Radiometrically determined dates and sedimentation rates for recent sediments in nine North African wetland lakes: the CASSARINA Project

Aquatic Ecology **35:** 347-367, 2001.

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Accepted 9 April 2001

Key words: lake sediments, North Africa, radiometric dating, ^{210}Pb, ^{137}Cs

Abstract

Sediment cores were collected from nine wetland lakes in Morocco, Tunisia and Egypt for the CASSARINA project investigating environmental change in Northern African wetlands. The cores were dated radiometrically by using natural (^{210}Pb) and artificial (^{137}Cs and ^{241}Am) radionuclides. At sites in Morocco and Tunisia with mean annual rainfall totals ranging from 500–1000 mm yr^{-1}, fallout records were generally satisfactory and it was possible to develop independent sediment chronologies based on the radiometric data alone. At the Egyptian sites, rainfall was less than 200 mm yr^{-1} and fallout records were much less distinct. At these sites the radiometric data could only be used to give an indication of mean sedimentation rates during the past 30–40 years. By using a combination of fallout radionuclide, pollen, and macrofossil stratigraphic records it was however possible to determine a credible sediment chronology spanning the major part of the 20th century. Applying this chronology to records of spheroidal carbonaceous particles (SCP) from the same sediment cores, the onset of significant levels of atmospheric pollution in the Nile Delta is dated in all three cores to the mid 1950s. Results from a number of lakes (Sidi Bou Rhaba, Ichkeul and Korba) revealed high and accelerating siltation rates, threatening their continued existence beyond the next few decades. In contrast, sedimentation rates at all three Nile Delta sites appear to have declined in recent decades, most probably due to the impact of the Nile barrages.

Introduction

Palaeolimnological techniques have been widely used in Europe and North America to reconstruct histories of recent environmental change from records in lake sediments. Of critical importance to this approach is a reliable means for dating sediment records. The most widespread technique on time-scales spanning the past 100–150 years uses the natural fallout radionuclide ^{210}Pb. The method is unequivocal where the unsupported ^{210}Pb concentration versus depth pro- file follows a simple exponential relation. Deviations from such a relation are however to be expected at sites where sedimentation rates have not been constant. Different models have been developed to account of such deviations (Appleby & Oldfield, 1978; Robbins, 1978) and the accuracy of ^{210}Pb dates in these cases will depend on the validity of the model used. The question is usually resolved by comparing dates given by the simple ^{210}Pb models with independently determined dates from stratigraphic records of the artificial fallout radionuclides ^{137}Cs (Pennington et al., 1973) and ^{241}Am (Appleby et al., 1991) from the atmospheric testing of nuclear weapons, or the 1986 Chernobyl reactor accident. The methods have previously been used successfully at a number of sites in Morocco (Flower et al., 1989) and Tunisia (Stevenson & Battarbee, 1991). This study is part of the CASSARINA project, an investigation of change, stress, sustainability and aquatic ecosytem resilience in North African wetlands during the 20th century (Flower, 2001). Palaeolimnological investigations were carried out in nine wetland lakes in coastal areas extending from north-west Morocco to the Nile Delta in Egypt. The objective of the present paper is to give an account of the fallout records in sediment cores from these lakes and to construct sediment chronologies based on these records. These dates are essential for dating changes in biostratigraphic records of the lake ecosystems (see Birks et al., 2001a, b; Peglar et al., 2001; Ramdani et al., 2001a; Flower et al., 2001) and for estimating sediment accumulation rates.

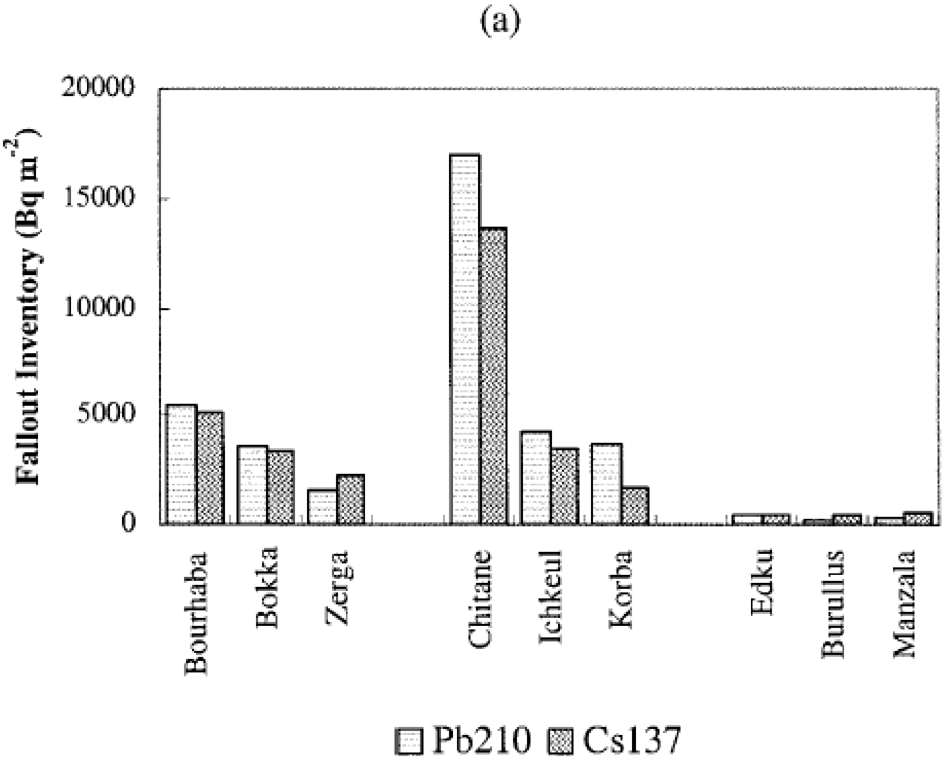
Figure 1. Map of the CASSARINA sites showing the locations of (1) Sidi Bou Rhaba, (2) Merja Zerga, (3) Merja Bokka, (4) Megene Chitane, (5) Gaeret El Ichkeul, (6) Lac de Korba, (7) Lake Edku, (8) Lake Burullus and (9) Manzala Lake.

Study sites

The sediment cores were all from shallow lakes or lagoons (mean depths less than 2 m) adjacent to or within a few kilometres of the coast. Three were located in north-west Morocco, three in northern Tunisia, and three in the Nile Delta, Egypt (Figure 1). Their surface areas vary from about 1 ha (Megene Chitane) to 910 km^2 (Manzala Lake). Mean annual rainfall during the past 50 years or so was 530– 550 mm yr^{-1} at the Moroccan sites, 450–920 mm yr^{-1} at the Tunisian sites, and 120–180 mm yr^{-1} at the Nile Delta sites in Egypt. The main physiographic parameters for each site are given in Table 1, together with a list of the cores discussed in this paper. More detailed site descriptions are given in Flower (2001), Ramdani et al. (2001b) and Fathi et al. (2000).

Methods

Sediment cores of up to 2 m in length were collected from each site using a rod operated piston corer and sectioned at intervals ranging from 1–2 cm (Flower, 2001). Sub-samples of dried sediment from each section of the cores listed in Table 1 were analysed at the University of Liverpool Environmental Radioactivity Research Centre for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). 210Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV, respectively. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy γ-rays within the sample (Appleby et al., 1992). Supported ^{210}Pb in each sample was assumed to be in equilibrium with the *in situ* ^{226}Ra. Unsupported ^{210}Pb was calculated by subtracting ^{226}Ra activity from total ^{210}Pb. Radiometric dates were calculated from the ^{210}Pb and ^{137}Cs records using the procedures described in Appleby and Oldfield (1983) and Appleby (1998). At sites with poor records of fallout radionuclides additional chronostratigraphic evidence was sought from macrofossil, pollen and spheroidal carbonaceous particle (SCP) records. Details of the analytical methods used are given in Birks et al. (2001a), Peglar et al. (2001), and Rose (1994).



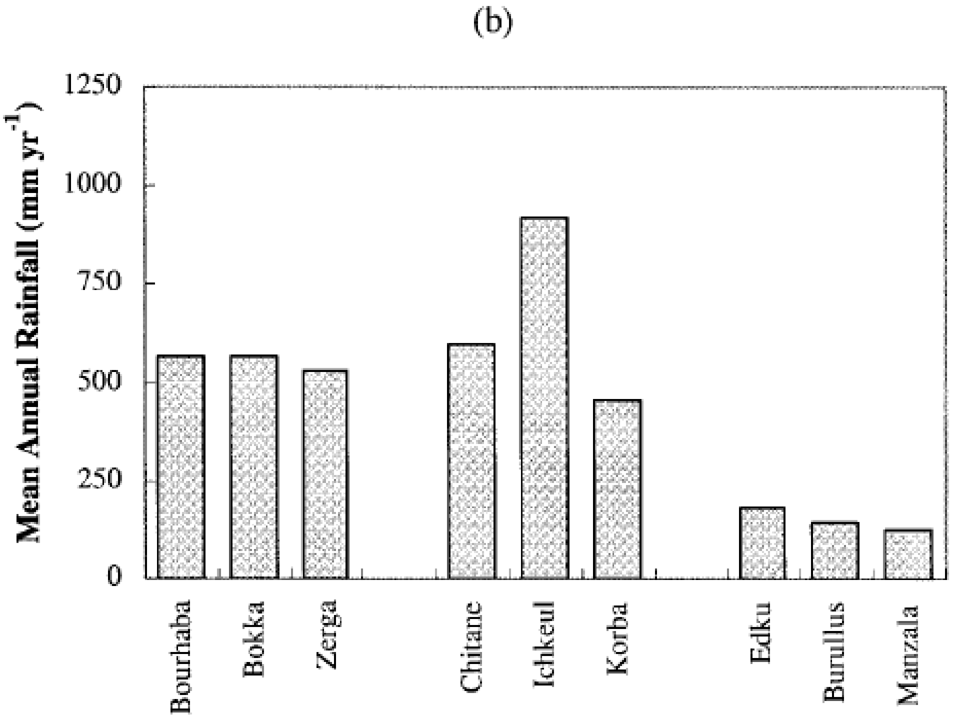


Figure 2. (a) Fallout ^{210}Pb and ^{137}Cs inventories in each of the CASSARINA cores compared with (b) mean annual rainfall at each site.

Table 1. Main site parameters for the CASSARINA lakes, and the list of cores analysed for fallout radionuclides

	Latitude	Longitude	Mean annual rainfall (mm yr^{-1})	Lake area (km^2)	Water type	Mean depth (m)	Dated core
Morocco							
Sidi Bou Rhaba	34°14′ N	6°40′ W	550	1.57	Fresh	1–2	RHAB2
Merja Zerga	34°50′ N	6°17′ W	530	30	Fresh	0.5	ZERG1
Merja Bokka	34°22′ N	6°17′ W	550	ca. 0.04	Lagoon	0.4–1.0	BOKK1
Tunisia							
Megene Chitane	37°09′ N	9°06′ E	600	ca. 0.01	Fresh	0.4–1.0	CHET1
Garaet El Ichkeul	37°10′ N	9°37′ E	920	89	Lagoon	0.6–1.5	ICHK2
Lac de Korba	36°37′ N	10°53′ E	450	ca. 3.2	Lagoon	0.5	KORB1
Egypt							
Lake Edku	31°15′ N	30°15′ E	180	126	Lagoon	1–2	IDKU1 IDKU3
Lake Burullus	31°30′ N	30°30′ to 31°10′ E	150	570	Lagoon	0.5–1.6	BULR1 BULR2
Manzala Lake	31°10′ to 31°30′ N	31°00′ to 31°30′ E	120	910	Lagoon	0.7–1.5	MANZ1

Results and discussion

Fallout of natural and artificial radionuclides is largely governed by rainfall, and this appears to have been one of the main factors controlling the quality of the radiometric records. Figure 2 compares the inventories of fallout ^{210}Pb and ^{137}Cs in each core with the mean annual rainfall at each site, and shows a good general correlation between these parameters. Fallout levels are significantly higher at the Moroccan and Tunisian sites where rainfall totals for the most part exceed 500 mm yr^{-1}. Although there is almost no data on direct atmospheric fluxes in North Africa, results from the Liverpool University ERRC global data base suggest that direct ^{210}Pb fallout should be ca. 80–150 Bq m^{-2} yr^{-1} per metre of rainfall, and that ^{137}Cs inventories from weapons test fallout (decay corrected to 1997) should be c.2400 Bq m^{-2} per metre of rainfall. One of the cores, Megene Chitane, evidently has significantly elevated inventories. Possible explanations are significant inputs of fallout radionuclides on eroded surface soils from the catchment, or sediment focussing. Inventories in the other cores are however reasonably comparable to the direct fallout values. ^{210}Pb fluxes at the Egyptian sites are a little lower than expected, though this might just be a consequence of the difficulty in measuring the low concentrations of unsupported ^{210}Pb in these cores. Table 2 summarises some of the main radiometric parameters determined for each core.

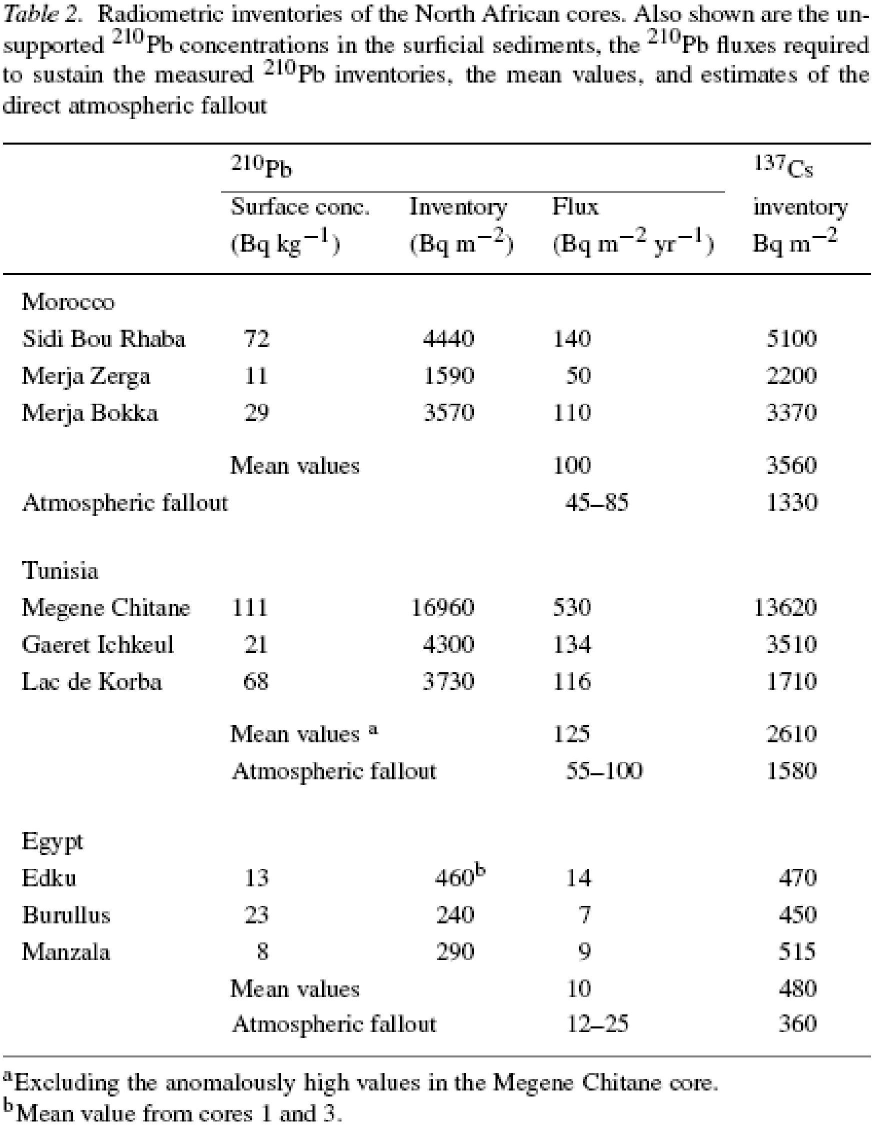


Table 2. Radiometric inventories of the North African cores. Also shown are the unsupported ^{210}Pb concentrations in the surficial sediments, the ^{210}Pb fluxes required to sustain the measured ^{210}Pb inventories, the mean values, and estimates of the direct atmospheric fallout

	^{210}Pb			^{137}Cs
	Surface conc. (Bq kg^{-1})	Inventory (Bq m^{-2})	Flux (Bq m^{-2} yr^{-1})	inventory Bq m^{-2}
Morocco				
Sidi Bou Rhaba	72	4440	140	5100
Merja Zerga	11	1590	50	2200
Merja Bokka	29	3570	110	3370
	Mean values		100	3560
Atmospheric fallout			45–85	1330
Tunisia				
Megene Chitane	111	16960	530	13620
Gaeret Ichkeul	21	4300	134	3510
Lac de Korba	68	3730	116	1710
	Mean values [a]		125	2610
	Atmospheric fallout		55–100	1580
Egypt				
Edku	13	460[b]	14	470
Burullus	23	240	7	450
Manzala	8	290	9	515
	Mean values		10	480
	Atmospheric fallout		12–25	360

[a] Excluding the anomalously high values in the Megene Chitane core.
[b] Mean value from cores 1 and 3.

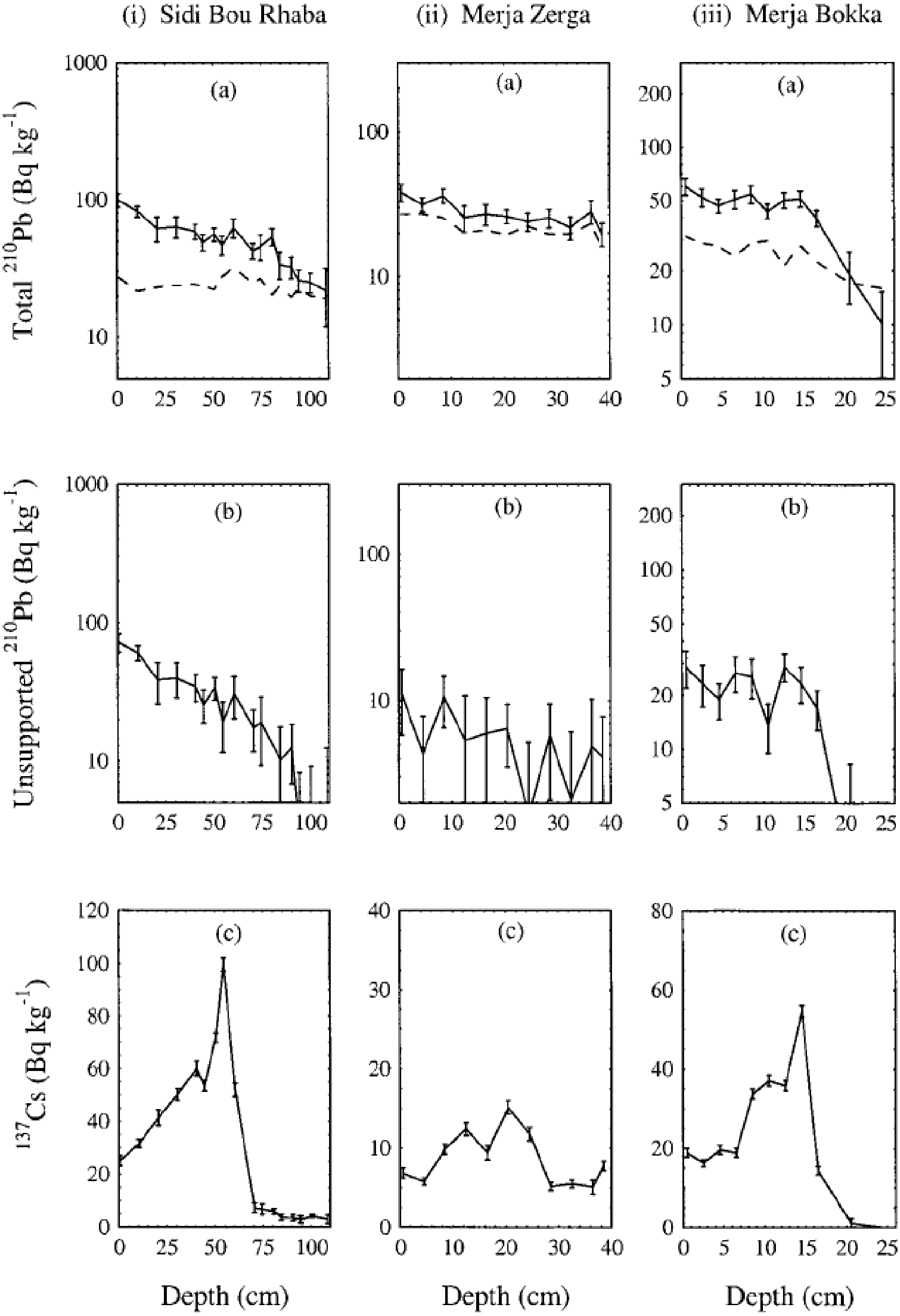


Figure 3. Fallout radionuclides in (i) Sidi Bou Rhaba, (ii) Merja Zerga, (iii) Merja Bokka plotting (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs activities versus depth in the core. Figures 3(a) also show the supported ^{210}Pb (^{226}Ra) activities (dashed line).

Moroccan sites

Results of the radiometric measurements for the Moroccan sites are shown in Figure 3. The cores all had similar supported ^{210}Pb (^{226}Ra) concentrations, with mean values ranging from 22–25 Bq kg^{-1}.

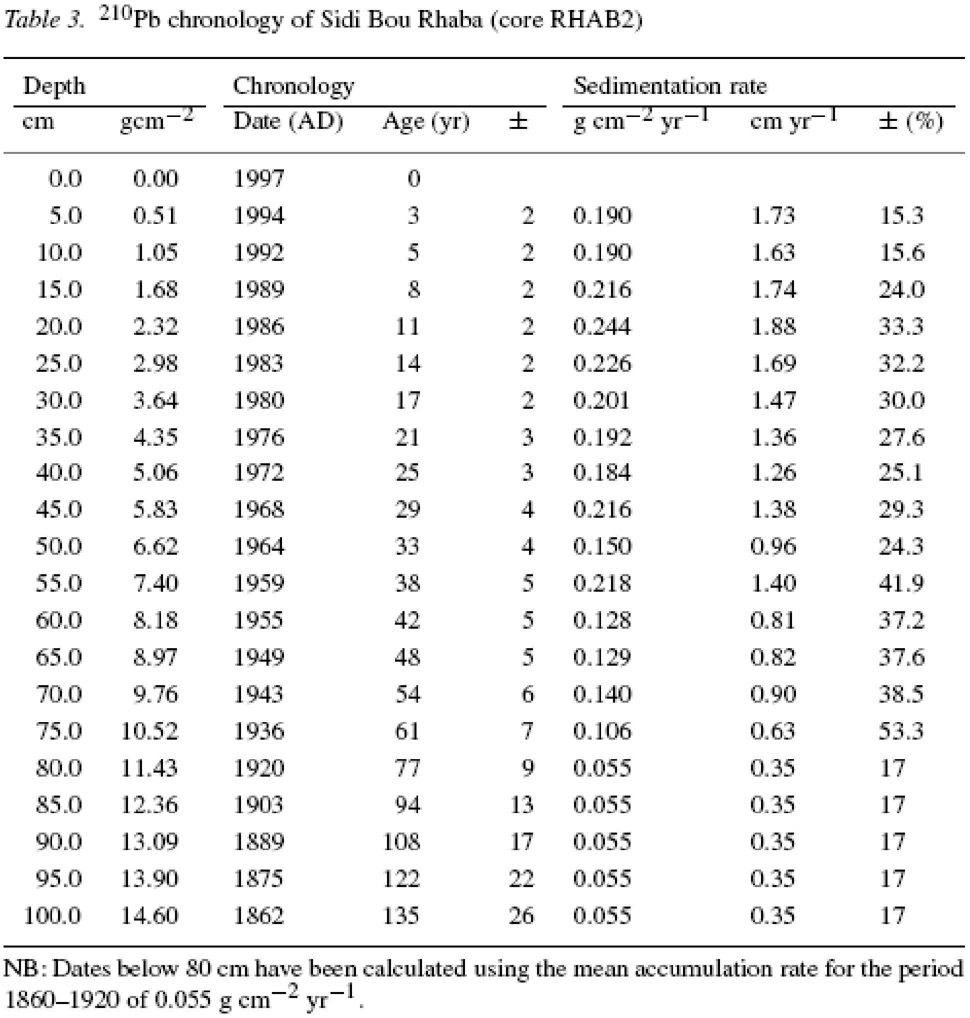


Table 3. ^{210}Pb chronology of Sidi Bou Rhaba (core RHAB2)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1997	0				
5.0	0.51	1994	3	2	0.190	1.73	15.3
10.0	1.05	1992	5	2	0.190	1.63	15.6
15.0	1.68	1989	8	2	0.216	1.74	24.0
20.0	2.32	1986	11	2	0.244	1.88	33.3
25.0	2.98	1983	14	2	0.226	1.69	32.2
30.0	3.64	1980	17	2	0.201	1.47	30.0
35.0	4.35	1976	21	3	0.192	1.36	27.6
40.0	5.06	1972	25	3	0.184	1.26	25.1
45.0	5.83	1968	29	4	0.216	1.38	29.3
50.0	6.62	1964	33	4	0.150	0.96	24.3
55.0	7.40	1959	38	5	0.218	1.40	41.9
60.0	8.18	1955	42	5	0.128	0.81	37.2
65.0	8.97	1949	48	5	0.129	0.82	37.6
70.0	9.76	1943	54	6	0.140	0.90	38.5
75.0	10.52	1936	61	7	0.106	0.63	53.3
80.0	11.43	1920	77	9	0.055	0.35	17
85.0	12.36	1903	94	13	0.055	0.35	17
90.0	13.09	1889	108	17	0.055	0.35	17
95.0	13.90	1875	122	22	0.055	0.35	17
100.0	14.60	1862	135	26	0.055	0.35	17

NB: Dates below 80 cm have been calculated using the mean accumulation rate for the period 1860–1920 of 0.055 g cm^{-2} yr^{-1}.

Sidi Bou Rhaba

Radiometric dating was carried out on core RHAB2. The results (Figure 3i) show that this core has a good record of fallout ^{210}Pb and ^{137}Cs. Equilibrium of total ^{210}Pb activity with the supporting ^{226}Ra (corresponding to ca. 100 years accumulation) occurred at a depth of about 110 cm (Figure 3i(a)). Below ca. 60 cm unsupported ^{210}Pb activity declines more or less exponentially with depth (Figure 3i(b)), indicating uniform sedimentation. The reduced gradient above this depth suggests a recent shift to more rapid accumulation.

The ^{137}Cs profile (Figure 3i(c)) has a well-resolved peak at 54.5 ± 3.5 cm depth. The presence of traces of ^{241}Am at about the same depth confirms that this feature records the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Appleby et al., 1991).

^{210}Pb dates calculated using the CRS model place 1963 at a depth of between 50-55 cm, in good agreement with the depth inferred from the 137Cs record. The results of the ^{210}Pb calculations, given in Table 3, indicate uniform sedimentation between 1860–1920, with a mean accumulation rate during this period of 0.055 ± 0.009 g cm^{-2} yr^{-1} (0.35 ± 0.06 cm yr^{-1}). Between 1920–1960 there was a steady acceleration in sedimentation rates, but since 1960 values have remained relatively stable. The mean post-1960 sedimentation rate is calculated to be 0.20 g cm^{-2} yr^{-1} (1.5 cm yr^{-1}).

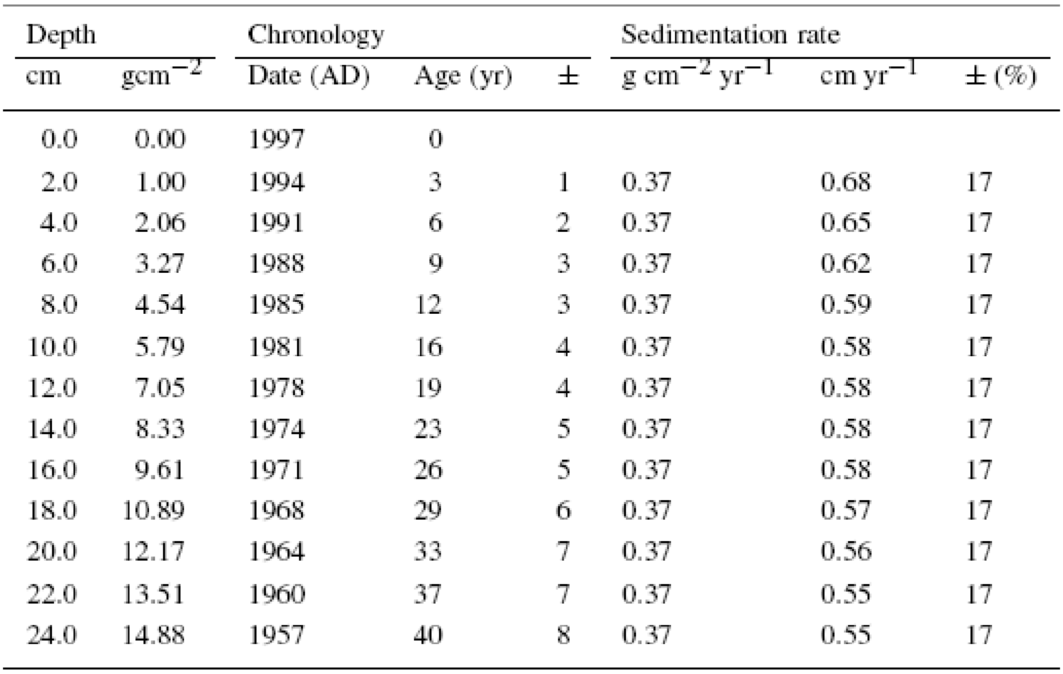
Merja Zerga

Radiometric dating at this site was carried out on core ZERG1. Results of the radiometric analyses are shown in Figure 3ii. In all samples, total ^{210}Pb activity at most barely exceeds the ^{226}Ra activity (Figure 3ii(a)). Unsupported ^{210}Pb activity (Figure 3ii(b)) in the surficial sediments is just 10 Bq kg^{-1}, limiting the ^{210}Pb dating horizon to no more than 30 years. Because of the large standard errors, little can be said about the shape of the ^{210}Pb profile though activity does appear to decline steadily with depth. The ^{137}Cs record of weapons test fallout is irregular (Figure 3ii(c)), with a double peak between 12–21 cm. The deeper peak at 20.5 cm is the most likely indicator of the 1963 level.

^{210}Pb dates calculated using the CRS model indicate a mid-1950s date for the base of the ^{210}Pb record at 36.5 cm and a mean sedimentation rate of 0.56 ± 0.17 g cm^{-2} yr^{-1} (0.87 cm yr^{-1}). The results do however have a high degree of uncertainty. Calculations using the suggested 1963 ^{137}Cs date give a lower post-1963 sedimentation rate of 0.37 ± 0.05 g cm^{-2} yr^{-1} (0.60 cm yr^{-1}), though even this value is higher than at the other two Moroccan sites.

^{137}Cs activity below 28 cm does not fall steeply with depth but remains relatively uniform at 35–40% of the peak value. One possible explanation for this is that sediments between 28–40 cm all post-date the onset of fallout in 1954. Accumulation rates between 1954–1963 would then have been more than 2 cm yr^{-1}, three times the post-1963 figure. Such high rates are thought to be possible, as a drainage canal was constructed in the mid 1950s that transported fine sediments into the lagoon near the coring site (Ramdani et al., 2001b). However, since there is no direct evidence for this increased sediment deposition, a reliable chronology cannot confidently be given for sediments significantly pre-dating 1963. Post-1963 dates, given in Table 4, have been calculated using the mean sedimentation rate determined from the ^{137}Cs record.

Table 4. ^{210}Pb chronology of Merja Zerga (core ZERG1)



Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1997	0				
2.0	1.00	1994	3	1	0.37	0.68	17
4.0	2.06	1991	6	2	0.37	0.65	17
6.0	3.27	1988	9	3	0.37	0.62	17
8.0	4.54	1985	12	3	0.37	0.59	17
10.0	5.79	1981	16	4	0.37	0.58	17
12.0	7.05	1978	19	4	0.37	0.58	17
14.0	8.33	1974	23	5	0.37	0.58	17
16.0	9.61	1971	26	5	0.37	0.58	17
18.0	10.89	1968	29	6	0.37	0.57	17
20.0	12.17	1964	33	7	0.37	0.56	17
22.0	13.51	1960	37	7	0.37	0.55	17
24.0	14.88	1957	40	8	0.37	0.55	17

NB: Dates are calculated using the mean accumulation rate for the period 1963–1997 of 0.37 ± 0.05 g cm^{-2} yr^{-1}.

Merja Bokka

Figure 3(iii) shows results of the radiometric analyses carried out on core BOKK1. The fallout record does not appear to be as well preserved as in RHAB2. ^{210}Pb activities are low and vary irregularly with depth, and unsupported ^{210}Pb was detected only in the top 17 cm of the core (Figure 3iii(b)). The 137Cs profile (Figure 3iii(c)) does however have a well-resolved peak (at 14.5 ± 1.5 cm depth) that almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons. The presence of this feature so close to the base of the unsupported ^{210}Pb suggests that there is a hiatus in the record, presumably related to a layer of low density/high water content sediments between 16–21 cm. In consequence there is a large discrepancy between the 1963 depths determined from the raw CRS model ^{210}Pb dates and the ^{137}Cs record. Corrected ^{210}Pb dates were calculated using the ^{137}Cs peak as a reference level. The results, given in Table 5, date the anomalous sediment layer to the late 1950s. The mean post-1960 sedimentation rate is calculated to be 0.30 g cm^{-2} yr^{-1} (0.43 cm yr^{-1}). The detailed results, given in Table 4, suggest brief episodes of more rapid accumulation in the late 1970s and early 1990s, doubtless related to local land-use changes (see Ramdani et al., 2001b; Birks et al., 2001a). The apparent lack of unsupported ^{210}Pb below 21 cm suggests that sedimentation rates below the hiatus are at least as high as those above it. Because of the low surficial concentrations the ^{210}Pb dating horizon would in this event be no more than two ^{210}Pb half-lives (less than 50 years).

Table 5. ^{210}Pb chronology of Merja Bokka (core BOKK1)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1997	0				
2.0	0.81	1995	2	2	0.43	0.82	27.4
4.0	2.05	1992	5	2	0.48	0.68	26.2
6.0	3.66	1988	9	2	0.35	0.43	25.8
8.0	5.35	1983	14	3	0.28	0.33	28.0
10.0	6.97	1978	19	3	0.39	0.49	33.1
12.0	8.54	1972	25	4	0.23	0.32	28.1
14.0	9.87	1965	32	5	0.17	0.28	31.2
16.0	10.89	1959	38	7	0.19	0.41	33.1

Tunisian sites

Results of the radiometric measurements for the Tunisian sites are shown in Figure 4. ^{226}Ra concentrations were more varied than at the Moroccan sites, reflecting different mineralogical backgrounds. Mean values ranged from 18 Bq kg^{-1} at Lac du Korba to 61 Bq kg^{-1} at Megene Chitane. All sites had significant records of fallout radionuclides. The quality was generally satisfactory though there were a number of irregularities.

Megene Chitane

Radiometric dating was carried out on core CHET1. The results of the radiometric measurements are shown in Figure 4i. Equilibrium between total ^{210}Pb activity and the supporting ^{226}Ra apparently occurs at a depth of ca. 35 cm (Figure 4i(a)). Unsupported ^{210}Pb activity varies irregularly with depth (Figure 4i(b)), and has a significant non-monotonic feature between 16–21 cm. There is little net decline in activity in the top 30 cm and the abrupt fall between 30–35 cm may indicate a hiatus in the ^{210}Pb record, presumably associated with the layer of low density/high water content sediment between 30–50 cm. The ^{137}Cs profile (Figure 4i(c)) has a well-resolved peak at 20.5 ± 3.5 cm recording the 1963 fallout maximum from the atmospheric testing of nuclear weapons. A large discrepancy between the raw CRS model ^{210}Pb chronology (which places 1963 at a depth of just 12.5 cm) and the ^{137}Cs results supports the inference that the ^{210}Pb record is incomplete. Corrected ^{210}Pb dates have been calculated using the 1963 ^{137}Cs peak as a reference point. The results, given in Table 6, date the onset of the ^{137}Cs record between 28.5–32.5 cm to the early 1950s, in good agreement with the fallout record. They also indicate that the apparent hiatus in the ^{210}Pb record below 30 cm was caused by an episode of very rapid sedimentation in the late 1940s and that the feature at 16–21 cm was due to a further episode in the early 1960s. Because of the complete absence of unsupported ^{210}Pb below 49 cm it was not possible to date sediments earlier than ca. 1945. Excluding the episodes of rapid accumulation, mean sedimentation rates are calculated to be ca. 0.20 g cm^{-2} yr^{-1} (0.86 cm yr^{-1}) during 1950–1960 and ca. 0.38 g cm^{-2} yr^{-1} (0.52 cm yr^{-1}) since 1970. The relatively high unsupported activity in the surficial sediments coupled with the high fallout inventories (Table 2) suggest that the high sedimentation rates are most likely due to inputs of surface soil from the valley mire above the lake (now used for crop production, Ramdani et al., 2001b). An alternative explanation is sediment focussing, though this is unlikely in view of the flat and shallow topography of the lake basin.

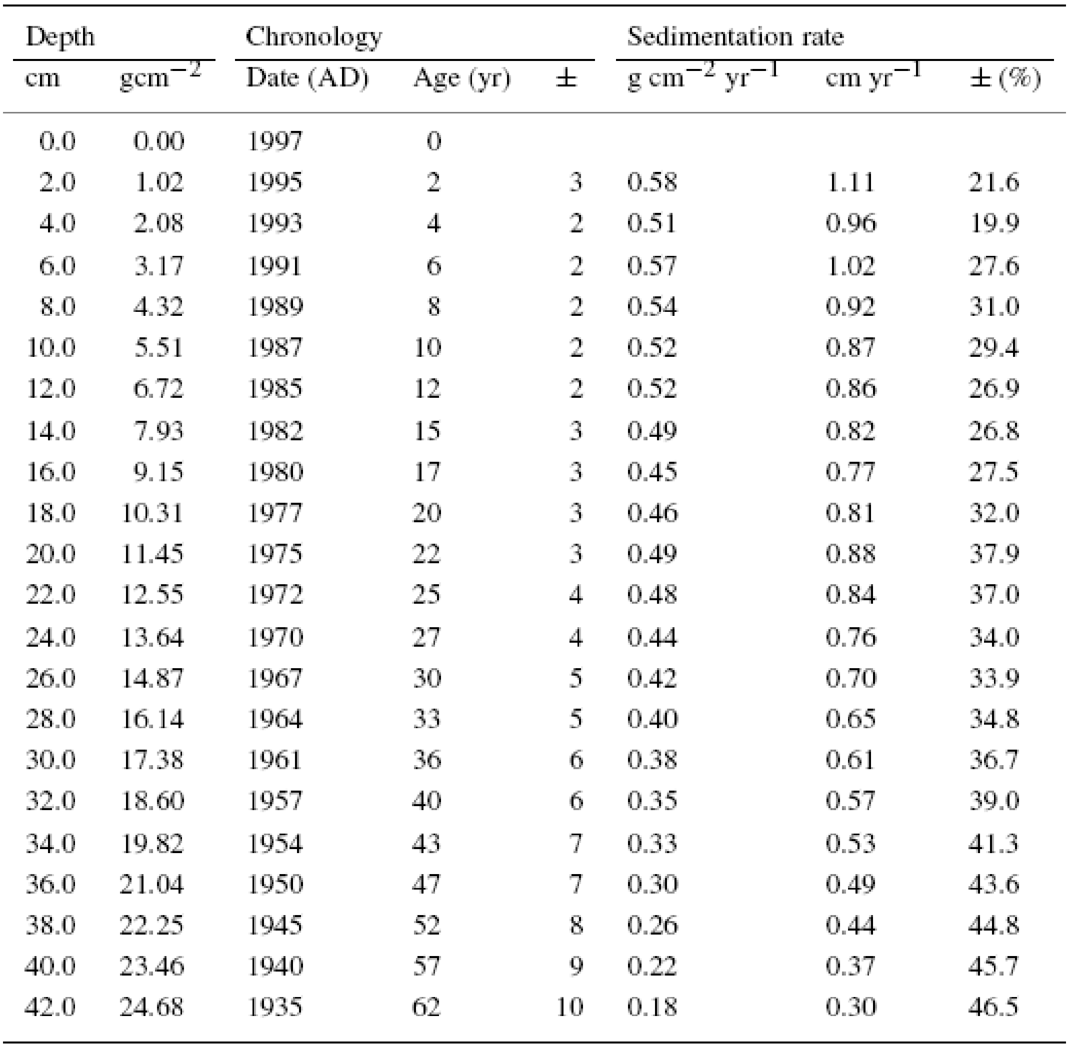
Table 6. ^{210}Pb chronology of Megene Chitane (core CHET1)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.0	1997	0				
4.0	3.2	1990	7	2	0.47	0.61	19.9
8.0	6.2	1983	14	3	0.35	0.49	21.2
12.0	8.9	1974	23	4	0.30	0.47	24.7
16.0	11.3	1967	30	6	0.39	0.74	32.8
20.0	13.2	1963	34	7	0.65	1.67	46.0
24.0	14.5	1960	37	8	0.25	0.78	39.2
28.0	15.7	1954	43	11	0.15	0.64	45.4
32.0	16.5	1949	48	13	0.25	1.16	52.1
36.0	17.4	1948	49	14	0.70	3.10	54.4
40.0	18.3	1947	50	14	0.73	3.77	59.3
44.0	18.9	1946	51	14	0.68	3.84	62.8
48.0	19.7	1944	53	14	0.47	1.94	61.3

Garaet El Ichkeul

Radiometric dating was carried out on core ICHK2. The results of the radiometric analyses are shown in Figure 4ii. ^{210}Pb activity exceeds that of the supporting ^{226}Ra above a depth of ca. 50 cm (Figure 3ii(a)). Since the maximum unsupported ^{210}Pb activity is just 22 Bq kg−1 the ^{210}Pb dating horizon is not expected to be more than about 50 years and the disappearance of the fallout record at 50 cm may just be due to values falling below the limit of detection. Within the dating horizon, unsupported ^{210}Pb activity declines more or less exponentially with depth (Figure 4ii(b)). ^{137}Cs activity increases sharply above ca. 50 cm (Figure 4ii(c)) and has a relatively well-defined peak at 28.5 cm depth recording the 1963 fallout maximum from the atmospheric testing of nuclear weapons. High activities in the more recent sediments point to continued inputs of ^{137}Cs at the core site. The most likely sources are reworked sediments from the margins of the lake, and eroded surface soils from the catchment. Increased salinity in the past two decades caused by inflow barrages has resulted in the destruction of the Ichkeuls's marginal weed beds (Birks et al., 2001a), exposing these sediments to wind induced disturbance. More intensive cultivation in the catchment and canalisation of the rivers has increased the susceptibility of the catchment to surface soil erosion. 210Pb dates calculated using the CRS model place 1963 at a depth of 28.5 cm, in good agreement with the 137Cs stratigraphy. The results indicate relatively uniform sedimentation since ca. 1970 with a mean accumulation rate of 0.50 ± 0.06 g cm^{-2} yr^{-1} (0.89 cm yr^{-1}). Dates earlier than 1960 are more equivocal. Whereas the ^{210}Pb calculations date 43 cm to the early 1930s, the onset of the ^{137}Cs record between 43–50 cm suggests a mid-1950s date. Since ^{137}Cs onset dates are generally unreliable, and results from an earlier (1980) Ichkeul core (Stevenson & Battarbee, 1991) suggest that sedimentation rates were significantly lower prior to ca. 1950, the dates given in Table 7 are those determined from the ^{210}Pb calculations. Dates below 30 cm must however be regarded as uncertain. Since the ^{210}Pb equilibrium depth in the 1980 core is less than half that in the present core, it does appear that there are significant spatial variations in the distribution of sediments over the bed of the lake.

Table 7. ^{210}Pb chronology of Garaet El Ichkeul (core ICHK2)



Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1997	0				
2.0	1.02	1995	2	3	0.58	1.11	21.6
4.0	2.08	1993	4	2	0.51	0.96	19.9
6.0	3.17	1991	6	2	0.57	1.02	27.6
8.0	4.32	1989	8	2	0.54	0.92	31.0
10.0	5.51	1987	10	2	0.52	0.87	29.4
12.0	6.72	1985	12	2	0.52	0.86	26.9
14.0	7.93	1982	15	3	0.49	0.82	26.8
16.0	9.15	1980	17	3	0.45	0.77	27.5
18.0	10.31	1977	20	3	0.46	0.81	32.0
20.0	11.45	1975	22	3	0.49	0.88	37.9
22.0	12.55	1972	25	4	0.48	0.84	37.0
24.0	13.64	1970	27	4	0.44	0.76	34.0
26.0	14.87	1967	30	5	0.42	0.70	33.9
28.0	16.14	1964	33	5	0.40	0.65	34.8
30.0	17.38	1961	36	6	0.38	0.61	36.7
32.0	18.60	1957	40	6	0.35	0.57	39.0
34.0	19.82	1954	43	7	0.33	0.53	41.3
36.0	21.04	1950	47	7	0.30	0.49	43.6
38.0	22.25	1945	52	8	0.26	0.44	44.8
40.0	23.46	1940	57	9	0.22	0.37	45.7
42.0	24.68	1935	62	10	0.18	0.30	46.5

Lac de Korba

Radiometric dating was carried out on core KORB1. The results of the radiometric analyses are given in Figure 4iii. ^{210}Pb/^{226}Ra equilibrium is reached at a depth of ca. 16 cm (Figure 4iii(a)), significantly shallower than in the other Moroccan or Tunisian sites. Unsupported ^{210}Pb activity is fairly uniform in the top 7 cm of the core (Figure 4iii(b)) but beneath this depth declines more or less exponentially with depth. The ^{137}Cs profile (Figure 4iii(c)) has a broad but relatively well defined peak between 4–9 cm that presumably records the 1963 fallout maximum from the atmospheric testing of nuclear weapons. The significant decline in ^{137}Cs activity above 4 cm precludes mixing as a cause of the uniform ^{210}Pb concentrations in the surficial sediments. ^{210}Pb dates calculated using the CRS model place 1963 at a depth of ca. 7 cm, in relatively good agreement with the ^{137}Cs record. The detailed results, given in Table 8, suggest a relatively uniform sedimentation rate up to ca. 1970 of 0.078 ± 0.005 g cm^{-2} yr^{-1} (0.090 cm yr^{-1}), but that this may have increased in recent decades to ca. 0.15 g cm^{-2} yr^{-1}. Even so, this site has the slowest overall sedimentation rate of all the CASSARINA cores.

Table 8. ^{210}Pb chronology of Lac de Korba (core KORB1)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1997	0				
1.0	0.29	1995	2	1	0.163	0.46	10.7
2.0	0.66	1993	4	1	0.155	0.37	12.0
3.0	1.11	1989	8	2	0.137	0.29	13.3
4.0	1.66	1985	12	2	0.111	0.21	14.5
5.0	2.22	1979	18	2	0.090	0.16	14.7
6.0	2.79	1972	25	2	0.078	0.12	12
7.0	3.41	1964	33	3	0.078	0.12	12
8.0	4.06	1956	41	4	0.078	0.11	12
9.0	4.83	1946	51	6	0.078	0.10	12
10.0	5.70	1934	63	8	0.078	0.09	12
11.0	6.63	1923	74	10	0.078	0.08	12
12.0	7.61	1910	87	13	0.078	0.08	12
13.0	8.57	1898	99	15	0.078	0.08	12
14.0	9.51	1885	112	16	0.078	0.08	12

NB: Accumulation rates below 6 cm are mean values for the period 1885–1972.

Egyptian sites

Sediment cores from three lakes were analysed for fallout radionuclides. The initial measurements carried out on cores IDKU1 and BURL1 from Lakes Edku and Burullus showed that these two cores had very poor fallout records. Additional measurements were subsequently carried out on two further cores, IDKU3 and BULR2. Results from all five cores are shown in Figure 5. ^{226}Ra concentrations were low and relatively uniform, with mean values ranging from 14 Bq kg^{-1} at Manzala to 24 Bq kg^{-1} at Burullus. Only the core from Lake Manzala, had a significant record of ^{210}Pb concentrations in excess of the ^{226}Ra. In Edku and Burullus, unsupported ^{210}Pb was detected only in the surficial sediments of cores IDKU1 and BULR2.

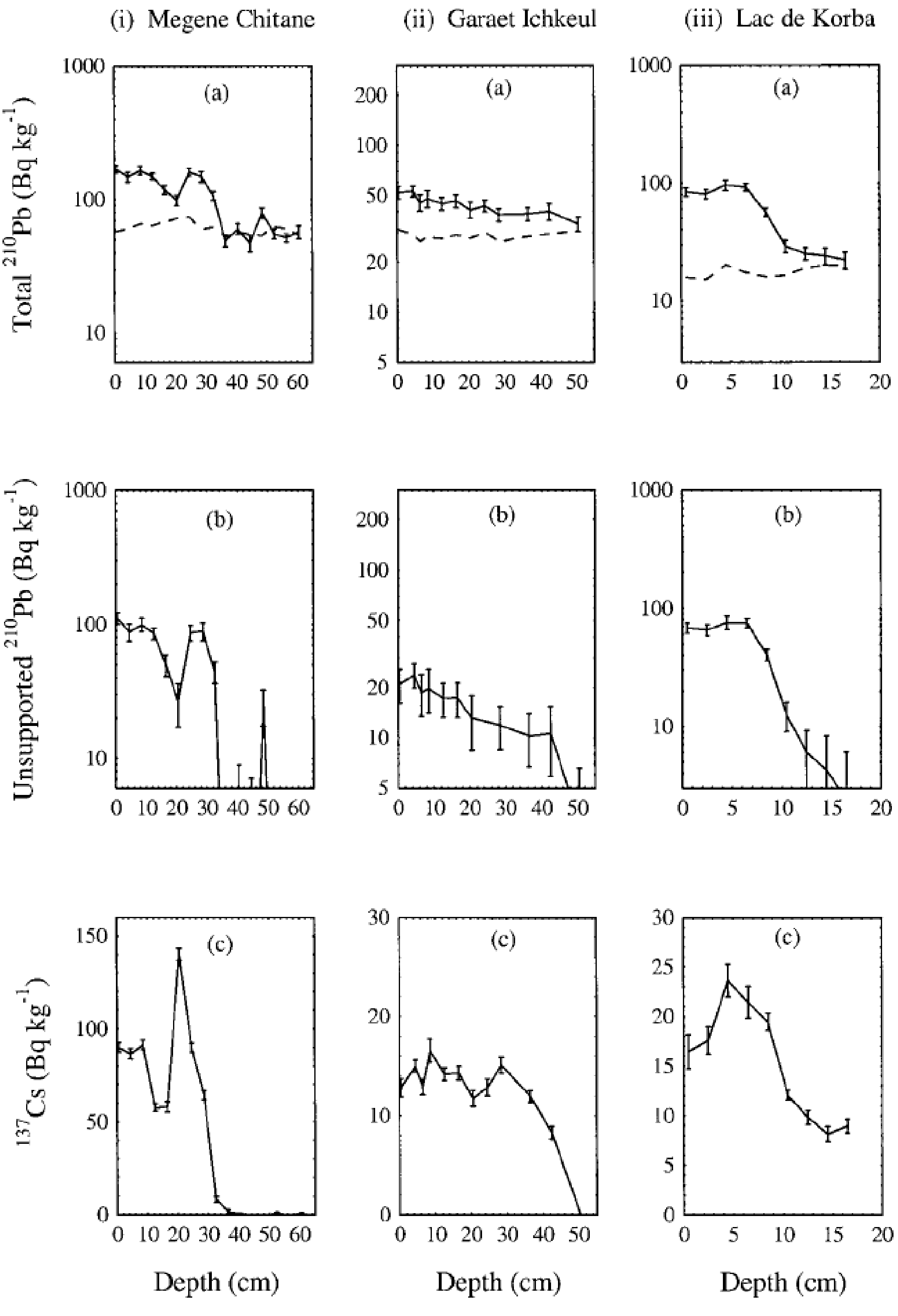


Figure 4. Fallout radionuclides in (i) Megene Chitane, (ii) Garaet Ichkeul, (iii) Lac de Korba showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs activities versus depth in the core. Figures 4(a) also show the supported ^{210}Pb (^{226}Ra) activities (dashed line).

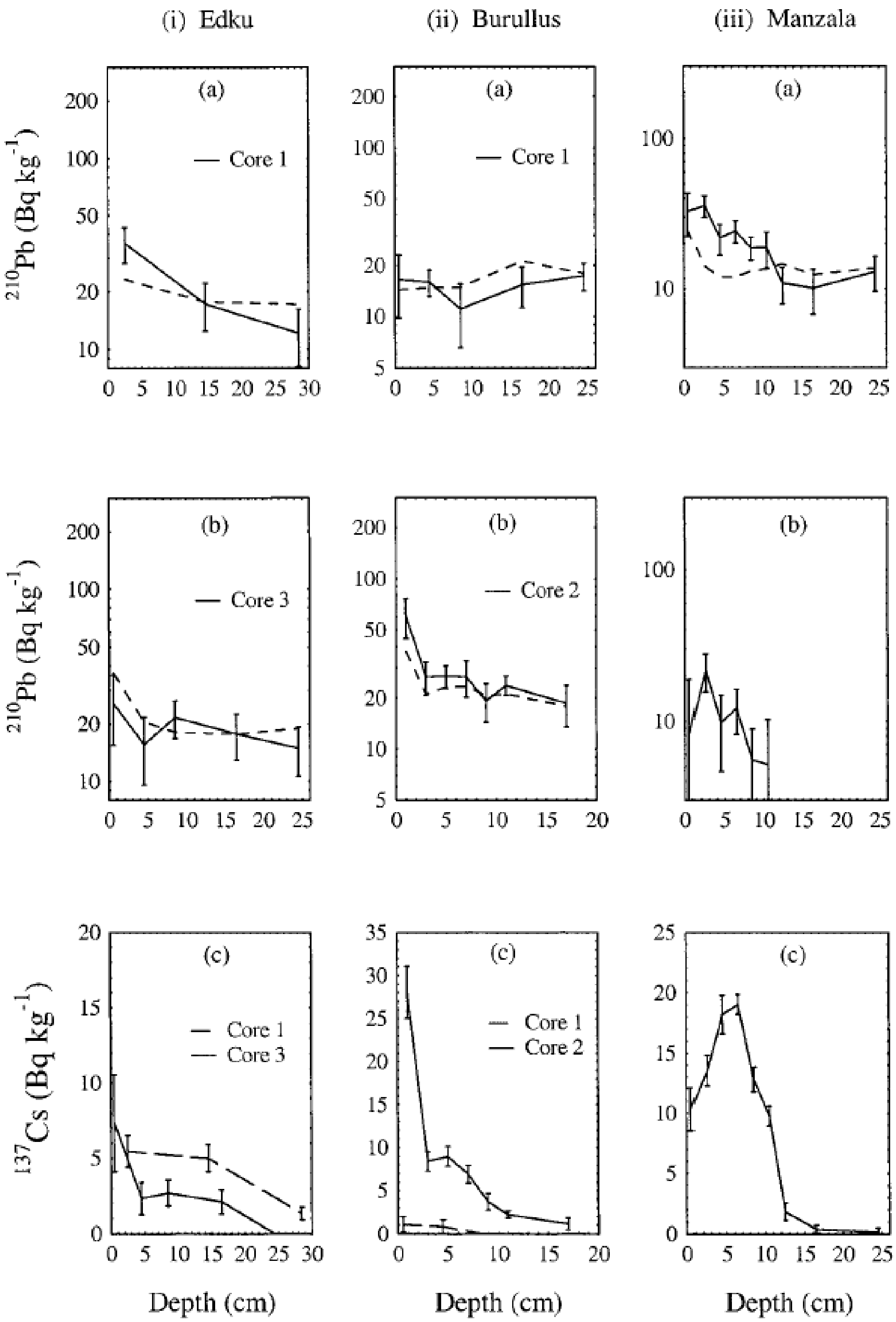


Figure 5. Fallout radionuclides in (i) Edku (cores 1 and 3), (ii) Burullus (cores 1 and 2) and (iii) Manzala showing (a) & (b) ^{210}Pb and (c) ^{137}Cs activities versus depth in the core. Figures (a), i(b) and ii(b) show total and supported (dashed line) ^{210}Pb activities, iii(b) shows unsupported ^{210}Pb.

^{137}Cs concentrations were also very low and again only in Manzala was there a significant fallout record. The core from this lake had a fairly well resolved subsurface peak at a depth of between 4–7 cm (Figure 5iii(c)). Three of the four cores from Edku and Burullus had significant ^{137}Cs concentrations down to depths of between 15–20 cm. Although there were no clear stratigraphic features recording major fallout events, these results do however show that the upper sections of these cores contain recent sediments. This does not appear to be the case with the first Burullus core in which ^{137}Cs concentrations were barely significant even in the uppermost sample (Figure 5ii(c)).

The data summarised in Table 2 and Figure 2 show that the poor fallout records in the Nile Delta cores can largely be attributed to the low fallout levels arising from the low rainfall in this region. Estimates of ^{210}Pb and ^{137}Cs fallout levels in the Nile Delta, based on the generally good relationship between atmospheric fallout and mean annual rainfall that has been observed at other sites, are comparable to measured values in the sediment cores. As a result, conventional radiometric dating techniques could not be used on their own. Sediment chronologies for these sites can only be constructed by piecing together information from a variety of sources in addition to the fallout radionuclides, including macrofossil, pollen, and spheroidal carbonaceous particle (SCP) records.

Lead-210

Although none of the cores had sufficiently good records of fallout ^{210}Pb to allow dating by this method alone, concentrations in the surficial sediments can be used to estimate contemporary sedimentation rates. Maximum concentrations in the three sites range from 13–23 Bq kg^{-1}, with a mean value of 19 Bq kg^{-1}. Assuming an atmospheric flux of between 12–25 Bq m^{-2} yr^{-1}, neglecting effects such as sediment focussing, these values suggest a contemporary sedimentation rate of between 0.05–0.2 g cm^{-2} yr^{-1}. Manzala would appear to be at the lower end of this range. Fitting a regression line to the unsupported ^{210}Pb profile for this core (Figure 5iii(b)) in fact gives a mean sedimentation rate during the past few decades of 0.05 ± 0.02 g cm^{-2} yr^{-1} (0.2 cm yr^{-1}). The poorer records at Burullus and Edku suggest that sedimentation rates at these sites are at the upper end (0.1–0.2 g cm^{-2} yr^{-1}, or 0.2–0.4 cm yr^{-1}).

Caesium-137

In determining stratigraphic dates based on ^{137}Cs records it is essential to determine the source of the fallout. Weapons fallout (peaking in 1963) occurred on a global scale and is almost certainly the main contributor to the records in Moroccan and Tunisian sites. Many parts of the eastern Mediterranean were however impacted by fallout from the 1986 Chernobyl accident and this is potentially a source for sites in the Nile Delta.

A detailed study of the spatial distribution of fallout ^{137}Cs in the Nile delta was carried out by Shawky and El-Tahawy (1999) using records in soil cores collected in 1988, two years after the Chernobyl accident. The results of their study indicated that cumulative ^{137}Cs deposition in the vicinities of Edku, Burullus, and Manzala were 610 Bq m^{-2}, 700 Bq m^{-2} and 390 Bq m^{-2} respectively. These values include both weapons and Chernobyl fallout and have been decay corrected to 1997. Although we do not have any direct estimates of the pre-1986 burden, estimates from the ERRC global data base based on sites at similar latitudes suggest weapons fallout values of between 300–400 Bq m^{-2} (decay corrected to 1997). It is thus possible, but not certain, that Chernobyl fallout represents 30–40% of the total ^{137}Cs record. The results obtained by Shawky and El-Tahawy (1999) from 9 regions spanning the delta indicate a relatively uniform deposition, with a mean value (decay corrected to 1997) of 515 Bq m^{-2}. Chernobyl fallout was mainly controlled by rainfall at the time the radioactive cloud was over head and was often very heterogeneously distributed. Further, the mean ^{137}Cs/^{90}Sr ratio in the soil cores was significantly lower than the value expected for weapons fallout (ca. 1.6). Since ^{90}Sr fallout from the Chernobyl accident was insignificant, substantial ^{137}Cs deposition from Chernobyl would have tended to increase this ratio.

For Manzala Lake, the main uncertainty concerns the origins of the subsurface ^{137}Cs peak. The ^{210}Pb results place 1986 at a depth of between 3–4 cm, and 1963 at between 7–8 cm, suggesting that it is too deep to be a record of Chernobyl fallout alone. Since ^{137}Cs records can however be degraded by sediment mixing or diffusion in pore waters, the peak may include contributions from both sources. Assuming that the sharp increase in concentrations above 12 cm is dominated by weapons fallout ^{137}Cs, the depth (ca. 6.5 cm) at which peak concentrations are initially reached can be dated 1963. The mean post-1963 sedimentation rate is then calculated to be ca. 0.042 g cm^{-2} yr^{-1}, in reasonable agreement with the ^{210}Pb value.

For cores without a subsurface peak the depth recording the onset of ^{137}Cs fallout in 1954 has been used as a chronostratigraphic marker. Although this is unreliable due to post-depositional mobility of ^{137}Cs within the sediments the distribution of the 137Cs inventory does however give some guide to the upper limits of the sedimentation rate. The depth containing 90% of the weapons 137Cs inventory represents the maximum depth of the 1956 level. The 50% depth similarly represents the maximum depth of the 1963 level. Applying these arguments to the Edku and Burullus cores, the 1963 depth is placed at between 8–13 cm in core IDKU3 and between 6–8 cm in core BULR2.

Chronostratigraphic evidence from the macrofossil and pollen records

Macrofossil and pollen records in the Egyptian cores contain a number of features associated with environmental changes in the Nile Delta region (Birks et al., 2001a; Peglar et al., 2001). Although the dates of these features are not precise, they can be used to establish approximate sedimentation rates over longer timescales.

Manzala Lake

Macrofossil records show an increasing abundance of freshwater molluscs in the upper part of the core. These changes are almost certainly due to water quality changes following the progressive damming of the Nile since ca. 1890 (Waterbury, 1979). Regulation of the annual floods has raised the freshwater water-table throughout the Delta, causing a significant reduction in the salinity of all the delta lakes. In the macrofossil record for Manzala the onset of the freshwater influence is seen at a depth of ca. 27 cm and is most probably associated with the construction of the first effective Nile Delta barrages between 1912–1930. Further changes starting at ca. 17 cm are below the onset of the ^{137}Cs record (at ca. 12 cm) and thus pre-date 1954. They most likely reflect the impact of the increasingly effective barrages constructed in 1933 and 1951. The most recent freshwater increase at 6 cm lies above the section of rapidly increasing ^{137}Cs concentrations (12–6 cm) and can be presumed to record the influence of the Aswan High Dam, construction of which began in 1960 and was essentially completed in 1964.

Casuarina is an Australian tree genus that has been widely planted in the Nile delta since about 1920 (Peglar et al., 2001). The pollen diagram from core MANZ3 (Peglar et al., 2001) (adjacent to MANZ1) shows the start of the *Casuarina* record at a depth of about 25 cm and sediments above this depth are likely to post-date ca. 1930. *Olea* (olive) and *Phoenix* (datepalm), although present since ancient times, have been planted much more extensively since ca. 1930 (Mehringer et al., 1979). The pollen values of *Olea* increase above 15 cm and it thus seems reasonable that sediments from above this depth post-date ca. 1940.

Figure 6 shows the CRS model 210Pb dates for core MANZ1, together with stratigraphic dates determined from the ^{137}Cs record in MANZ1, and the biostratigraphic records in the parallel core MANZ3. The post-1960 dates are all in relatively good agreement. Fitting a regression line to the data gives a mean post-1960 sedimentation rate of 0.041 g cm^{-2} yr^{-1} (0.2 cm yr^{-1}). The sequence of pre-1960 pollen and macrofossil dates is also relatively conformable, but suggests a much higher accumulation rate. The regression line to these data gives a mean pre-1960 sedimentation rate of 0.030 g cm^{-2} yr^{-1} (0.51 cm yr^{-1}). This value is comparable to the long-term rate of 0.5 cm yr^{-1} determined by ^{14}C dating of long cores (Stanley, 1988, 1990). A detailed chronology based on these results is given in Table 9. The inferred decline in dry matter accumulation rates after ca. 1960 may be due to the influence of the Aswan Dam. The greatly reduced dry bulk density of these sediments and increased organic content indicate a reduced silt input and increased organic productivity.

Table 9. Chronology of Manzala Lake (core MANZ1)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	$g\ cm^{-2}\ yr^{-1}$	$cm\ yr^{-1}$	± (%)
0.0	0.00	1997	0				
0.5	0.04	1996	1	1	0.041	0.34	20.0
2.5	0.31	1990	7	2	0.041	0.19	20.0
4.5	0.82	1977	20	4	0.041	0.21	20.0
6.5	1.43	1962	35	7	0.041	0.24	20.0
8.5	2.11	1958	39	8	0.30	0.33	20.0
10.5	2.83	1956	41	8	0.30	0.58	20.0
12.5	3.75	1953	44	8	0.30	0.56	20.0
14.5	5.04	1948	49	9	0.30	0.50	20.0
16.5	6.33	1944	53	9	0.30	0.47	20.0
18.5	7.56	1940	57	10	0.30	0.49	20.0
20.5	8.77	1936	61	12	0.30	0.50	20.0
22.5	9.92	1932	65	13	0.30	0.51	20.0
24.5	11.08	1928	69	15	0.30	0.51	20.0
26.5	12.24	1924	73	17	0.30	0.50	20.0
28.5	13.40	1920	77	19	0.30	0.49	20.0
30.5	14.68	1916	81	21	0.30	0.48	20.0
32.5	15.96	1911	86	23	0.30	0.46	20.0
34.5	17.22	1907	90	26	0.30	0.45	20.0
36.5	18.54	1903	94	28	0.30	0.45	20.0

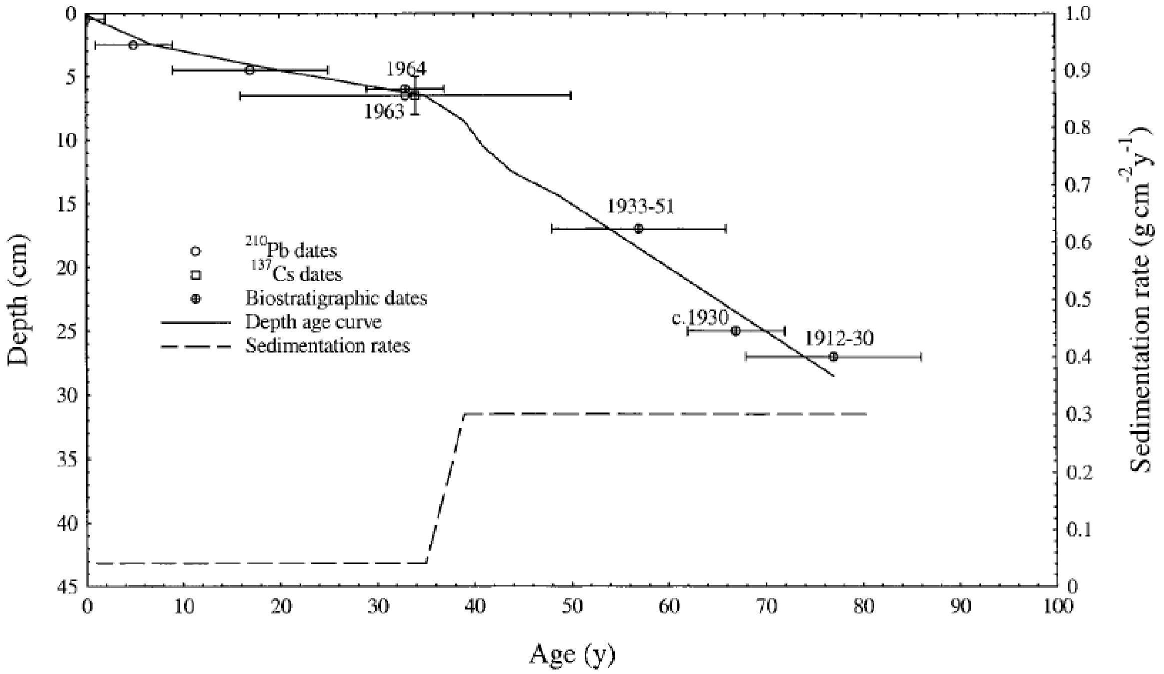


Figure 6. Chronology of Manzala Lake core MANZ1 showing CRS model ^{210}Pb dates together with stratigraphic dates determined from the ^{137}Cs, pollen and macrofossil records. Also shown are the pre- and post-1960 sedimentation rates calculated by fitting regression lines to the dated points, and the depth versus age curve determined from these values.

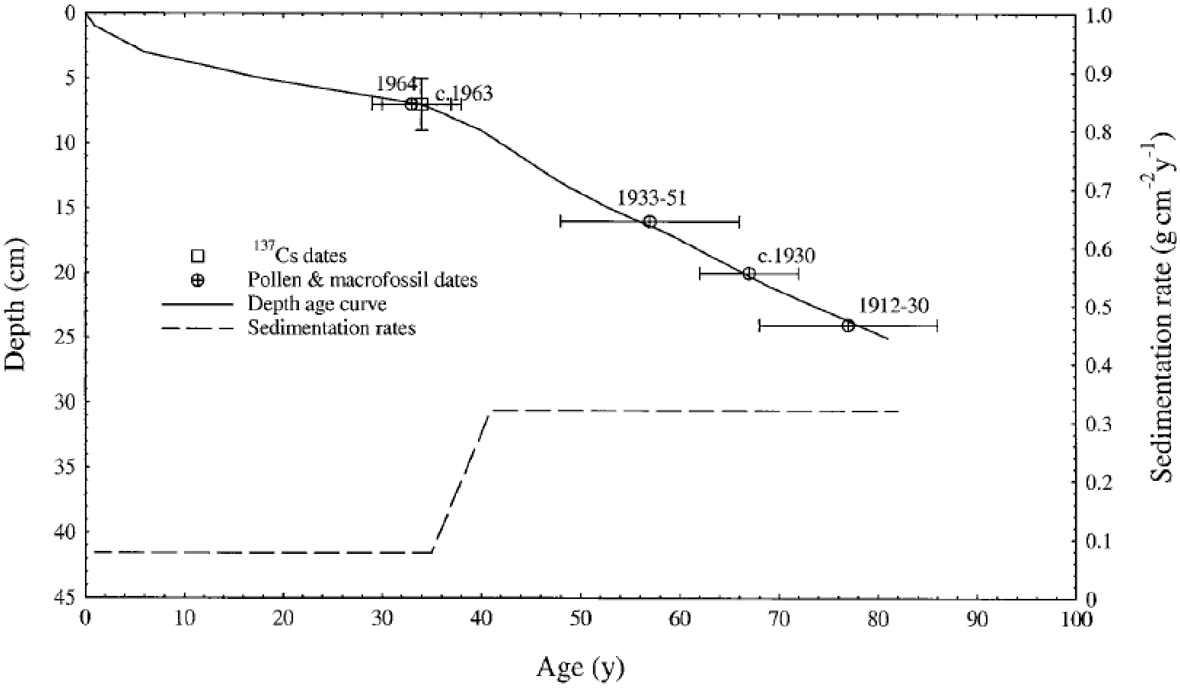


Figure 7. Chronology of Lake Burullus core BURL2 showing stratigraphic dates determined from the ^{137}Cs, pollen and macrofossil records. Also shown are the pre- and post-1960 sedimentation rates calculated by fitting regression lines to the dated points, and the depth versus age curve determined from these values.

Burullus Lake

Although Burullus is more saline than the other two lakes, there have nonetheless been significant reductions in salinity during the 20th century. The macrofossil record (Birks et al., 2001a) indicates an initial shift towards a freshwater environment at ca. 24 cm, with further significant changes at 16 cm, and 7 cm. The earliest of these features was probably caused by the initial impact of the first effective Nile barrages, and can be dated to the early 20th century. The later change at 16 cm is a little below the onset of the ^{137}Cs record (dated 1954) and is most likely associated with the impact of later barrages constructed during 1933-1951. The most recent change is close to the 1963 depth determined from the ^{137}Cs record, and is probably a response to the essential completion of the Aswan High Dam in 1964.

Pollen records in the Burullus Lake core BULR2 show increases in *Olea* and *Phoenix* at a depth of ca. 20 cm that could indicate a date of around 1930. The later appearance of *Casuarina* (at ca. 13 cm) is probably due to the fact that the lake shore near the core site is arid and few trees were planted in this area.

These results, plotted in Figure 7, suggest a significant reduction in sedimentation rates after ca. 1960, similar to that in Manzala Lake. The trend of the pre-1960 biostratigraphic dates suggests that the first significant freshwater changes (ca. 24 cm) can again be dated ca. 1920. The pre-1960 sedimentation rate is calculated to be 0.32 g cm^{-2} yr^{-1} (0.39 cm yr^{-1}), significantly higher than the post-1960 value of 0.075 g cm^{-2} yr^{-1} (0.21 cm yr^{-1}) estimated from the ^{137}Cs record. Sediments in the top 7 cm have a very much lower dry bulk density than those beneath this depth. These results may further indicate reduced minerogenic sediment inputs as a consequence of irrigation/ drainage changes, and the end of Nile floods and input of silt following construction of the Aswan High Dam. A detailed chronology based on these results is given in Table 10.

Table 10. Chronology of Lake Burullus (core BULR2)

Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	$\mathrm{g\ cm}^{-2}\ \mathrm{yr}^{-1}$	$\mathrm{cm\ yr}^{-1}$	± (%)
0.0	0.00	1998	0	0			
1.0	0.06	1997	1	1	0.077	0.47	20
3.0	0.49	1992	6	2	0.077	0.23	20
5.0	1.42	1980	18	5	0.077	0.23	20
7.0	2.61	1964	34	7	0.077	0.24	20
9.0	3.80	1958	40	8	0.32	0.24	20
11.0	5.12	1954	44	9	0.32	0.26	20
13.0	6.51	1950	48	10	0.32	0.30	20
15.0	8.11	1945	53	11	0.32	0.42	20
17.0	9.80	1939	59	12	0.32	0.39	20
19.0	11.43	1934	64	13	0.32	0.37	20
21.0	13.25	1929	69	14	0.32	0.36	20
23.0	15.11	1923	75	15	0.32	0.36	20
25.0	16.92	1917	81	16	0.32	0.37	20
27.0	18.63	1912	86	17	0.32	0.38	20
29.0	20.12	1907	91	18	0.32	0.39	20
31.0	21.65	1902	96	19	0.32	0.41	20

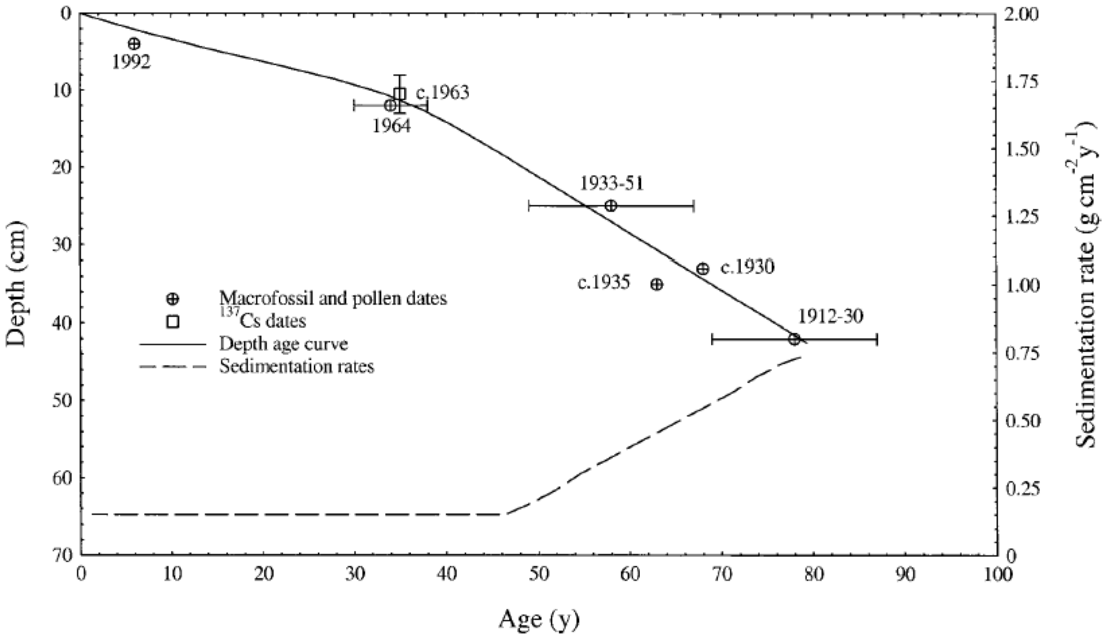
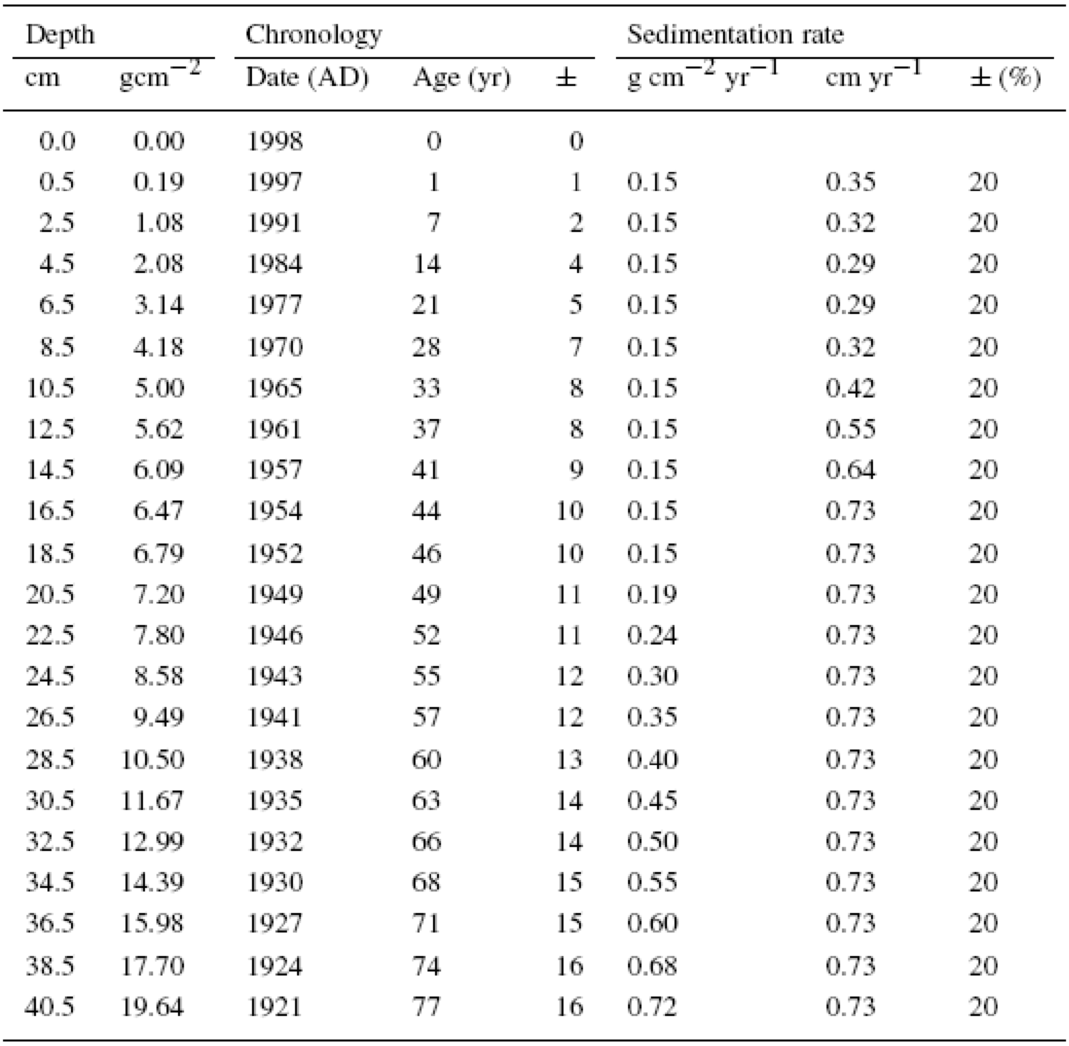


Figure 8. Chronology of Lake Edku core IDKU3 showing stratigraphic dates determined from the ^{137}Cs, pollen and macrofossil records. Also shown are the pre- and post-1960 sedimentation rates calculated from the stratigraphic dates, and the depth versus age curve determined from these values.

Lake Edku

The macrofossil records for Edku Lake (Birks et al., 2001a) suggest that the onset of freshwater conditions begins at ca. 42 cm, with further major increases at 25 cm and 12 cm. Since the beginning of the ^{137}Cs record lies between 24–16 cm, the freshwater increase at 25 cm almost certainly predates 1954, whilst that at 12 cm post-dates the early 1960s. The earlier of these two features probably records the impact of the barrages constructed during 1933–1951, and the latter the impact of the Aswan High Dam after 1964. Seeds of the aquatic plant *Eichhornia* (water hyacinth), first noted as being abundant in Nile delta lakes by the 1930s (Zahran & Willis, 1992), first appear in the sediments at 35 cm. A peak in *Azolla filiculoides* (water fern), first recorded as abundant in Edku in 1992 (El-Shenaway, 1994), occurs at 4 cm. The pollen records (Peglar et al., 2001) show that the onset of *Casuarina* and *Eucalyptus* (ca. 1930) occurs at ca. 33 cm. *Olea* and *Phoenix* rise at ca. 17 cm. The estimated dates of all these biostratigraphic features are plotted in Figure 8. The trend again suggests a date of ca. 1920 for the earliest impact of the freshwater changes. It also suggests a significant reduction in sedimentation rates since ca. 1950, slightly earlier than at the other two sites. A detailed chronology based on a curve-fit to the results is given in Table 11. Because of the irregular changes in dry bulk density, a best fit to the pre-1950 dates was given by the depths measured in cm. In consequence the pre-1950 dry-mass sedimentation rates vary with time, declining from ca. 0.7 g cm^{-2} yr^{-1} in 1920 to 0.15 g cm^{-2} yr^{-1} by ca. 1950, since when it appears to have remained relatively constant.

Table 11. Chronology of Edku Lake (core IDKU3)



Depth		Chronology			Sedimentation rate		
cm	gcm^{-2}	Date (AD)	Age (yr)	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± (%)
0.0	0.00	1998	0	0			
0.5	0.19	1997	1	1	0.15	0.35	20
2.5	1.08	1991	7	2	0.15	0.32	20
4.5	2.08	1984	14	4	0.15	0.29	20
6.5	3.14	1977	21	5	0.15	0.29	20
8.5	4.18	1970	28	7	0.15	0.32	20
10.5	5.00	1965	33	8	0.15	0.42	20
12.5	5.62	1961	37	8	0.15	0.55	20
14.5	6.09	1957	41	9	0.15	0.64	20
16.5	6.47	1954	44	10	0.15	0.73	20
18.5	6.79	1952	46	10	0.15	0.73	20
20.5	7.20	1949	49	11	0.19	0.73	20
22.5	7.80	1946	52	11	0.24	0.73	20
24.5	8.58	1943	55	12	0.30	0.73	20
26.5	9.49	1941	57	12	0.35	0.73	20
28.5	10.50	1938	60	13	0.40	0.73	20
30.5	11.67	1935	63	14	0.45	0.73	20
32.5	12.99	1932	66	14	0.50	0.73	20
34.5	14.39	1930	68	15	0.55	0.73	20
36.5	15.98	1927	71	15	0.60	0.73	20
38.5	17.70	1924	74	16	0.68	0.73	20
40.5	19.64	1921	77	16	0.72	0.73	20

SCP records

Although SCP records are commonly used as indicators of industrial pollution, as information on their temporal record becomes better established they are increasingly being used as chronostratigraphic markers, particularly at sites where dating by ^{210}Pb is problematic. Figure 9 summarises the data on SCP concentrations in cores from each of the Nile Delta sites. The depths of the onset of the SCP record in each core, and the SCP inventories (as particles per m2) are:

	Onset	Inventory
Edku	ca. 15.5 cm	595 × 105 m^{-2}
Burullus	ca. 9.5 cm	102 × 105 m^{-2}
Manzala	ca. 11.5 cm	703 × 105 m^{-2}

From the sediment chronologies given in Tables 9– 11 the onsets in Edku and Manzala are dated 1956 and 1955, respectively. The SCP measurements in Burullus were carried out on core BULR1 which could not be dated. The date of sediments at depth 9.5 cm in BULR2 is however 1957. It would thus appear from these results that the onset of the SCP record in Nile delta lakes can be dated to the mid 1950s. The fact that all three records start at about the same time (mid 1950s) suggests that the chronologies constructed using radionuclides and event stratigraphy are conformable, and gives confidence in their validity. Figure 9 shows that there are significant differences in the maximum SCP concentrations at the different sites, and these are also reflected in the core inventories. The higher inventories at Edku and Manzala may reflect the influence of local sources. Alternatively, the low inventory in the Burullus core may be a further indication of the poor record at this particular core site.

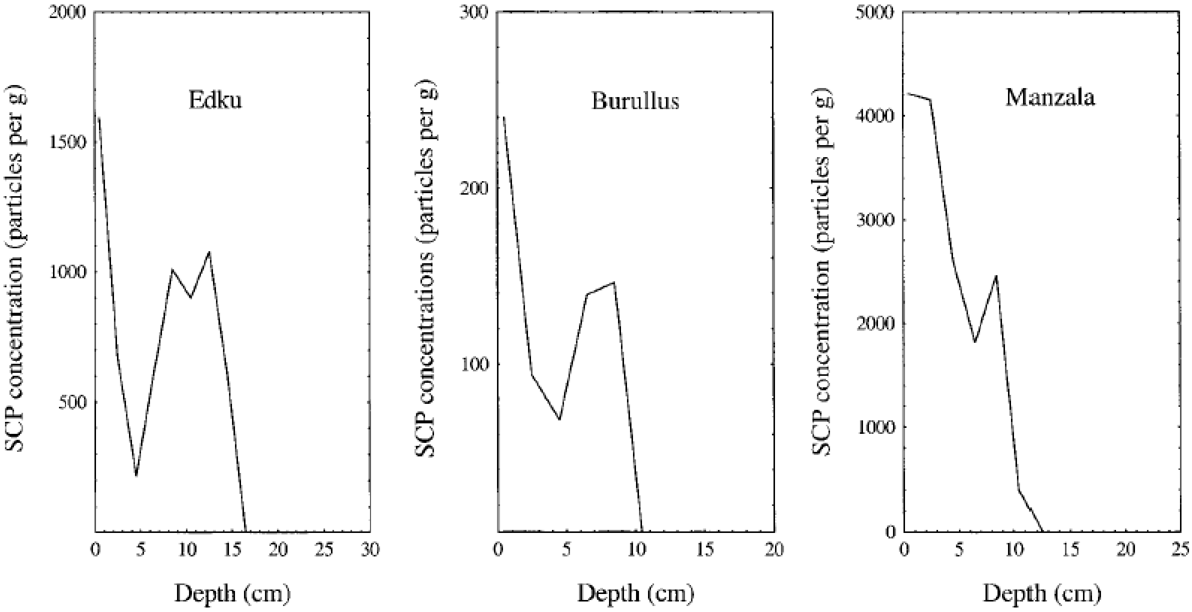
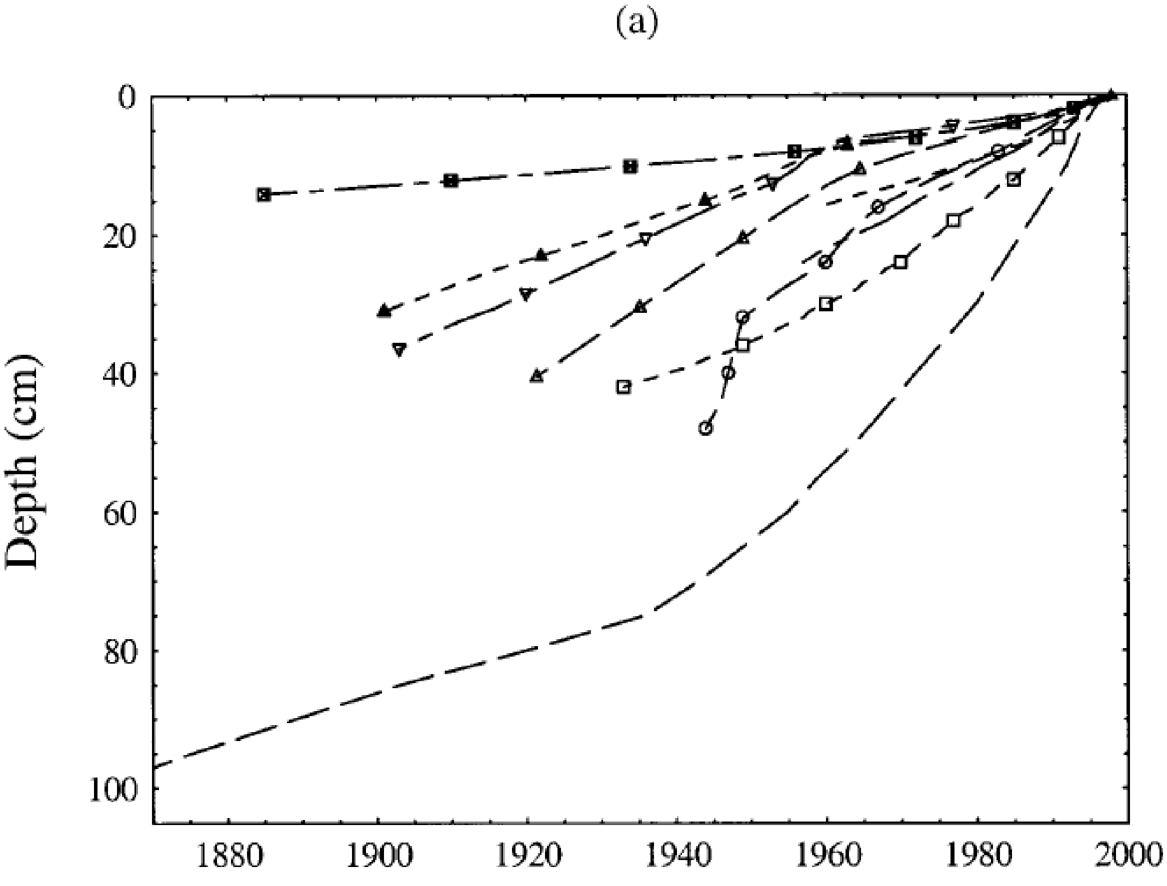


Figure 9. SCP concentrations in (a) Edku Lake core IDKU1, (b) Burullus core BURL1 and (c) Manzala core MANZ1.

Conclusions

In spite of the relatively poor fallout records in a number of cores, where mean annual rainfall exceeded ca. 500 mm yr^{-1} it was possible to construct sediment chronologies using a combination of ^{210}Pb and ^{137}Cs dating techniques, even at sites with high sedimentation rates. Although the radiometric methods essentially failed at the Nile Delta sites, due to a combination of high sedimentation rates and low rainfall, it was still possible to determine credible sediment chronologies using macrofossil and pollen records in conjunction with the radiometric data. The similarity of the SCP onset dates determined from these chronologies lends credibility to the results. It also suggests that this feature may be a useful chronostratigraphic marker in future studies. Results from all nine CASSARINA sites are summarised in Figure 10. The depth versus time plots (Figure 10(a)) illustrate the very large range in sediment accumulation rates, measured in volumetric terms. Accumulated sediment depths during the period 1900–1997 range from about 13 cm in Lac de Korba to 86 cm in Sidi Bou Rhaba. A different picture emerges when we consider accumulation rates measured in terms of cumulative dry mass (Figure 10(b)), due to the large differences in sediment densities. Measured in these terms, Sidi Bou Rhaba, which has a relatively low dry bulk density sediment (being essentially carbonates, diatoms and organic matter), has one of the lowest accumulation rates. Contemporary sedimentation rates are highest at Zerga, Bokka, Chitane, and Ichkeul. Values at these sites range from 0.4–0.6 g cm^{-2} yr^{-1}, an order of magnitude higher than in Sidi Bou Rhaba. At four sites, Sidi Bou Rhaba, Bokka, Ichkeul and Korba, there is evidence of accelerating dry matter sedimentation during the past few decades, due to increased minerogenic input. These increases together with various hydrological factors are a threat to the continued existence of all four sites. Indeed, Merja Bokka had dried up by late 1998 due to increased siltation combined with reduced water availability (Ramdani et al., 2001b). In contrast, sedimentation rates in the Nile Delta sites appear to have declined during this period, most likely due to reduced silt input due to the influence of the various Nile barrages. The reduced sediment densities reflect associated changes in aquatic vegetation, and increased organic productivity.



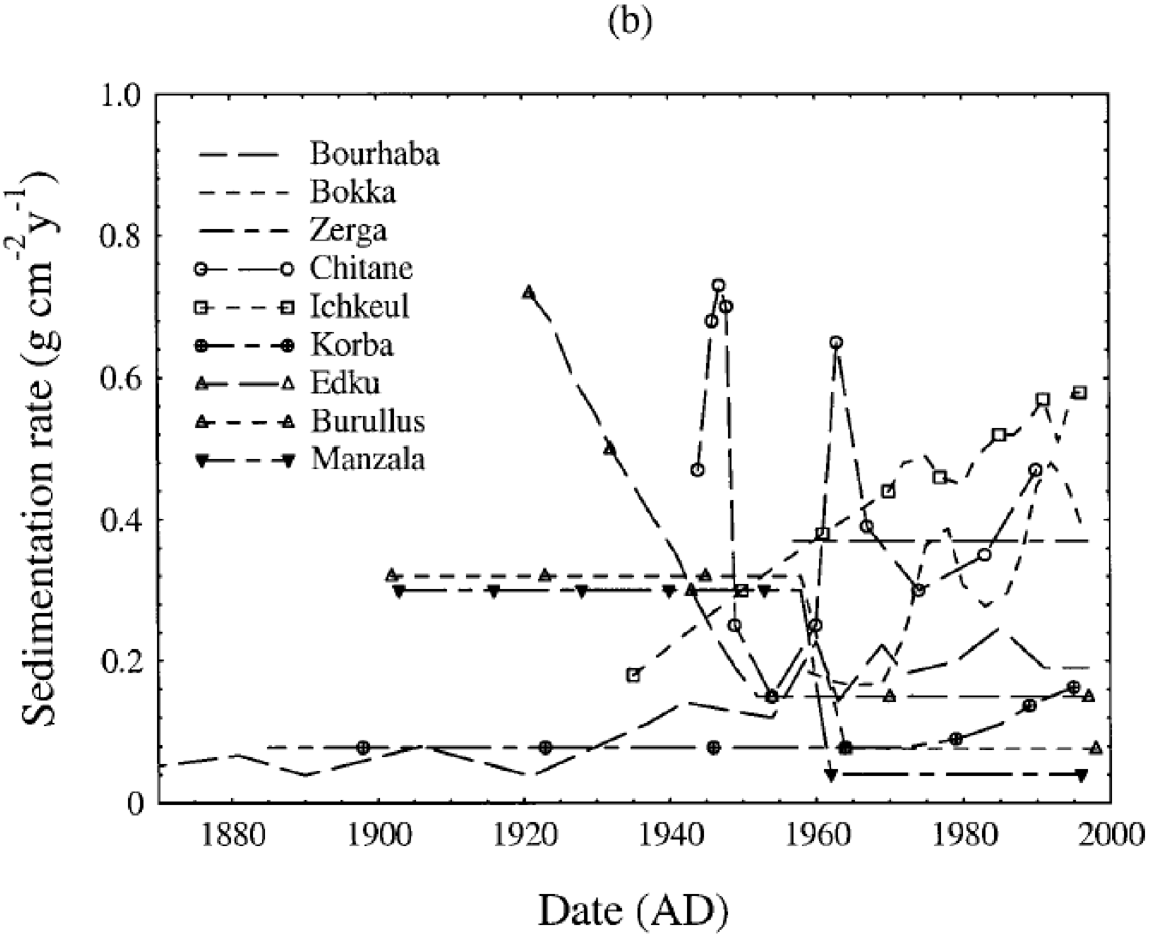


Figure 10. Summary chronologies for all 9 sites showing (a) sediment depths and (b) sedimentation rates versus time. Moroccan sites are shown without data markers, Tunisian sites with circles and squares, and Egyptian sites with triangles.

Acknowledgements

We are grateful to the European Union for their financial support of this project (award ERBIC 18CT960029), and for the help and advice provided by colleagues at the co-operating institutions.

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