	68	2			
9.00	0.81	1919	73	2	0.0108	0.114	8.0
9.50	0.85	1915	77	3	0.0107	0.113	8.6
10.00	0.90	1911	81	3	0.0105	0.111	9.1
10.50	0.95	1906	86	3	0.0103	0.110	9.7
11.00	0.99	1901	91	3	0.0096	0.102	10.7
11.50	1.04	1896	96	4	0.0088	0.093	11.7
12.00	1.09	1890	102	4	0.0081	0.085	12.7
12.50	1.13	1885	107	4	0.0074	0.077	13.7
13.00	1.18	1877	115	5	0.0069	0.072	17.5
13.50	1.23	1870	122	6			
14.00	1.28	1862	130	7			
14.50	1.33	1855	137	8			
15.00	1.38	1847	145	10	0.0064	0.065	~11%
15.50	1.43	1839	153	12			
16.00	1.48	1832	160	13			
16.50	1.53	1824	168	15			

Fig.1a

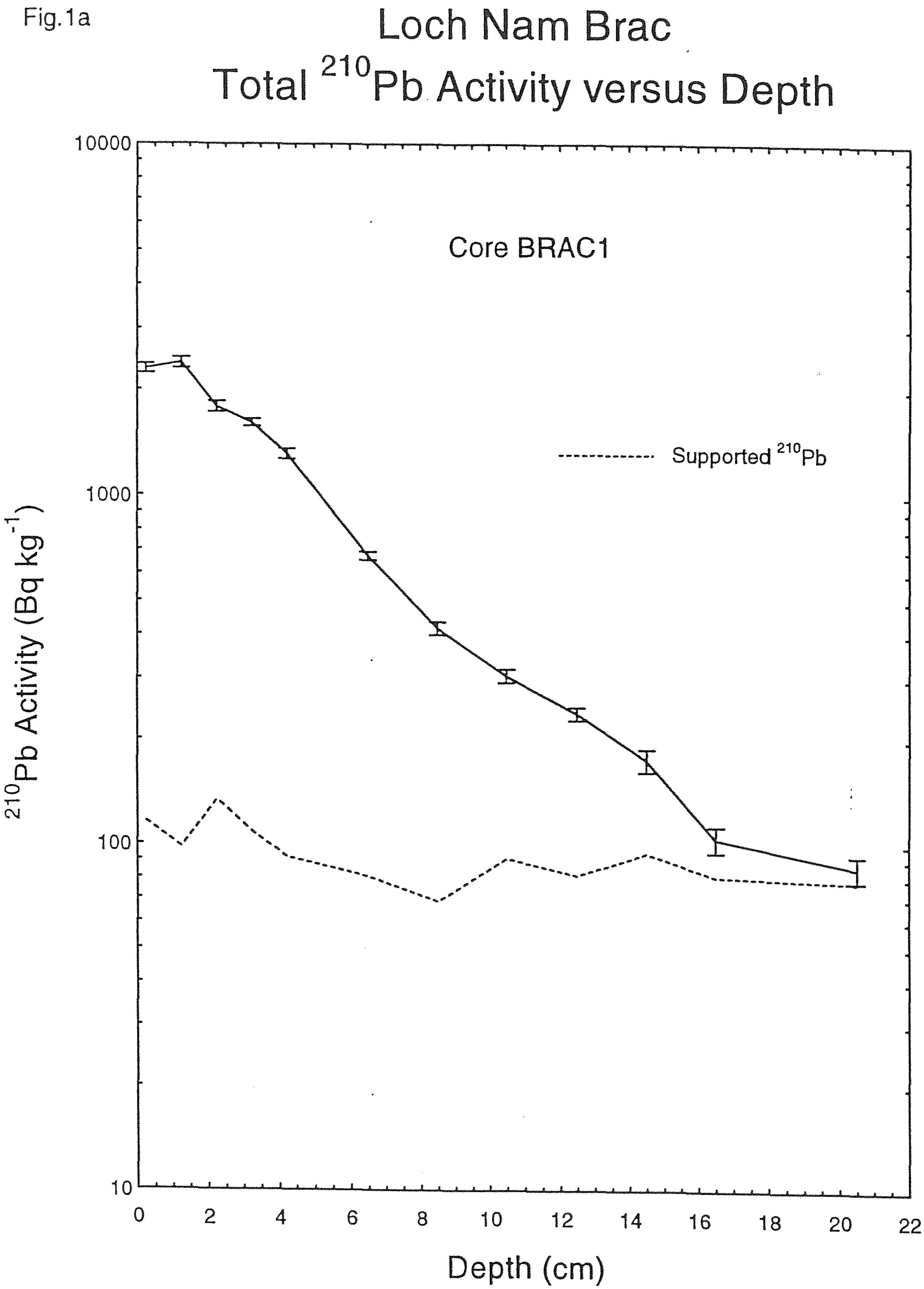

Loch Nam Brac
Total 210Pb Activity versus Depth
Core BRAC1
Supported 210Pb
210Pb Activity (Bq kg-1)
10000
1000
100
10
0
2
4
6
8
10
12
14
16
18
20
22
Depth (cm)

Fig.1b

Loch Nam Brac
Unsupported ^{210}Pb Activity versus Depth

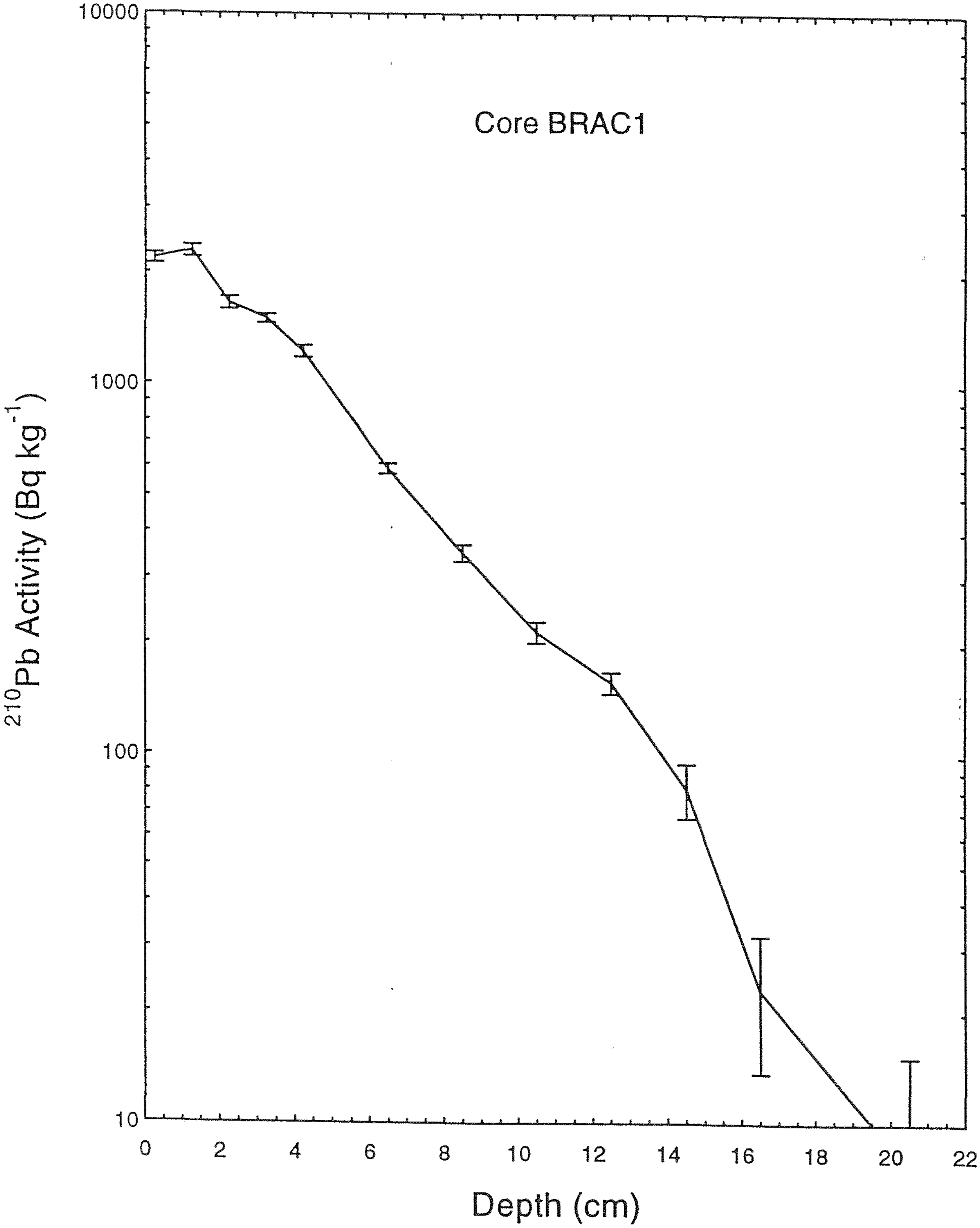


Fig.2

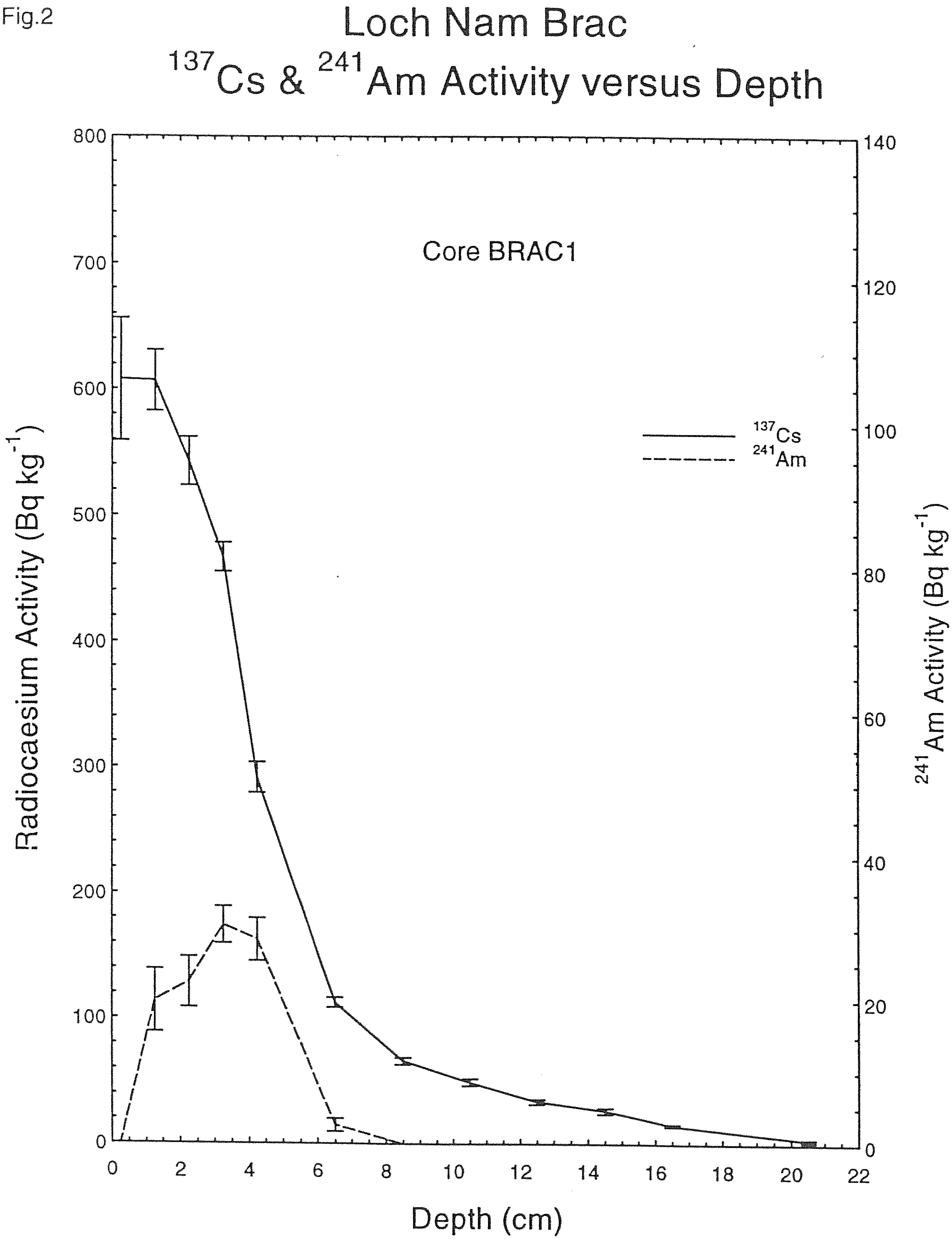
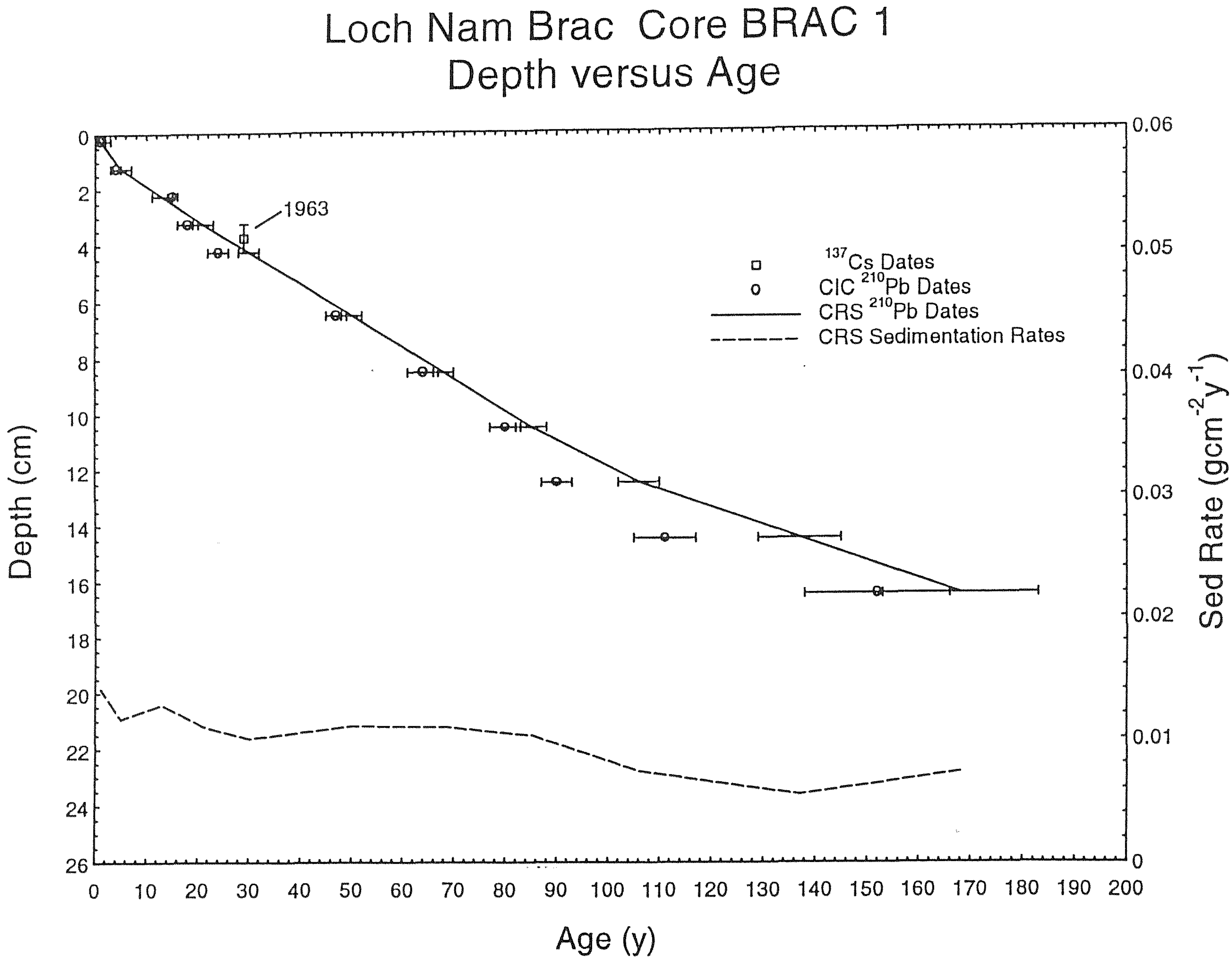

Loch Nam Brac
137Cs & 241Am Activity versus Depth
Core BRAC1
137Cs
241Am
Radiocaesium Activity (Bq kg-1)
241Am Activity (Bq kg-1)
Depth (cm)
0
100
200
300
400
500
600
700
800
20
40
60
80
120
140
2
4
6
8
10
12
14
16
18
22

Fig.3



Loch Nam Brac Core BRAC 1
Depth versus Age
1963
137Cs Dates
CIC 210Pb Dates
CRS 210Pb Dates
CRS Sedimentation Rates
Depth (cm)
Sed Rate (gcm-2y-1)
Age (y)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0.06
0.05
0.04
0.03
0.02
0.01
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200