IMPORTANCE OF SURFACE SEDIMENTS FOR RELIABLE 210Pb DATING

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ABSTRACT

Lead-210, ^{137}Cs and ^{241}Am dating techniques have been extensively used in the dating of recent sediments. However, collection of an intact core is the first essential step towards having reliable ^{210}Pb chronologies for the sediments. We collected short gravity cores from Loch Morar, a deep (310 m max. depth), steep-sided lake in Scotland. Lead-210 chronologies for one of the cores did not match with the ^{137}Cs and ^{241}Am records, and the radionuclide data indicate that surface sediments in this core were likely missing. Therefore, sediment chronologies and accumulation rates calculated from unsupported ^{210}Pb activities in the core were deemed unreliable, as confirmed by another core from the same lake. Dating of the cores suggests that sediment dating not only depends on accurate counting of radionuclide activities, but also on the integrity of the cores, in turn determined by sampling location. Importantly, however ^{210}Pb, ^{137}Cs and ^{241}Am data can be carefully assessed to determine the integrity of sediment cores.

Keywords: Sediment dating, Pb-210, Cs-137, Intact sediment core, Reliable chronology

INTRODUCTION

^{210}Pb (half-life 22.3 years) is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). Cesium (half-life 30 years) and ^{241}Am are artificially-produced radionuclides, introduced to the environment by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. They have been extensively used in the dating of recent sediments to establish the timing of ecological or environmental changes, especially in lakes for which long-term limnological data are lacking.

For calculating sediment chronologies based on unsupported ^{210}Pb activities, several models have been developed, including the Constant Rate of ^{210}Pb Supply (CRS) model and the Constant Initial Concentration (CIC) model [1]. Where possible, independent assessments of a 1963 date are also used, derived from the peak activities of ^{137}Cs and ^{241}Am stratigraphic records. These represent a global peak in fall-out prior to the Partial Nuclear Test Ban Treaty in that year. In regions where it is detectable, a second peak in ^{137}Cs occurs in 1986 due to the Chernobyl nuclear reactor accident in Ukraine. In general, ^{210}Pb chronologies need to be validated by independent time markers such as ^{137}Cs and ^{241}Am peaks.

While the CRS model is suitable in most cases, the CIC model may provide a valid alternative if primary sedimentation rates have been constant. In many cases, one or other of these simple models is valid for use. In complex situations, it may be necessary to apply them in a 'piece-wise' way to different sections of the sediment sequence.

However, all of these assumptions are based on collection of an intact core. If surface sediments are missing from a core, as can occur through in-lake sediment slumping events prior to sampling or during sample collection, the real age of the surface in the collected core is unknown. In this case, ^{210}Pb dating is problematic, and the chronologies are difficult to match with the ^{137}Cs and ^{241}Am dates. Conversely, it may suggest changes in ^{210}Pb deposition or sedimentation, or even lack of surface sediments.

This study provides an example to show the importance of surface sediments for ^{210}Pb dating, and how to examine ^{137}Cs, ^{241}Am and ^{210}Pb activities in sediment core to assess if the surface sediments are missing.

METHODS

Study Site

Loch Morar is a freshwater loch, lying in a glacial trough, orientated on an east-west axis and dammed by a natural rock threshold, in Lochaber, Highlands, Scotland (Fig. 1). It is the fifth-largest loch by surface area in Scotland, at 26.7 km^2, and the deepest freshwater body in the British Isles, with a maximum depth of 310 m. The loch was created by glacial action around 10,000 years ago, and has a surface elevation of 9 metres above sea level. The loch is designated as Site of Special Scientific Interest (SSSI) for its clear, oligotrophic waters and has a low catchment to lake ratio (6.3), with a minimal intake of nutrients.

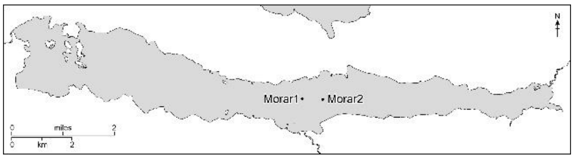

Fig. 1 Sampling locations of the sediment cores (MORAR1 and MORAR2) at Loch Morar, Scotland, UK

Sample Collection and Gamma Dating

Two sediment cores were taken in February 2015, MORAR1 and MORAR2, at depths of 310m and 285m respectively, using an HTH Renberg gravity corer [2]. The sediment cores were sampled at 0.25 cm intervals throughout the cores using the HTH extrusion device [2]. Sediment wet density measurements were conducted using a 2cm^3 container. Moisture content and organic matter (as loss-on-ignition) were measured according to standard methods [3], samples were then freeze-dried.

Dried sediment samples from the cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV [4]. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy gamma rays within the sample [5].

RESULTS AND DISSCUSION

Core MORAR1

Lead-210 Activity

The base of the core has not reached equilibrium depth of total ^{210}Pb activity with supported ^{210}Pb activity. Unsupported ^{210}Pb activities, calculated by subtracting supported ^{210}Pb activity from total ^{210}Pb activity, decline with depth more or less following an exponential trend with some small departures (Fig. 2b; Table1), suggesting relatively stable sedimentation rates with small changes.

Table 1 ^{210}Pb concentrations in core MORAR1 taken from Loch Morar, Scotland

Depth	Dry Mass	Pb-210			
		Total		Unsupported	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.75	0.0283	2815.55	155.49	2719.35	157.57
2.75	0.1796	2338.25	73.19	2261.93	74.18
4	0.2845	2441.88	121.75	2392.41	123.29
5.13	0.3932	1557.29	80.58	1527.82	81.71
6.5	0.5311	1084.52	92.35	992.13	94.44
7.5	0.6336	1630.72	80.55	1561.09	82.29
8.38	0.7168	1557.31	38.18	1512.71	38.6
9.25	0.8002	968.33	85.08	878.63	88.63
11.13	0.9878	856.29	27.24	810.35	27.6
12.13	1.0835	598.03	25.34	550.86	25.78
14.38	1.3071	506.86	41.72	400.15	43.07
15.38	1.4125	479.68	20.81	430.29	21.19
16.13	1.492	572.06	14.72	521.87	14.96
17.25	1.6084	454.93	19.22	416.16	19.59

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Fig. 2c; Table2) shows two peaks at 5.13 and 8.38 cm, which are likely to be derived from fallout of 1986 Chernobyl accident and the atmospheric testing of nuclear weapons with maximum fallout in 1963, respectively. Notable ^{241}Am activities between 5.13 and 12.13 cm sediments confirm nuclear weapon testing fallout.

Table 2 Artificial fallout radionuclide activities in core MORAR1

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.75	149.91	19.62	0	0
2.75	361.52	13.99	0	0
4	426.19	24.6	0	0
5.13	479.6	19.39	13.25	4.37
6.5	378.1	22.9	13.29	6.99
7.5	475.48	18.86	0	0
8.38	481.51	9.55	18.74	2.32
9.25	414.33	20.14	0	0
11.13	343.49	6.86	21.78	2.01
12.13	208.19	5.96	12.9	1.94
14.38	75.73	7.33	0	0
15.38	78.62	3.52	0	0
16.13	70.92	2.32	0	0
17.25	54.24	3.24	0	0

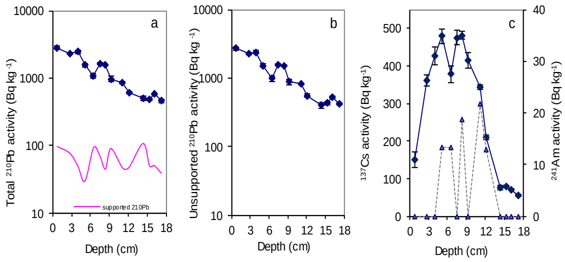

Fig. 2 Fallout radionuclide concentrations in core MORAR1, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs and ^{241}Am concentrations versus depth

Core Chronology and Sedimentation Rates

The simple CRS and CIC models all place 1963 at around 12.13 cm, which is considerably deeper than the 1963 depth suggested by the ^{137}Cs record, while the CRS model puts 1986 depth at 7.5 cm, also deeper than the ^{137}Cs peak at 5.13 cm (Fig. 3). In addition, both models suggest a relatively uniform sedimentation rate with a mean value of 0.023 ± 0.003 g cm^{-2} yr^{-1}. If we assume that the sediments at 8.4 cm was formed in 1963/4, with a mean sedimentation rate of 0.023 g cm^{-2} yr^{-1}, the surface of the core can be assigned to 1995. All of these suggest that the real surface sediments of the core might be missing.

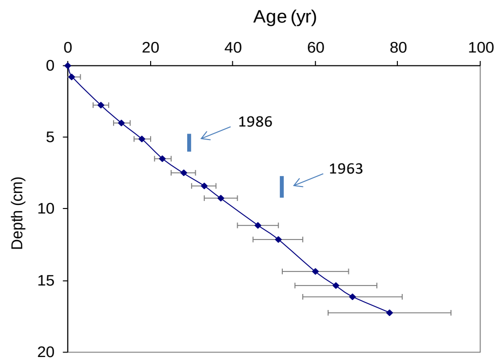

Fig 3 Radiometric chronology of core MORAR1 taken from Loch Morar, Scotland, showing the CRS model ^{210}Pb dates and the ^{137}Cs and ^{241}Am time markers

Core MORAR2

Lead-210 Activity

Similar to MORAR1, unsupported ^{210}Pb activities in MORAR2 also decline more or less exponentially with depth. However, there is little net decline in unsupported ^{210}Pb activities in the top 4 cm (Fig. 4b; Table 3), suggesting possible increase in sedimentation rates towards the sediment surface. There are some small fluctuations in unsupported ^{210}Pb activities at different depths such as at 12 cm and 26 cm, which also suggest possible changes in sedimentation rates. Overall, the more or less exponential decline would suggest that changes in sedimentation rates are relatively small.

Table 3 ^{210}Pb concentrations in core MORAR2 taken from Loch Morar, Scotland

Depth	Dry Mass	Pb-210			
		Total		Unsupported	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.13	0.0051	3047.33	103.04	2957.5	104.28
1.38	0.067	2957.65	89.8	2892.36	90.81
2.38	0.1235	3095.23	97.13	3046.02	97.87
3.88	0.2176	2921.98	79.08	2876.44	79.58
4.63	0.2669	2596	66.1	2538.01	66.54
5.38	0.3213	2330.34	69.74	2272.17	70.32
6.13	0.3866	1974.62	65.88	1931.42	66.49
7.13	0.472	1894.95	62.8	1854.19	63.36
8.63	0.5967	1628.99	42.4	1582.94	42.8
9.88	0.6958	1281.72	36.58	1235.44	36.97
10.63	0.7621	1077.74	32.5	1021.84	32.86
11.88	0.8808	1061.52	45.51	993.45	46.04
12.88	0.9746	1091.49	44.08	1041.36	44.53
13.88	1.0665	1062.74	45.78	1021.64	46.32
14.88	1.1603	875.27	43.28	821.3	43.8
15.88	1.2561	861.91	42.54	806.12	43.03
16.88	1.356	691.74	25.96	642.42	26.32
17.88	1.4586	655.19	42.22	613	42.84
18.88	1.5658	594.58	25.22	538.72	25.64
20.13	1.6981	484.47	22.27	429.19	22.76
22.13	1.9124	388.73	23.81	341.88	24.47
24.13	2.1335	312.52	18.91	258.98	19.36
26.13	2.3657	312.9	21.8	255.56	22.36
28.13	2.6085	198.52	16.98	141.71	17.54
30.13	2.8624	135.46	15.33	82.84	15.89
32.13	3.1332	109.51	11.81	57.46	12.2

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Fig. 4c; Table 4) also shows two peaks: The peak at around 13 -15 cm derived from maximum fallout of the atmospheric testing of nuclear weapons in 1963, and the peak at 8.5 – 10 cm from the 1986 Chernobyl accident fallout. The ^{241}Am profile of the core also shows a good peak at around 15.88 cm, confirming that the ^{137}Cs peak at around 13 – 15 cm was derived from the atmospheric testing of nuclear weapons.

Table 4 Artificial fallout radionuclide concentrations in core MORAR2

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.13	251.17	13.59	0	0
1.38	224.99	12.25	0	0
2.38	265.03	14.67	0	0
3.88	379.39	12.98	0	0
4.63	393.02	11.36	0	0
5.38	453.44	13.72	10.47	3.66
6.13	520.92	14.61	5.51	3.45
7.13	555.38	14.34	12.17	3.43
8.63	578.91	10.48	9.38	2.4
9.88	565.48	9.7	9.21	2.36
10.63	488.82	8.46	13.07	2.08
11.88	487.58	11.91	13.68	3.13
12.88	496.55	11.53	23.24	3.07
13.88	548.68	12.9	25.73	3.56
14.88	548.43	12.85	31.43	3.42
15.88	437.16	11.08	34.79	3.31
16.88	268.54	6.08	21.11	2
17.88	176.52	8.91	7.63	2.97
18.88	131.23	4.88	4.28	1.86
20.13	90.57	3.71	0	0
22.13	67.76	4.02	0	0
24.13	42.96	3.08	0	0
26.13	32.5	2.87	0	0
28.13	30.55	2.53	0	0
30.13	16.52	2.06	0	0
32.13	11.45	1.43	0	0

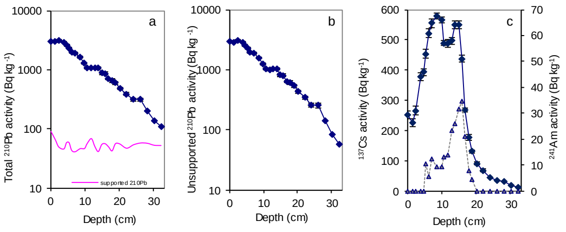

Fig. 4 Fallout radionuclide concentrations in core MORAR2, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs and ^{241}Am concentrations versus depth

Core Chronology

Use of the CIC model was precluded by the non-monotonic features in the unsupported ^{210}Pb profile. Lead-210 dates were calculated using the CRS model [3]. The simple CRS dating model places 1963 and 1986 at c. 16.5 and c. 10 cm, respectively, which are in reasonable agreement with the ^{137}Cs and ^{241}Am records. Sediment accumulations calculated using ^{210}Pb data in the core are given in Table 5 and shown in Fig. 5. Overall, sedimentation rates were relatively stable over the last one and half centuries or so, with a mean at 0.022 g cm^{-2} yr^{-1}.

Table 5 ^{210}Pb chronology of core MORAR2 taken from Loch Morar, Scotland

Depth	Dry mass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2015	0				
0.13	0.0051	2015	0	2	0.0283	0.582	3.8
1.38	0.067	2013	2	2	0.027	0.512	3.5
2.38	0.1235	2010	5	2	0.0239	0.396	3.6
3.88	0.2176	2006	9	2	0.0223	0.349	3.2
4.63	0.2669	2004	11	2	0.0236	0.341	3.2
5.38	0.3213	2002	13	2	0.0246	0.308	3.6
6.13	0.3866	1999	16	2	0.0267	0.31	3.9
7.13	0.472	1996	19	2	0.0251	0.299	4
8.63	0.5967	1991	24	2	0.0252	0.31	3.5
9.88	0.6958	1987	28	2	0.0288	0.348	3.8
10.63	0.7621	1985	30	2	0.0325	0.352	4
11.88	0.8808	1981	34	2	0.0297	0.315	5.3
12.88	0.9746	1978	37	2	0.0255	0.275	5.1
13.88	1.0665	1974	41	2	0.0231	0.249	5.5
14.88	1.1603	1970	45	2	0.0255	0.269	6.3
15.88	1.2561	1966	49	2	0.0229	0.234	6.5
16.88	1.356	1962	53	2	0.0253	0.25	5.8
17.88	1.4586	1958	57	2	0.0232	0.221	8.3
18.88	1.5658	1953	62	2	0.0229	0.215	7
20.13	1.6981	1948	67	2	0.0241	0.226	8
22.13	1.9124	1939	76	3	0.0227	0.209	10.3
24.13	2.1335	1929	86	3	0.0221	0.195	12.2
26.13	2.3657	1916	99	5	0.0151	0.127	16.1
28.13	2.6085	1901	114	7	0.0169	0.136	24.1
30.13	2.8624	1886	129	10	0.0184	0.14	36.5
32.13	3.1332	1871	144	16	0.0164	0.123	45.6

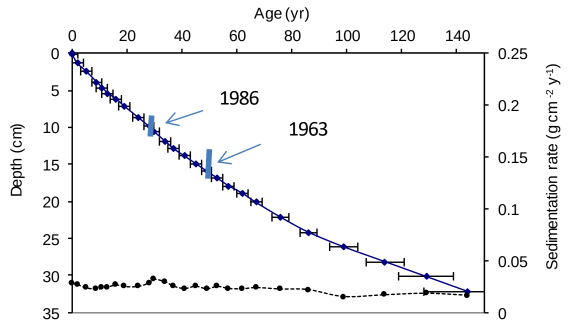

Fig. 5 Radiometric chronology of core MORAR2 taken from Loch Morar, Scotland, showing the CRS model ^{210}Pb dates, ^{137}Cs time markers, and sedimentation rates. The solid line shows age while the dashed line indicates sedimentation rate.

Lead-210 chronologies in MORAR2 match the dates suggested by the ^{137}Cs and ^{241}Am records of the core, while there are considerable discrepancies between ^{210}Pb and ^{137}Cs ages in MORAR1. Although unsupported 210Pb activities in the surface sediments of MORAR2 only slightly higher than that in MORAR1, they show a clear relatively uniform in the top 4 cm, while MORAR1 does not show this feature. Comparison of MORAR1 and MORAR2 would also suggest that the real surface sediments in MORAR1 are likely to be missing.

This study shows that having an intact sediment core is important for ^{210}Pb dating, and that lack of surface sediments could result in inaccurate chronologies. Sediment ^{210}Pb chronologies need to be validated by independent time markers. By examining sediment ^{210}Pb, ^{137}Cs and ^{241}Am data, the integrity of sediment cores can be assessed.

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REFERENCES

[1] Appleby PG, Chronostratigraphic techniques in recent sediments, Tracking Environmental Change Using Lake Sediments. Last and Smol, Ed. Vol. 1, Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, 2001, pp. 171-203.

[2] Renberg I, Hansson H. The HTH sediment corer, J. Paleolimnol., Vol. 44, 2008, pp. 655-659.

[3] Heiri O, Lotter AF, Lemcke G, Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results, J. Paleolimnol., Vol. 25, 2001, pp. 101-110.

[4] Appleby PG, Nolan PJ, Gifford DW, Godfrey MJ, Oldfield F, Anderson NJ, Battarbee RW, 210Pb dating by low background gamma counting, Hydrobiologia, Vol. 141, 1986, pp. 21-27.

[5] Appleby PG, Richardson N, Nolan PJ, Self-absorption corrections for well-type germanium detectors, Nucl. Inst. & Methods B, Vol. 71, 1992, pp. 228-233.