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THE VALUE OF ^{210}Pb IN DATING SCANDINAVIAN AQUATIC AND PEAT DEPOSITS*

FARID EL-DAOUSHY

Institute of Physics, Box 530, S-751 21 Uppsala, Sweden

ABSTRACT. Sediment and peat chronologies have been further improved allowing alternative radiometric methods to complement ^{14}C dating. Lacustrine and coastal marine sediments as well as peat deposits in various parts in Scandinavia are studied using ^{137}Cs, ^{210}Pb, ^{14}C and other methods primarily to evaluate the ^{210}Pb but also to extend the ^{14}C chronology. The sampling sites have various sources of input and are characterized by different geochemical, depositional, and post-depositional conditions.

INTRODUCTION

During the past three decades several alternative methods have been developed for dating recent aquatic and peat deposits. However, the possibilities to date sediments and peat earlier than 50,000–70,000 BP are quite limited and further research is required to improve the available techniques.

The ^{238}U series provides several chronologies which are based on the fact that the secular equilibrium in the series is broken under favorable conditions. This gives rise to either a deficiency or an excess of certain nuclides. For ^{210}Pb, eg, an excess activity (unsupported ^{210}Pb) is created through the emanation of ^{222}Rn and its subsequent decay in the atmosphere. This ^{210}Pb is then introduced to different water systems through atmospheric and hydrologic processes. In the case of marine environments unsupported ^{210}Pb could be produced in water columns as well because of high amounts of ^{226}Ra in the waters. The pre-existing ^{210}Pb, which is available in local deposits, is called supported ^{210}Pb which may or may not be in secular equilibrium with its precursor ^{226}Ra. The unsupported ^{210}Pb, particularly when combined with other techniques, yielded credible chronologies for the past 150 yr (Pennington *et al,* 1976; Krishnaswamy & Lal, 1978). Further, the ^{210}Pb method (Robbins, 1978; Oldfield & Appelby, 1984) is used to study the influence of external and internal processes on the depositional pattern of aquatic systems. Absolute and relative dating techniques can be combined to construct whole body chronologies of lakes, marine coasts, and peat bogs (Thompson *et al,* 1980). Such studies are of major importance for mass-balance calculations and modeling of multi-system interactions (Fyfe, 1981; Dearing *et al,* 1986). This would provide information on the production, circulation, and accumulation of various chemical species in aquatic environments.

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RECENT ACCUMULATION RATES OF SEDIMENTS AND PEATS IN SCANDINAVIAN SITES

Forty-two cores from Sweden, Norway, and Finland (Fig 1) have been analyzed using ^{238}U series and other complementary methods. These cores were collected from lakes, marine coasts, and peat bogs primarily to evaluate the ^{210}Pb methodology (El-Daoushy, 1981) in dating aquatic and peat deposits and solving problems related to aquatic systems. The sediment cores, save Sites 23 and 24, were sampled from accumulation bottoms with more or less stable sedimentary conditions. In most cases, the coring sites were flat bottoms at maximum depths and the sampling procedures were carried out carefully to avoid possible disturbances.

The unsupported ^{210}Pb is calculated using the total ^{210}Pb and the supported ^{210}Pb. The latter ^{210}Pb is based on ^{226}Ra profiles and/or total ^{210}Pb in deposits older than 150–200 yr. A detailed description of the evaluation of supported ^{210}Pb is given elsewhere (El-Daoushy, ms in preparation). Table 1

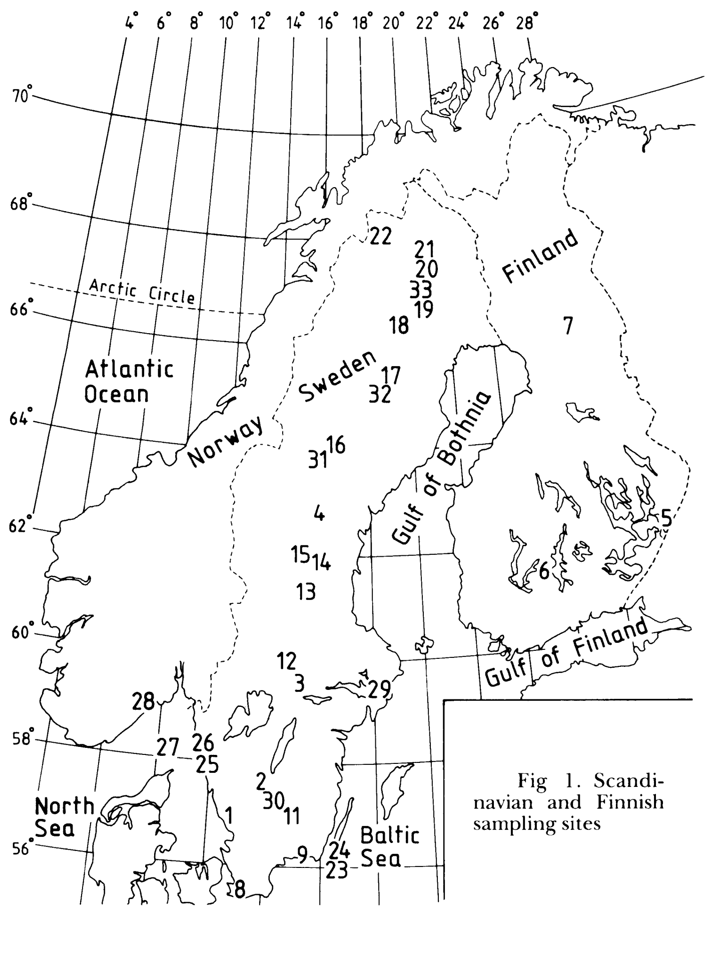

Fig 1. Scandinavian and Finnish sampling sites

TABLE 1

^{210}Pb parameters used in the calculations of deposited matter. Mean deposition rates in Scandinavian sites (Fig 1) and total organic matter in the past 150 ± 20 yr. Total deposited matter in the same time interval are given in brackets.

Coring site, number on figure 1	Mean deposition rate, $mg \cdot cm^{-2} \cdot y^{-1}$	Total organic matter, $g \cdot cm^{-2}$	Unsupported ^{210}Pb flux#, $pCi \cdot cm^{-2} \cdot y^{-1}$	Initial unsupported Pb-210 activity, $pCi \cdot g^{-1}$	^{226}Ra; supported ^{210}Pb activity*, $pCi \cdot g^{-1}$
Lake Tussjön, 1	≃ 5	0.32 (0.69)	≃ 0.01	≦ 2.7 ± 0.5	---; 0.36 ± 0.06
Lake Skärvsjön, 2 (two cores)	S1) 5.0 ± 0.4	0.21 (0.62)	0.26 ± 0.03	66.6 ± 7.3	≦ 2.0 ± 0.1; 0.95 ± 0.1
	S2) 3.0 ± 0.4	0.19 (0.53)	0.09 ± 0.01	35.9 ± 5.8	---; 0.95 ± 0.1
Lake Björken, 3	6 ± 2	≃ 0.2 (0.9)	0.16 ± 0.02	33.4 ± 5.4	Variable (6.7 ± 0.3 - 4.9 ± 0.2); Variable (6.2 ± 0.5 - 3.9 ± 0.6)
Lake Väster-Täckelsjön, 4	11 ± 2	0.38 (1.23)	0.17 ± 0.02	22.3 ± 2.7	2.0 ± 0.1; 1.6 ± 0.15
Kunonniemensuo bog (core F9), 5	21.1	3.2 (2 % ash)	0.15 ± 0.01**	> 6**	0.12 ± 0.04; 0.08 ± 0.01
Kärpänsuo bog (core 1), 6	9.3	1.4 (2 % ash)	0.12 ± 0.02**	>6**	0.12 ± 0.04; 0.20 ± 0.03
Lake Säynäjälampi, 7	(sedimentation rate 1.0 ± 0.1 $mm \cdot y^{-1}$)	---	short core		Variable (1.9 ± 0.1 - 0.08 ± 0.04); ---
Lake Havgårdssjön, 8 (two cores)	BPM) 55 ± 11	1.45 (7.45)	0.51 ± 0.06	11 ± 3	Variable (1.6 ± 0.07 - 0.81 ± 0.05); ≦1.2 ± 0.1
	C3) 17 ± 3 +	0.44 (2.29) +	---	---	---; ≦ 1.2 ± 0.1
Lake Hallsjön, 9	10 ± 3	0.65 (1.42)	0.24 ± 0.02	31.5 ± 2.7	1.3 ± 0.6; 1.3 ± 0.2

TABLE 1 (continued)

Lake Sännen, 9	9 ± 3	0.43 (1.60)	0.33 ± 0.04	25.4 ± 4.6	1.55 ± 0.04; ≤ 1.55 ± 0.11
Lake Växjösjön, 11	(sedimentation rate 5.5 ± 0.5 $mm \cdot y^{-1}$)	---	---	12.7 ± 1.8	Variable (2.0 ± 0.1 - 3.5 ± 0.2); Variable (3.5 -1.5)
Lake Saxen, 12 (two cores)	(20 ± 10) +	0.12 (1.5) + uncertain	≈ 0.06 + uncertain	---	Variable (1.9 ± 0.1 - 3.1 ± 0.1); very uncertain
Lake Uggsjön, 13	3.5 ± 0.5	0.22 (0.66)	0.37 ± 0.04	143 ± 19	1.2 ± 0.3; 1.1 ± 0.1
Lake Ramsjön, 14	94 ± 15	2.21 (10.05)	(0.21 ± 0.04)	1.9 ± 0.3	---; 1.7 ± 0.1
Lake Karsvattnet, 15	3.3 ± 0.6	0.22 (0.44)	0.09 ± 0.01	25.9 ± 2.1	0.4 ± 0.6 ‡ 0.64 ± 0.02
Lake Rensjön, 16	4.5 ± 0.7	0.34 (0.89)	0.10 ± 0.01	23.5 ± 3.1	1.1 ± 0.2; 1.2 ± 0.1
Lake Ellisjaur, 17	7 ± 1	0.52 (1.41)	0.26 ± 0.03	56.1 ± 5.0	2.2 ± 0.1 ‡ 2.6 ± 0.2
Lake Sårvatjärvi, 18	6 ± 0.7	0.34 (0.76)	0.16 ± 0.02	32.3 ± 3.0	0.6 ± 0.2; 0.8 ± 0.1
Lake Nattajärvi, 19	7 ± 3	0.67 (1.62)	0.12 ± 0.01	23.6 ± 2.2	0.70 ± 0.05 ‡ 0.90 ± 0.1
Lake Ala Makkarijärvi, 20	11 ± 2	0.69 (2.0)	0.20 ± 0.02	34.3 ± 2.1	0.30 ± 0.04; 0.52 ± 0.04
Lake Tunturijärvi, 21	13 ± 3	0.37 (1.64)	0.08 ± 0.01	6.9 ± 2.0	Variable (1.5 ± 0.1 - 3.6 ± 0.2); ≥ 1.55 ± 0.2
Lake Vasajaure, 22	(sedimentation rate 0.1 $mm \cdot y^{-1}$)	---	Deficient Pb-210 in the surface layers		Variable (1.1 ± 0.1 - 2.7 ± 0.2); (1.4 ± 0.2 - 2.6 ± 0.2)

TABLE 1 (continued)

The Baltic Sea, 23	≃ 0	≃ 0	≃ 0	≃ 0	Variable (0.40 ± 0.04 - 2.1 ± 0.1); Variable (0.45 ± 0.04- 2.83 ± 0.12)
Öland's coast, The Baltic Sea, 24	---	---	---	2.9 ± 0.1	0.2 ± 0.1; ---
Stenungsund Sound, Skagerrak, 25 (three cores)	H3) 52 ± 6	---	≃ 0.16	2.5 ± 0.1	0.95 ± 0.05; ---
	HgI) 40 ± 10	---	≃ 0.39	3.2 ± 0.5	0.55 ± 0.2; ---
	HgII) 38 ± 9	---	≃ 0.26	3.2 ± 0.5	0.75 ± 0.1; ---
Gullmarsfjorden Fjord, Skagerrak, 26 (two cores)	C3) 115 ± 7	1.67 (15.83)	0.60 ± 0.04	5.3 ± 1.0	0.35 ± 0.2; 0.50 ± 0.05
	C1) 166 ± 10	1.59 (17.70)	0.61 ± 0.03	4.8 ± 1.0	0.50 ± 0.15; 0.65 ± 0.10
Skagerrak, 27	111 ± 16	0.32 (13.35)	0.55 ± 0.04	7.7 ± 0.6	0.55 ± 0.03; 0.55 ± 0.04
Frierfjorden Fjord, 28 (two cores)	F1) 110 ± 22	1.07 (16.90)	0.50 ± 0.04	6 ± 2	0.4 ± 0.2; 0.6 ± 0.1
	F6) 187 ± 20	1.27 (28.01)	0.70 ± 0.06	8 ± 2	---; 0.6 ± 0.1
Edsviken Bay, The Baltic Sea, 29	60 ± 8	1.04 (9.20)	0.35 ± 0.03	8.8 ± 4.2	Variable (1.4 ± 0.1 - 0.45 ± 0.05); 1.0 ± 0.1
Store mosse bog, 30 (two cores)	Hummock ≃ 2.6 + Hollow ≃ 4.4 +	0.34 + 0.59 +	0.10 ± 0.04 + 0.20 ± 0.07 +	≧ 15 ≧ 10	0.1 ± 0.1 § 0.09 ± 0.05 §
Fen I, Västerbotten, 31	≃ 3.8 +	0.45 +	0.12 ± 0.04 +	≧ 7	0.3 ± 0.2 §
Fen II, Norrbotten, 32	≃ 3.1 +	0.37 +	0.07 ± 0.03 +	≃ 8	0.2 ± 0.2 §
Fen III, (Saltmyran), Norrbotten, 33	≃ 1.3 +	0.15 +	0.04 ± 0.02 +	≃ 4	0.2 ± 0.1 §

* Weighted and arithmetic averages are used
** Average of two laboratories
\+ Estimated values (densities of sediments and peats are assumed)
‡ One measurement
§ Supported ^{210}Pb is very low and is taken equal to ^{226}Ra
≠ Uncertainties due to supported ^{210}Pb are not included.

summarizes mean deposition rates calculated using the constant initial concentration model of the ^{210}Pb method (except for Sites 5 and 6). In this model the initial specific activity of unsupported ^{210}Pb, C_0, is assumed "constant" within selected intervals beneath disturbed surface zones. These disturbed zones caused obvious anomalies in the obtained ^{210}Pb profiles (El-Daoushy *et al*, ms in preparation). At some sites the surface layers of the sediments, near the sediment-water interface, are found to be physically or biologically mixed. The bioturbated zones; Lake Sännen, Lake Ramsjön, and Gullmarsfjorden Fjord, are excluded and the initial unsupported ^{210}Pb is corrected (Robbins, 1978). One core, Site 24, from Öland's coast is found to be totally bioturbated and only used to determine the unsupported ^{210}Pb concentration in the transported deposits of the island's coast. Other sites showed a pronounced decrease in ^{210}Pb activities towards the water/sediment interface. This is probably caused by acidification (Davis, Galloway & Nordstrom, 1982; El-Daoushy & Johansson, 1983) and/or increasing deposition rate. Several sites have shown such character (El-Daoushy, Johansson & Garcia-Tenorio; El-Daoushy & Franzén, mss in preparation) and the anomalous zones are rejected. Frierfjorden seems to have a variable sediment composition (Erlenkeuser & Pederstad, 1984) which would alter the initial concentration (Smith & Walton, 1980; Chanton, Martens & Kipput, 1983). Thus, grain-size analyses are needed for further evaluation of our data. Lake Växjösjön (Batterbee & Digerfeldt, 1976; El-Daoushy, ms in preparation), Lake Säynäjälampi (Olsson, El-Daoushy & Vasari, 1983) and Lake Havgårdssjön (Dearing *et al*, 1985) showed an increased sedimentation rate due to modern human activities. The initial concentration of the latter lakes has been influenced by such perturbations.

Using the least squares method an average value is calculated for C_0. The extrapolated initial concentrations are found higher than the actual C_0 values (El-Daoushy, 1986). A mean deposition rate, m, is estimated using the bulk density of the studied deposits. The uncertainties in C_0 and m show high variations in the deposition rates. The unsupported ^{210}Pb flux at the studied sites (Table 1) is calculated using the constant rate of supply model. In this model, the unsupported ^{210}Pb flux is assumed constant while mass-sedimentation rates are considered variable. The wide variations of the ^{210}Pb flux (Table 1) indicate that the processes by which the ^{210}Pb is introduced to the studied aquatic deposits, are quite different. However, single cores are not likely to represent the systems they were taken from because of the varying character of bottom dynamics and/or geochemical conditions. The atmospheric fluxes of unsupported ^{210}Pb over Scandinavian sites seem to be rather uniform and constant. For the past 150 yr an average value of 0.15 ± 0.05 $pCi.cm^{-2}.y^{-1}$ can be estimated. The total organic and deposited matter in the past 150 ± 20 yr (Table 1) are estimated using the constant rate of supply model. The mean deposition rates as derived from the two models agree well in most cases and the discrepancy is only high in few cases. Nevertheless, the ^{210}Pb models give different chronologies for these sediments and peats (El-Daoushy, ms in preparation) and other chronologic tools are used to examine the obtained model ages.

CHRONOLOGIES OF RECENT DEPOSITS

Lake Sediments

Most of the investigated lakes (Fig 1) have low accumulation rates which limited the applicability of alternative methods. Heavy metal profiles as well as fluxes could give some information on various sources and processes controlling the ^{210}Pb distribution in Scandinavian aquatic systems (El-Daoushy & Johansson, 1983; El-Daoushy, Johansson & Garcia-Tenorio, ms in preparation). Both ^{137}Cs and ^{210}Pb indicated a major bioturbation in Lake Sännen. Bioturbation in lakes with low deposition rates creates further difficulties in developing reliable chronologies.

Earlier ^{14}C studies showed that recent deposits of lakes do not agree with expected ages: variations in the cosmogenic production (Stuiver, 1978), atomic bomb tests (Nydal, 1963), modern human activities (Oldfield *et al,* 1979) as well as exchange processes and *in situ* contamination (Olsson, 1979) introduce various errors in ^{14}C dating of recent aquatic deposits. Sediment cores from Lake Säynäjälampi were examined using lithostratigraphy, density profiles, ^{210}Pb, ^{226}Ra and ^{14}C analyses. The results showed a higher accumulation rate during post settlement periods. However, sediment layers younger than ca 10 yr BP, showed an apparent ^{14}C age of ca 2000 yr (Olsson, El-Daoushy & Vasari, 1983). Another lake from southern Sweden, Site 11, demonstrated the increasing influence of human activities on sediment accumulation rates and lake eutrophication. The decreasing concentration of both ^{226}Ra and ^{210}Pb in sediments older than ca 120 yr BP indicated a variable sediment composition as a result of a strong change in the rate of sediment accumulation. These data (El-Daoushy, ms in preparation) agree well with earlier studies on the same lake (Battarbee & Digerfeldt, 1976) which showed a change in sedimentation rate of about a factor 10 in the past two centuries. The latter estimation was based on ^{210}Pb, ^{137}Cs, ^{14}C and an historical event based on lowering the water level of the lake.

Lake Havgårdssjön indicated disequilibrium between ^{226}Ra and supported ^{210}Pb, as determined from the total ^{210}Pb in sufficiently old sediments. The unsupported ^{210}Pb flux and the mean deposition rate (Table 1) were calculated using the latter alternative. However, comparing the ^{210}Pb chronologies of the given alternatives with ^{137}Cs and palaeomagnetic dates it was possible to obtain a reliable sediment chronology (Dearing *et al,* 1986). The ^{210}Pb data of the CRS model agreed only with palaeomagnetic dates. A whole lake chronology was constructed by correlating 47 cores from the lake via magnetic susceptibility profiles. The average ^{210}Pb flux was found to be 0.35 pCi.cm^{-2}.y^{-1}. The mean deposition rate for the whole lake, during the past 60 and 150 yr, was 25 and 22mg.cm^{-2}.y^{-1}, respectively. However, during 4950-1950 BP the deposition rate was lower by a factor 10 (Dearing *et al,* 1986).

Only one core, Lake Vasajaure, showed a deficiency in unsupported ^{210}Pb in the upper 1 to 2 cm. This core was 120cm long and covered the past 12,000 yr (V Karlén, pers commun.) The ^{210}Pb and ^{226}Ra results indicated a state of secular equilibrium between these nuclides.

Marine Sediments

Site 23 showed a zero deposition rate and no unsupported ^{210}Pb flux. This core was collected from a transportation bottom (M Notter, pers commun), ^{210}Pb and ^{226}Ra are in secular eqilibrium and decreasing with depth. This demonstrates the importance of ^{226}Ra in ^{210}Pb dating. Judging from the total ^{210}Pb alone a sedimentation rate of ca $0.2 mm.yr^{-1}$ could be estimated.

Gullmarsfjorden Fjord showed that surface layers of the sediments are bioturbated. ^{137}Cs and heavy metal profiles were used for the evaluation of the ^{210}Pb results. Data on the benthic organisms are in progress. After correcting the ^{210}Pb data for bioturbation, both the cic and crs models gave similar results (El-Daoushy & Josefsson, ms in preparation). The ^{210}Pb results of Skagerrak were compared with heavy metal profiles and showed undisturbed sites with stable conditions (El-Daoushy & Swinder, ms in preparation).

Sediments from Edsviken Bay were analyzed using X-rays. Supported ^{210}Pb was found in excess of ^{226}Ra. Similar results were also obtained for Gullmarsfjorden Fjord. Comparison of x-ray results and the unsupported ^{210}Pb data showed that the crs chronology agrees well with x-ray laminations when the ^{210}Pb in samples older than 150 yr is used as supported ^{210}Pb (El-Daoushy & Axelsson, ms in preparation).

Peat Deposits

Ombrotrophic (rain-fed) peat with little humification were used in this investigation. The ^{210}Pb of this peat is only supplied by direct atmospheric precipitation. The ^{210}Pb fluxes (Table 1) are among the lowest of all examined aquatic systems. Almost all the investigated sites (5, 6 and 30–33) are peat hummocks with water tables below the peat surface. The ^{210}Pb fluxes of such peat might give a lower estimate of the atmospheric ^{210}Pb fluxes. The peat hollow, which has a water table over its surface, showed a flux value higher than the corresponding hummock by a factor of two. Oldfield *et al* (1979) showed that the ^{210}Pb fluxes of peat hollows are generally higher than the neighboring peat hummocks. This could be explained by higher availability of ^{210}Pb for submerged peat hollows.

Very limited work has been done to construct recent peat chronologies. However, Sites 5 and 6 (El-Daoushy, Tolonen & Rosenberg, 1982) agreed well between the ^{210}Pb ages of the crs model and the moss-increment dating. The mean deposition rates at these sites (Table 1) were calculated using crs and moss-increment chronologies. The obtained data also extended earlier ^{14}C and pollen chronologies of the studied peats. However, the criteria of peat dating using ^{210}Pb are still in their infancies and further research is required. If ombrotrophic peats are carefully selected and properly treated one may indeed obtain good chronologies. This would allow new possibilities of studying atmospheric transportation processes and extending our knowledge on other ecosystems (El-Daoushy & Tolonen, 1984).

CONCLUSIONS

Results presented here demonstrate the importance of evaluating various dating techniques in order to obtain reliable chronologies. The use of alternative dating methods allow broader understanding of natural processes which might introduce errors in dating aquatic deposits.

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ERRATUM

BACKGROUND MEASUREMENT WITH DIFFERENT SHIELDING AND ANTICOINCIDENCE SYSTEMS

H H LOOSLI, MARKUS FORSTER, and R L OTLET

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On page 615, line 9, under INTRODUCTION, 0.2cpm should read 0.02cpm.