Schweiz. Z. Hydrol. 49/3, 1987

0036-7842/87/030275-09$1.50 + 0.20/0

Sedimentation rates in the central Lake Constance determined with ^{210}Pb and ^{137}Cs

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Manuscript received on 11 February 1987

ABSTRACT

Sediment cores from central Lake Constance were dated with ^{210}Pb and ^{137}Cs. A sedimentation rate of (0.11±0.02) $g \cdot cm^{-2} \cdot y^{-1}$ was determined with the ^{210}Pb method. ^{137}Cs measurements revealed sedimentation rates of (0.11±0.01) $g \cdot cm^{-2} \cdot y^{-1}$ and (0.08±0.01) $g \cdot cm^{-2} \cdot y^{-1}$, respectively for two different cores sampled at the same location. The lower Cs-dated value indicates incomplete core recovery and demonstrates the sensitivity of this simple dating method to small losses of material at the water/sediment interface. An unambiguous application of the ^{137}Cs method is, therefore, only possible if complete core recovery is ensured. Sedimentation rates based on particulate matter, collected in sediment traps at various water depths, agree with the results of the radioisotope methods. Estimates of 30–125 days residence times for suspended particulate matter were calculated from ^{7}Be meausurements.

Introduction

The sediments of lakes contain valuable historic information. Dated sediments, combined with measurements of other parameters (chemical, physical, biological), allow studies of environmental changes and the impact of man on lakes and lake catchment areas. Lead-210, a member of the ^{238}U decay series, generally provides a reliable method of dating sediments deposited over the last 100 years. Since its first use by Goldberg [1], the method has been refined and is now widely employed for dating marine, estuarine and lake sediments (e.g. references [2–4]). However, recent sudies led to the hypothesis that ^{210}Pb mobilizes under anoxic or suboxic conditions [5, 6] thus producing erraneous results. Another possible tool for dating recent sediments is based on the measurement of ^{137}Cs which was deposited in sediments during the extensive testing of nuclear weapons between 1954 and 1963. A comparable timemarker for future sediment dating will be the deposition of ^{137}Cs from the accident at Chernobyl in May 1986. Short-term processes may be investigated by the cosmic-ray produced radionuclide ^{7}Be (half-life 53 days).

Lake Constance, with a surface area of 540 km^2, a water volume of 29 km^3 and a maximum depth of 252 m, is one of the largest lakes of Central Europe. It consists of an upper basin and a lower basin. The Rhine River discharges into the upper basin and supplies about 90% of the total allochthonous particulate material which makes up to about 80% of the composition of the lake sediments. The sediments of Lake Constance have been extensively studied by Müller and coworkers [7–10]. The chronological framework for these studies was provided by Dominik et al. [11] using various radioisotopic methods for dating. Moreover in 1900, the Rhine River was artificially shifted to a new bed. It is believed by many authors that this also caused a change in the distribution pattern of the sediments producing changes in their textural, mineralogical and chemical properties. Consequently, the horizon of 1900 has also been used in estimations of sedimentation rates [12–14].

In this work we used both ^{210}Pb and ^{137}Cs for dating sediments from the central part of Lake Constance. The results obtained in this study are compared with data from literature on Lake Constance sediments. In order to prove total core recovery the topmost samples of core B were analyzed for the short-lived radionuclide ^{7}Be. Furthermore, suspened particulate matter, collected at various water-depths at the location of the dated cores, has been analyzed for ^{7}Be, for an estimation of particle sinking verlocities.

Knowledge of the vertical particle transport rate in water is important for understanding the aquatic aspects of biogeochemical cycles [15, 16]. Comparing sediment fluxes in the water column and at the sediment/water interface provides information about the mechanism of settling and the resuspension of particulate matter [17]. Analysis of suspended material contributes to the knowledge of mechanisms for particle formation and transportation processes in the water column during sedimentation [18].

Experimental

Sediment cores from central Lake Constance were recovered using a gravity corer with transparent PVC-tubes (inner diameter 6.3 cm). The cores were dissected in 1-cm intervals immediately after recovery onboard ship to provide accurate porosity data. A 66 cm long core (core A) recovered in June 1981 at a water depth of 250 m from the middle of the lake was used for ^{137}Cs dating. Another core (core B) of 40 cm length recovered in April 1982 at the same locality was used for both ^{210}Pb and ^{137}Cs dating. The topmost samples of this core were also used for ^{7}Be analysis. At each time, parallel cores were taken and analyzed for sedimentary texture. Suspended material was collected at four different water depths in 1981 and 1982 using sequencing traps with an active area of 1122 cm^2 and cylinder traps with an active area of 2 × 65 cm^2 [18] and which were moored at the location of the sediment cores (fig. 1). ^{210}Pb was determined by its daughter ^{210}Po as described by Erten et al. [6]. Samples for ^{137}Cs and ^{7}Be measurements were freeze dried and homogenized before analysis in a well-type Ge(Li) gamma-ray spectrometer.

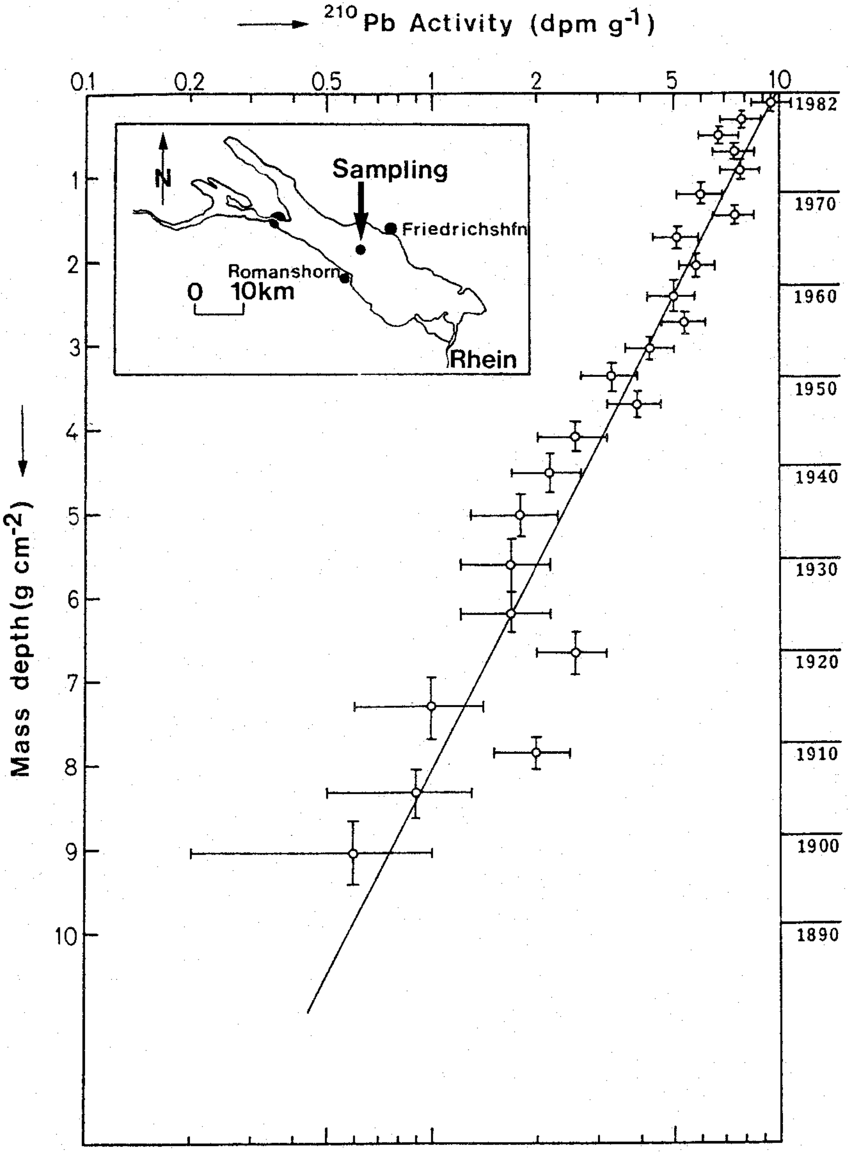

Figure 1. Activities of 'unsupported' ^{210}Pb (core B) versus depth of sediment. Solid line: Least squares fit to the data points (see text). Errors are 1 sigma. Insert: Location of the cores and the sediment traps in Lake Constance (coordinates: 740.700/270.600).

Results and discussion

The results of the ^{210}Pb/^{210}Po measurements of core B (1982) are shown in table 1. The depth in cm was converted into mass depth (g·cm^{-2}), to account for compaction of the sediments, using the sediment densities and the porosities given in table 1. The measured activities of ^{210}Pb consist of essentially constant 'supported' fraction and an 'unsupported'

Table 1. Measured and 'unsupported' activities of ^{210}Pb for sediment core B.

Depth (cm)	Porosity	Mass depth ($g \cdot cm^{-2}$)	Measured activity ($dpm \cdot g^{-1}$)	'Unsupported activity ($dpm \cdot g^{-1}$)
0– 1	0.951	0.12	11.5 ± 1.2	9.5 ± 1.2
1– 2	0.925	0.31	9.8 ± 1.0	7.8 ± 1.0
2– 3	0.926	0.50	8.8 ± 0.9	6.8 ± 0.9
3– 4	0.923	0.69	9.5 ± 1.0	7.5 ± 1.0
4– 5	0.910	0.92	9.8 ± 1.0	7.8 ± 1.0
5– 6	0.895	1.19	8.0 ± 0.9	6.0 ± 0.9
6– 7	0.897	1.45	9.5 ± 1.0	7.5 ± 1.0
7– 8	0.895	1.72	7.1 ± 0.7	5.1 ± 0.8
8– 9	0.875	2.04	7.8 ± 0.8	5.8 ± 0.8
9–10	0.855	2.42	7.0 ± 0.7	5.0 ± 0.8
10–11	0.885	2.72	7.4 ± 0.7	5.4 ± 0.8
11–12	0.875	3.04	6.3 ± 0.6	4.3 ± 0.7
12–13	0.875	3.36	5.3 ± 0.5	3.3 ± 0.6
13–14	0.870	3.70	5.9 ± 0.6	3.9 ± 0.7
14–15	0.850	4.08	4.6 ± 0.5	2.6 ± 0.6
15–16	0.830	4.52	4.2 ± 0.4	2.2 ± 0.5
16–17	0.805	5.02	3.8 ± 0.4	1.8 ± 0.5
17–18	0.775	5.61	3.7 ± 0.4	1.7 ± 0.5
18–19	0.780	6.18	3.7 ± 0.4	1.7 ± 0.5
19–20	0.815	6.65	4.6 ± 0.5	2.6 ± 0.6
20–21	0.750	7.30	3.0 ± 0.3	1.0 ± 0.4
21–22	0.790	7.84	4.0 ± 0.4	2.0 ± 0.5
22–23	0.815	8.32	2.9 ± 0.3	0.9 ± 0.4
23–24	0.720	9.04	2.6 ± 0.3	0.6 ± 0.4
24–25	0.650	9.94	–	–
25–26	0.670	10.80	2.5 ± 0.3	–
26–27	0.670	11.65	1.9 ± 0.2	–
27–28	0.670	12.50	2.6 ± 0.3	–
28–29	0.670	13.35	–	–
29–30	0.670	14.18	2.0 ± 0.2	–
30–31	0.670	15.03	2.2 ± 0.2	–
31–32	0.670	15.88	2.3 ± 0.2	–
32–33	0.670	16.73	1.6 ± 0.2	–
33–34	0.670	17.58	2.1 ± 0.2	–
34–35	0.670	18.42	2.1 ± 0.2	–
35–36	0.670	19.27	1.5 ± 0.2	–
36–37	0.670	20.12	1.9 ± 0.2	–
37–38	0.670	20.97	–	–
38–39	0.670	21.82	1.6 ± 0.2	–

(excess) activity which decreased with depth. A mean 'supported' activity of (2.0±0.3) disintegrations per minute and gram ($dpm \cdot g^{-1}$), corresponding to the ^{210}Pb/^{210}Po in secular equilibrium with ^{226}Ra, was assumed for the whole depth range and was calculated from the 12 deepest sediment samples of core B. This mean activity was subtracted from the measured activites in order to obtain the 'unsupported' ^{210}Pb (half-life 22.3 years). The errors (1sigma) in the ^{210}Pb activities are due to counting statistics and uncertainties in the efficiency calibration of the detectors and in the determination of the chemical yields. The errors in the 'unsupported' ^{210}Pb activities also include the propagated errors of the 'supported' ^{210}Pb.

Figure 1 shows a graphical presentation of the results for the unsupported ^{210}Pb of core B. A least-squares fit through these data lead to a sedimentation rate of (0.11±0.02) $g \cdot cm^{-2} \cdot y^{-1}$. The inventory of ^{210}Pb in this profile amounts to > 90%, if an atmospheric flux of ^{210}Pb of 0.8–1 $dpm \cdot cm^{-2} \cdot y^{-1}$ is assumed (A. Mangini, pers. communication) [19]. This almost complete ^{210}Pb inventory contrasts to that determined recently in Lake Zurich by Erten et al. [6]. There only ~ 50% of the expected atmospheric ^{210}Pb fallout was found in the lake sediments. Furthermore, they observed a distinct plateau-like region at the top of the ^{210}Pb activity-profile of Lake Zurich, a lake which has remained highly eutrophic over the last 100 years. The ^{210}Pb deficit and the plateau region in the ^{210}Pb profile were tentatively explained as produced by a remobilization process [6]. Mixing of the topmost layers of sediments, which could also produce a plateau in the ^{210}Pb profile [20] were excluded for the sediments of Lake Zurich, due to several facts given in Erten et al. [6]: 1. The short lived radionuclide ^{7}Be was measured only at the top of the sediment; 2. ^{137}Cs developed a dinstinct, sharp peak; 3. Undisturbed annual laminae (anoxic varves) were developed troughout the topmost sediment.

In the ^{210}Pb profile of core B of Lake Constance (fig. 1) no plateau region was observed, thus indicating that a remobilization of ^{210}Pb has not occurred in these sediments. This results is in agreement with the work of Dominik et al. [11] for a comparable sampling location. In other parts of Lake Constance, however, Dominik et al. [11] measured ^{210}Pb profiles with very expressed plateau regions close to the sediment/water interface; these regions were considered the consequence of changes in the sedimentation rates due to anthropogenic activities. The profiles showing this anomaly were recovered from parts of the lake with a high degree of eutrophication (e.g. at the 'Konstanzer Trichter' [21]).

Based on our results for Lake Constance and other work [6, 11, 21], we postulate that remobilization of ^{210}Pb may occur in sediments of eutrophic lakes and that its magnitude may depend on the redox-potential at the water/sediment interface. An indication of Pb remobilization at the water/sediment interface was recently also given by Wan et al. [5] and by White and Driscoll [22]. In order to make the ^{210}Pb method more reliable, additional careful investigations of the remobilization processes and mechanisms should be undertaken in other lakes with anoxic conditions.

The results of the ^{137}Cs measurements of cores A and B are shown in figures 2a and 2b. The activity profiles of ^{137}Cs correlate with its delivery pattern from the atmosphere [23], where the maximum activity corresponds to the year 1963. The ^{137}Cs inventories in both cores are in very good agreement. Sedimentation rates, based on the 1963 peak, have been calculated to be (0.11±0.01) $g \cdot cm^{-2} \cdot y^{-1}$ for core A and (0.08±0.01) $g \cdot cm^{-2} \cdot y^{-1}$ for core B. The difference in the sedimentation rates determined by the ^{137}Cs method may be due to a loss of the uppermost section (< 1 cm) of core B.

Table 2. Sedimentation rates obtained by different techniques.

Method	Sedimentation rate $g \cdot cm^{-2} \cdot y^{-1}$	
^{210}Pb	0.11 ± 0.02	(core 2, 1982)
^{137}Cs	0.11 ± 0.01	(core 1, 1981)
	0.08 ± 0.01	(core 2, 1982)
'1900 horizon'1)	0.12 ± 0.01	(both cores)
Sediment traps	0.14	(1981–1982)2)

1) According to Dominik et al. [11].

2) M. Sturm, unpublished.

Table 3. ^{7}Be measurements of particulate matter collected with sediment traps in 1982.

	Water depth (m)	^{7}Be activity (dpm/g)
Sampling period 18.6.–8.7.1982	19.5	24.6 ± 4.2
	60	42.6 ± 6.0
	120.5	21.0 ± 2.4
	210.5	18.0 ± 5.4
Sampling period 20.8.–9.9.1982	44.5	71.4 ± 5.4
	84.5	61.2 ± 10.2
	143.5	68.4 ± 6.6
	234.5	58.8 ± 9.0

Sedimentation rates calculated by using the ^{210}Pb method are not influenced by this loss of material, since the slope of the decay curve is used to determine sedimentation rates; however, loss of sediment material would slightly affect the estimated age of the sediments. The indication of a loss of the top sediment in core B is supported by the fact that no ^{7}Be could be detected in the uppermost part of this core.

Losses of core material probably also occurred, but to a larger extent, in the work of Dominik et al. [11] who found the 1963 peak of ^{137}Cs at the very top of the sediments in some of their cores from the central lake area. To explain this surprising result they followed Alberts et al. [24] and Ostendorp and Frevert [25], who postulated seasonal cycling of ^{137}Cs, together with the cycles of iron [24] or manganese [25]. This mechanism seems rather unlikely since it is well known that Cs is strongly sorbed by clay minerals and does not co-precipitate with iron- or manganese oxides. Furthermore, this cyclic process would probably lead to a stratification of ^{137}Cs within the sediments and not to an accumulation at or near the sediment/water interface. Another explanation put foreward by Dominik et al. [11] would be the near-bottom transport of resuspended material. The sharp peaks of ^{137}Cs found in our work (fig. 2) do not support any of these explanations. However, the existence of bio-erosive humpack-structures as described from Lake Geneva [26] may explain the observed differences also in the sediments of Lake Constance.

The sedimentation rate of 0.11 $g \cdot cm^{-2} \cdot y^{-1}$ from the ^{137}Cs measurement of the 1981 core A is in perfect agreement with the ^{210}Pb results of the 1982 core B. This is a good crosscheck that the average sedimentation rate in the central region of the lake did not change during the last 100 years, which confirms the results of Dominik et al. [11] for this part of the lake. A sedimentation rate of (0.11 ± 0.02) $g \cdot cm^{-2} \cdot y^{-1}$ is also consistent with that of (0.12 ± 0.01) $g \cdot cm^{-2} \cdot y^{-1}$, deduced from the '1900 horizon' in sediments of Lake Constance, which seems to result from the correction of the Rhine River according to [11]. This horizon was present in all recovered cores at a depth of about 24–25 cm.

The comparison of the data from [11] with core A of this study, using the turbidite of 1910 as a reference, shows that 10 to 12 cm are missing atop core SM-2 (see fig. 3). This gives a direct confirmation to explain the observed differences in the radionuclide data between our work and that of Dominik et al. [11].

Although the flux of particulate matter, as determined by sediment traps was found to vary considerably during summer and winter, an average flux of about 0.14 $g \cdot cm^{-2} \cdot y^{-1}$, calculated from sampling periods of the years 1981, 1982 and 1985 (M. Sturm, unpublished results) agrees with the sedimentation rates given above. The sedimentation rates

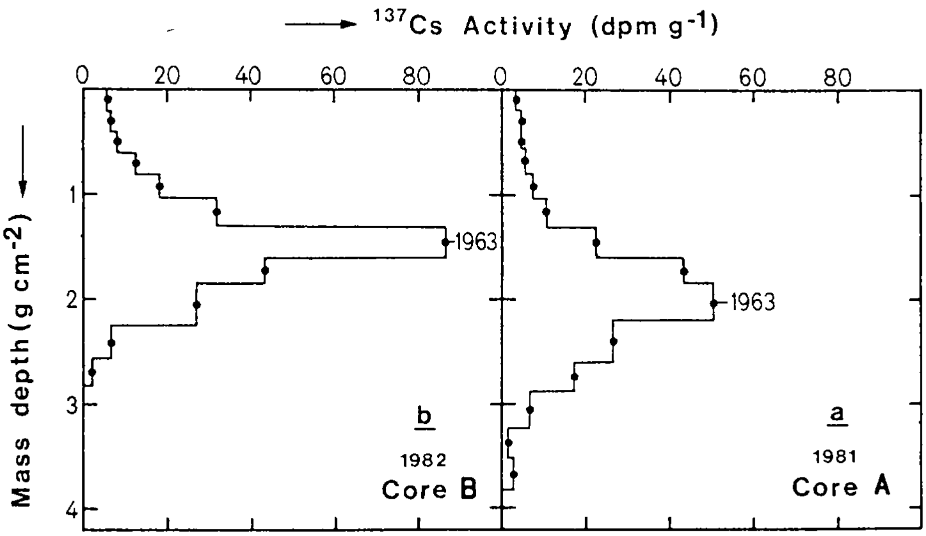

Figure 2. Activity profiles of ^{137}Cs of two cores recovered in 1981 (core A) and 1982 (core B). (Errors are 1 sigma).

determined by the different methods are summarized in table 2. With the exception of one ^{137}Cs result they are in good agreement. However, they contrast with results of Dominik et al. [11], who found sedimentation rates between 0.048 and 0.066 $g \cdot cm^{-2} \cdot y^{-1}$ in cores recovered at about the same sampling location in central Lake Constance. Discrepancies of this kind could however be due to even slight differences in the location of the sampling places as the sedimentation rates vary considerably in the E–W axis of the lake [11].

Results of ^{7}Be measurements of particulate material collected at different water depths were used to estimate sinking velocities of the particles (table 3). Values ranging between 2 and 8 $m \cdot d^{-1}$ were estimated from rather poor least square fits through the data. Based on these rough velocity estimates (only two measurements have been used and input of ^{7}Be may vary considerably) particle residence times between 30 days and 125 days were obtained for the vertical water column at the deepest part of Lake Constance. This range in bulk particle sinking velocities is in agreement with recent results from Lake Zug [27]. Much higher velocities of > 35 m d^{-1} (residence times < 7 days) were calculated by Sturm et al. [18] for calcite particles (diameter 20–40 µm) of Lake Constance. These differences are explained by the fact, that velocities of bulk material are smaller, because all kinds of particles regardless of their size, shape and density, are included.

The presented results of sediment core dating show that under stable, oxic conditions both the ^{210}Pb and the ^{137}Cs method are equally useful for dating of lake sediments. However, one should bear in mind that the ^{137}Cs method is very sensitive to sample losses. In order to ascertain the achievement of a complete core recovery, ^{7}Be should therefore be measured in the topmost samples. This can easily be done along with the measurement of ^{137}Cs.

As sedimentation rates are determined just from the slope of the activity profile, losses of sediment at the top of a core do not affect sedimentation rate estimates, when using the

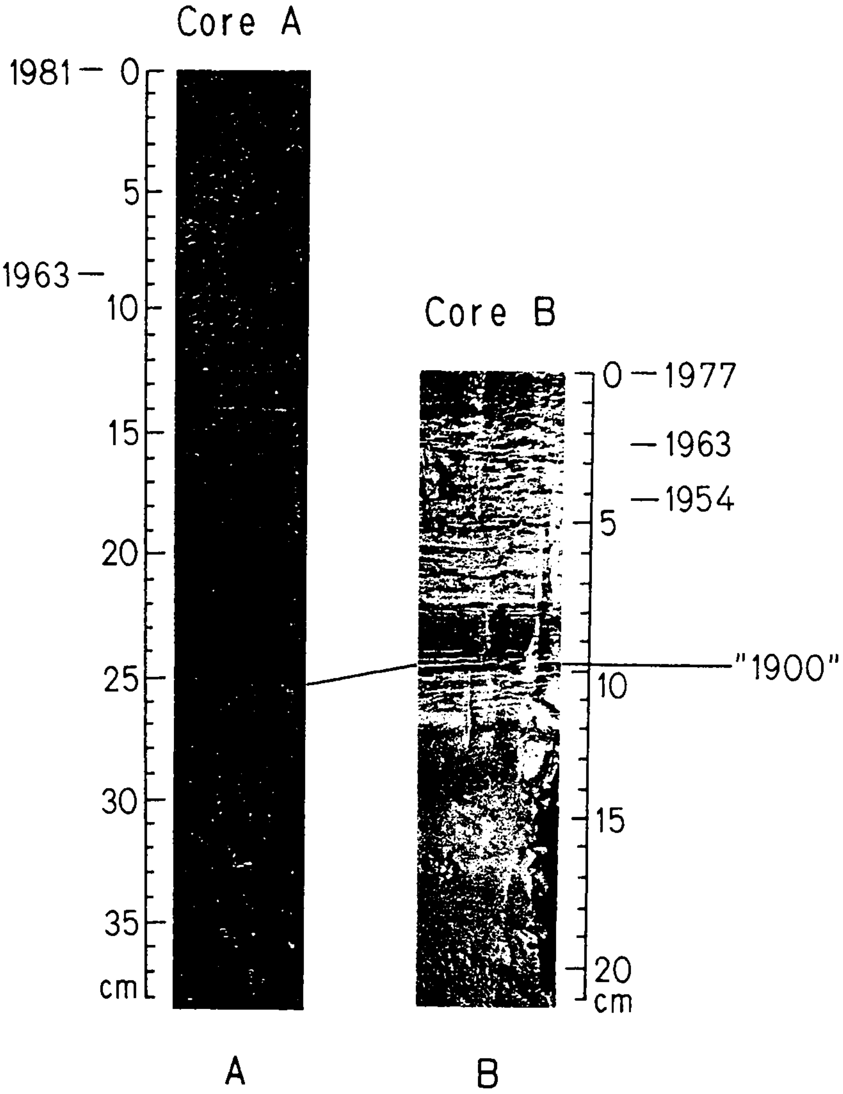

Figure 3. Comparison of photographs of two cores from the central part of Lake Constance (250 m water depth). The '1900-horizon' [11] atop a significant turbidite layer was used as key for comparison.
A: Core A, taken on 12 June 1981 with the position of the 1963 ^{137}Cs peak (this work).
B: Core SM-2 from [11] taken in 1977; scale and dating according to [11]. Note absence of about 10–12 cm of sediment on top of core SM-2 (see text).

^{210}Pb method. Nevertheless, such losses may produce errors in aging the sediments at certain depths of a core. More importantly, the results of the ^{210}Pb method may be influenced by remobilization processes during anoxic conditions in a lake and at the sediment/water interface.

ACKNOWLEDGMENT

The authors thank A. Grütter, P. Santschi and U. Krähenbühl for helpful discussions. A Mangini helped with critical remarks and B. Honeyman improved the last version of the manuscript. One of us (H.N.E.) thanks EIR for the hospitality. We acknowledge the help of the Limnological Institute of the University of Constance and A. Wiedemann as captain of the Institute's research vessel for sampling at the lake. This work was partly supported by the Swiss National Science Foundation and by a EAWAG/U+F grant.

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