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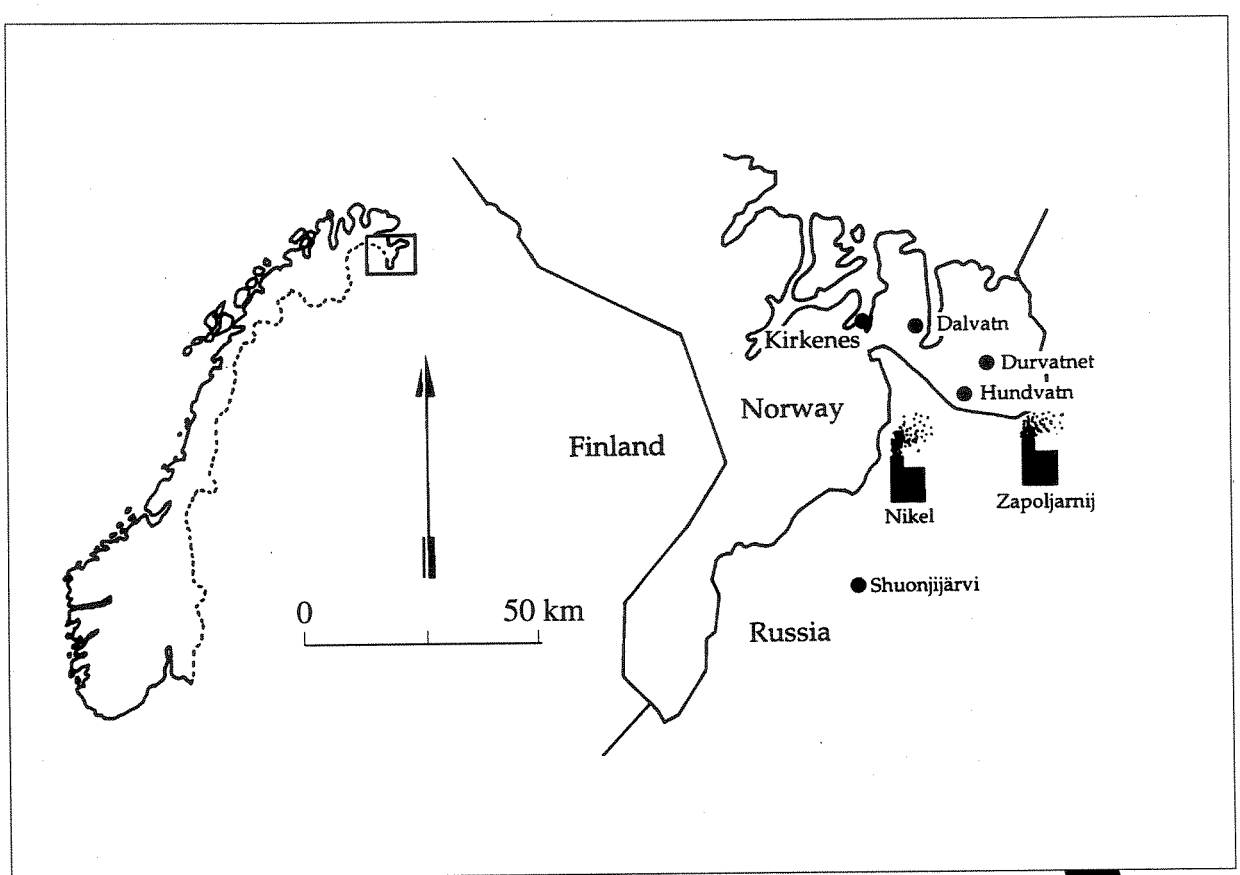
Trace metal pollution in Eastern Finnmark, Norway and Kola Peninsula, Northwestern Russia as evidenced by studies of lake sediment



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TRACE METAL POLLUTION IN EASTERN FINNMARK, NORWAY AND KOLA PENINSULA, NORTHWESTERN RUSSIA AS EVIDENCED BY STUDIES OF LAKE SEDIMENT

by

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ABSTRACT

Piston sediment cores from Lakes Hundvatn (eastern Finnmark, Norway) and Shuonijärvi (northwestern Russia) in March 1993 were dated with ^{210}Pb. Sedimentation rates at Hundvatn are 1.9±0.3 mg cm^{-2} y^{-1} (0.028 cm y^{-1}) below a sediment depth of 4.0 cm and 4.0 mg cm^{-2} y^{-1} above; in Shuonijärvi the rate is 2.4 mg cm^{-2} y^{-1} (0.032 cm y^{-1}) over the last 170 years. Cs isotopes from thermonuclear bomb fallout have been redistributed through the core, rendering them useless for dating using ^{137}Cs. ^{134}Cs (from Chernobyl) was detected in Shuonijärvi sediment. ^{241}Am distribution in the sediment is consistent with the ^{210}Pb chronology. Concentrations and fluxes of Cd, Co, Cu, Ni, Pb, and Zn increase within the last century. All the fluxes except that of Pb are higher to the northeast of the Nikel and, in combination with data from Dauvalter (1994), indicate that smelters of the Pechenga-Nikel Company have been a major source of metal pollution since their start-up and the effects are at a maximum in the youngest sediment, representing approximately the last ten years of sedimentation (up to 1993). No regional pollution of the metals (except Pb) is evident in sediment prior to the 20th century. However, the histories of Pb fluxes and concentrations indicate a pollution history probably in excess of 2000 years.

INTRODUCTION

Surveys of lake and stream water chemistry (Traaen et al., 1993), stream sediment chemistry (Rognerud, 1990), lake sediment chemistry (both surface samples; Dauvalter, 1992: and undated cores; Rognerud et al., 1993; Dauvalter 1994), and undated ombrogenic peat cores (Traaen et al., 1994) in eastern-most Norway (County Finnmark) and northwestern-most Russia (the Kola Peninsula) clearly indicate regional pollution as a consequence of atmospheric emissions from the Pechenga Ni-smelter at Nikel, Russia. This facility began operation in 1932 and was joined by several other smelting facilities eastnortheast from Nikel. The annual regional emissions are about 250,000 tons of SO_2 and up to about 500 tons of Ni (Sivertsen et al., 1991; Kryuchkov and Makarova, 1989). In 1990, short sediment cores were obtained from Dalvatn and Durvatnet, 40 km north and 35 km northeast, respectively, of Nikel (Norton et al., 1992a), (Figure1). These studies provided the first temporal dated record of air pollution in the area. The current studies reported herein were a cooperative effort between the Norwegian and Russian governments through the Norwegian Institute for Water Research (Oslo) and the Institute of the North Industrial Ecology Problems (Apatity), respectively. The goal of this research was to gather

additional evidence for the chronology of air pollution in the vicinity of Nikel by sampling a lake upwind and downwind of this major source of atmospheric pollution.

METHODS

Lake Selection, Coring, and Sediment Processing: The lakes selected represent an upwind (Shuonijärvi, southwest from Nikel) and downwind (Hundvatn, north of Nikel) from the major atmospheric point source (Figure 1). Lake Shuonijärvi (30° E. Long.; 69°15' N. Lat.) is located approximately 23 km southsouthwest from Nikel, Russia. The lake is about 8 km long (northeast-southwest) and has a maximum width of 2 km. It was reached by gravel road to the outlet at the north end. Drainage is northerly, ultimately into Passvikelva west of Nikel, and then northerly to Kirkenes, Norway. Hundvatn (30°32' E. Long.; 69°30'30"), wholly within Norway, is located about 24 km northnortheast of Nikel adjacent to the Norwegian-Russian border but receives drainage from about 1 km within Russia. The outlet of Hundvatn is the Karpelva, draining northerly into Jarfjorden. The lake is approximately 2.5 km long (notheast-southwest) and 0.5 km wide at the widest point. Access is limited to foot paths in the summer and snowscooter in the winter.

We cored through the ice (ca. 0.8m) using a Davis-Doyle piston corer (Davis and Doyle, 1969) with a diameter of 6 cm. Water depth was obtained with a plumb sounding and then the coring apparatus (tripod plus corer) was relocated approximately 3 m away to avoid disturbed sediment. The sediment core (56 cm long) from Shuonijärvi was taken at a depth of 14 m in a region of relatively low topography on 3/24/93. The Hundvatn core (37 cm long) was retrieved on 3/26/93 from a water depth of 11.5 m in mid-lake near the point of maximum curvature. Both cores had undisturbed sediment-water interfaces. Air temperature during coring and sectioning ranged from 0°C to -9°C. Sediment was kept from freezing prior to extrusion by wrapping the core tube in foam insulation. The cores were sectioned at the lake by upward extrusion as follows: 0 to 20 cm in 1 cm intervals; 20 to 40 cm in 2 cm intervals; 45-46 cm and 50-51 cm. Sediments were stored in Whirl Pak™ bags and shipped to Orono, Maine, USA by express mail from Norway.

In the laboratory, sediment was homogenized in the Whirl Pak™ bags, transferred to porcelain crucibles, and air dried at 95°C. Weight loss was calculated as water content. Selected intervals (see Table 1) were sent to P. G. Appleby at Liverpool for gamma analysis for dating (see below).

The dated samples were returned from Liverpool to Orono, Maine and recombined with the remaining sequence of intervals for a complete stratigraphy. Air dried samples were homogenized with an acid-cleaned mortar and pestle (agate) and aliquots placed in porcelain crucibles at 550°C ("ignited") for three hours. Weight loss was calculated as oxidizable hydrocarbons, or concentration of organic matter. A laboratory accident caused the complete loss of the ignited material for a number of intervals in both cores. Sufficient archived unashed material was available for a second aliquot of ashed material for most of the lost intervals. However, for 0 to 1 cm in Shuonijärvi and 0 to 2 cm in Hundvatn, we substituted sediment intervals dated by Appleby.

Radiometric dating:

Sediment samples from cores C-1 (Shuonijärvi, in Russia) and C-2 (Hundvatn, Norway) were analyzed for ^{210}Pb, ^{226}Ra, ^{137}Cs, ^{134}Cs, ^{40}K, ^{238}U, and ^{241}Am by gamma spectrometry using a well-type coaxial low background intrinsic germanium detector fitted with a NaI(Tl) escape

suppression shield (Appleby et al., 1986). The results for ^{134}Cs were corrected for decay since May 5, 1986. ^{210}Pb chronologies were calculated using both the CRS and CIC ^{210}Pb dating models (Appleby and Oldfield, 1978)

Chemical analyses:

Approximately 0.1000 g of "ignited" sediment was placed in solution using the methods of Buckley and Cranston (1971). This process places the entire sample (except graphite) into solution. Thus "bulk" chemistry is determined. Standards were made up in the same matrix from reagent grade oxides, metals, and carbonates in concentrations similar to the bulk chemistry of the sediment. Chemical analyses were performed by Atomic Absorption Spectrophotometry (Perkin-Elmer) with a graphite furnace or flame, whichever was appropriate for the element and concentration range. Silica, the most abundant metal in the sediment was not determined directly but may be calculated by difference, in as much as all the major elements are measured except for S and O. Detection limits for the trace elements were, on an ignited weight basis: Cd, 0.06 parts per million (ppm); Co, 1.0 ppm; Ni, 0.7 ppm; Pb, 1 ppm; and Zn, 11 ppm. For the three sediment intervals that had been lost in the laboratory accident, we leached dried sediment (not ashed) with 10% HNO_3 for 3 hours at 50°C. Samples were then filtered and analyzed as for the other sediment intervals. We also processed and reanalyzed several intervals previously digested by the Buckly and Cranston (1971) method and got comparable results for concentrations of trace elements. Tables 3 and 4 use the combined data. Because of the accident, we also had to estimate, by extrapolation, the concentration of organic matter in the same three intervals.

RESULTS

Radiometric dating:

For the Shuonijärvi core (Tables 1 and 2), there is little difference between the chronology based on the CRS and CIC models (Figure 1; Table 4). Both models indicate a more or less constant sedimentation rate of 2.4±0.3 mg cm^{-2} y^{-1} (or 0.032±0.004 cm y^{-1}).

In the Hundvatn core (Tables 1 and 2) the two dating models agree and indicate a fairly constant sedimentation rate up to a depth of about 4 cm, with a mean value of 1.9±0.3 mg cm^{-2} y^{-1} (0.028±0.004 cm y^{-1}). Above 4 cm, sedimentation rates appear to have been significantly higher, the onset of the change being marked by a significant reduction in unsupported ^{210}Pb activity in the 3 to 4 cm section (Figure 3; Table 1b). The CRS model calculations suggest that this feature represents an episode of rapid sedimentation some time in the period 1922-1944. Following this event, sedimentation rates appear to have remained at a slightly higher value than before, with a mean post-1950 value of 4.0±0.2 mg cm^{-2} y^{-1}. The CIC model sugests more recent and dramatic changes, the event at 3 to 4 cm being dated at ca. 1960 and a mean sedimentation rate since then of 7.4±0.7 mg cm^{-2} y^{-1}. We chose the CRS dating model for calculation of absolute ages and fluxes of metals. Extrapolation of the sediment accumulation rate downward from the 6 cm interval, where 1 cm equals 35 years results in an estimated age of 300 years A.D. at the base of the core.

The ^{137}Cs results are of little chronological value. In both cores the maximum ^{137}Cs activity occurs in the topmost sample (Table 2). In Shuonijärvi, the ^{210}Pb dates put 1963 (the time of maximum worldwide deposition of ^{137}Cs) at a depth of 1.5 to 2.0 cm. In the Hundvatn core, 1963 is between 2 (CRS model) and 3 cm (CIC model). Neither core has any ^{137}Cs peak at these levels.

Traces of ^{134}Cs in the surficial sediments of Shuonijärvi suggest that the high surficial ^{137}Cs activities in that core may be due partly to fallout from the Chernobyl incident, although when this is taken into account it still appears that ^{137}Cs mobility in the porewaters has been sufficient to destroy any record of the 1963 weapons ^{137}Cs fallout maximum. Direct evidence for this mobility is seen in the fact that 25% of the ^{137}Cs inventory in the Shuoijarvi cores lies below 3.5 cm (dated 1932), and 10% lies below 5.5 cm (dated 1874). In Hundvatn, 25% of the ^{137}Cs lies below 4.5 cm (dated 1911-1936) and 10% is below 7.5 cm (dated 1805-1830). Further evidence of the ^{137}Cs mobility is indicated by the reduced ^{137}Cs activity in the anomalous 3.5 cm layer in the Hundvatn core. Such variations may be expected where there is reduced cation adsorption capacity due to a different lithologic or organic character of the sediment.

In both cores, traces of ^{241}Am were detected in the top 3 cm. In the Shuonijärvi core, ^{241}Am activity had a peak value in the 1.5 cm sample, in reasonable support of the ^{210}Pb dates which put 1963 at a depth of ca. 1.75 cm. No such peak was observed in the Hundvatn core, although detection would be difficult in view of the large standard errors in the ^{241}Am determinations. Detection of the ^{241}Am peak, using the 59.5 keV gamma peak, was more difficult in Hundvatn because of the relatively large ^{234}Th peak at 63.5 keV arising from the higher ^{238}U activity (Table 3) in this core.

The Shuonijärvi core has a significantly lower mean ^{226}Ra (supported ^{210}Pb) and ^{238}U activity than does Hundvatn (Table 3), a much lower unsupported ^{210}Pb flux, but a significantly higher ^{137}Cs inventory. The Shuonijärvi core has an anomalous ^{226}Ra-rich layer at 4.5 cm (dated ca. 1870). The absence of any disturbance in the unsupported ^{210}Pb profile suggests that the events giving rise to this anomaly do not appear to have influenced the rate of sedimentation.

Chemistry:

Shuonijärvi -
The most obvious feature of the major element concentration distribution in this core is the dramatic variation in Fe, as shown by four Fe-rich bands centered at 6 to 7, 17 to 18, 20 to 22, and 28 to 30 cm. The most Fe-rich interval (6 to 7 cm) reaches 35% Fe (45% as FeO). That interval was distinctly brown and black flecked with orange mottling, indicative of iron enrichment. These chemical variations cause reciprocal variations in other elements (Ca, Mg, K, Na, Si, and Al). Manganese covaries with Fe. The variation in Fe in the core may be associated with changes in hydrology of the watershed, vegetation, or even water chemistry. The changes are clearly pre-industrial (pre-18th century) in age.

Trace metal concentration trends for Shuonijärvi parallel those of Dalvatn and Durvatn, to the north in Norway (Norton et al., 1992a). Pb increases from a background value of about 5 ppm to 10 ppm from 28 to 18 cm, returns to background for a short period and then climbs steadily to the surface with surface values exceeding background by a factor of about 25. Nickel remains relatively constant from the base of the core up to 5 cm and then increases dramatically from that time (ca. 1850) to the top (1993). The most dramatic increase occurs early in the 20th century. Cd varies unsystematically throughout the core. Zinc undergoes a long term decrease in concentration in the upper half of the core, clearly unrelated to industrialization in the region. Cobalt concentrations are relatively variable but with low values and no trend throughout the core.

Hundvatn -
Hundvatn sediment was also Fe-rich with notable enrichment in the 2 to 7 cm intervals. The wet sediment was conspicuously orange/brown flecked in the 2 to 5 cm interval. Manganese covaries with Fe. Apart from the dilution of other elements by the Fe, there are few indications of long term trends for Al, Mg, Ca, or K. Sodium varies very erratically throughout the core.

From a background of 3 or 4 ppm, Pb increases in concentration from about 28 cm to the 2 to 3 cm interval (1944 to 1966) and then declines to the surface. Maximum enrichment is about 30 times. The small peak between 32 and 38 cm may corrrespond to a similar peak in Shuonijärvi. Cadmium is clearly enriched in the 2 to 3 cm interval but data are not available for 0 to 2 cm. Nickel ranges from 37 to 142 ppm (an isolated sample) up to 6 cm and then increases dramatically to a surface maximum of 2363 ppm. Zinc varies randomly over a 100 ppm range up to the 0 to 1 cm interval where it doubles to 375 ppm. Copper is enriched in only the upper 3 cm of the core, reaching 1,020 ppm - a seven-fold enrichment over background. Cobalt is approximately double the background values in the upper two intervals.

Fluxes of trace metals:

In Shuonijärvi, fluxes of Cd and Co vary erratically with no apparent tendency to increase above background. The flux of Zn decreases in the sediment younger than 1957. Copper and Ni fluxes increase in post-World War II sediment with Zn following shortly thereafter. The flux of Pb increases by a factor of 5, peaking between 1966 and 1982. The earliest ^{210}Pb age for the sediment (1783) is in sediment with a Pb concentration 10 times that of background (base of the core). Thus it appears that the flux of Pb has increased by approximately a factor of 50 over the last two millenia.

For Hundvatn, the five trace metals all have increased fluxes within the range of the ^{210}Pb dating. The timing of the initial increase are as follows: Cd, in sediment dated younger than 1944; Co, 1966; Cu, 1922; Ni, 1922; Pb, 1922 (although it was by that time already elevated); and Zn, 1966. The detection of the increase in each case is a function of the natural variation and absolute concentration of the metal, relative to the anthropogenic contribution.

DISCUSSION

It is uncertain whether the anomalous 4 to 5 cm layer in Hundvatn consists of redistributed older sediment arising from, e.g., a slump event, a resuspension and deposition of older sediment (from shallow water), or an inwash of freshly eroded allochthonous material. The relative radioactive equilibrium between ^{226}Ra and ^{238}U in the sediments of this section (compared with other sediment intervals) suggests that the sediment may be relatively unweathered, perhaps supporting the latter view. However, the only other unusual aspect of this interval is the elevated concentration of Na.

Care must be taken in strict comparisons of accumulation rates between the two lakes because the cores from both lakes were not taken at the deepest area and thus probably underrepresent the maximum accumulation rates. The accumulation rates of mass for both cores are low but typical of lakes in the region (Norton et al., 1992a) and of alpine lakes in Norway (Norton and Davis, unpublished). The accumulation rate in Hundvatn is about twice that of Shuonijärvi. Thus one might expect that the inventory of atmospherically derived substances might follow this relationship. The unsupported ^{210}Pb inventory of Hundvatn is twice that of Shuonijärvi as expected (Norton et al, 1992a) but the inventory of ^{137}Cs in Shuonijärvi is twice that of

Hundvatn. Similarly, excess Pb (the concentration of Pb present in the sediment in excess of background concentrations (Norton et al., 1992b) derived from the atmosphere is twice as high in Hundvatn. However, when focusing is factored out , the fluxes of unsupported ^{210}Pb and anthropogenic Pb are comparable at the two lakes, suggesting that the fluxes may be attributed to long distance transport of Pb, rather than a local point source. The distribution of Pb in surface sediments from mostly shallow lakes (Dauvalter, 1994) suggests that much of the Pb may originate from the northwest and west (Finland and Norway). The initial increase of anthropogenic Pb in both cores occurs in sediments that almost certainly are older than 1,000 years and possibly as much as 2,000 years. Norton et al. (1992a) found Pb concentrations declining in Dalvatn and Durvatn, further to the north and northeast from Nikel but the cores were not sufficiently long to reach background values. Comparison with the very long Pb pollution scenario developed by Renberg et al. (1994) is not possible because of the lack of absolute dating below the applicable range of ^{210}Pb. The modest peak in Pb concentration at 32 to 38 and 17 to 28 cm in Hundvatn and Shuonijärvi, respectively, are at approximately the correct proportional depth, considering the accumulation rates, to suggest that they are related. If so they probably indicate a period of slightly elevated atmospheric flux of Pb related to remote emissions. The major increase in Pb can not be precisely dated because of the low resolution of the sampling. However, it occurs sometime after 1926 (Shuonijärvi) and 1944 (Hundvatn). Most likely it represents long range transport of Pb from post World War II use of leaded gasoline. The decline of Pb seen in Hundvatn in the post-1966 intervals, probably starting in the 1980s, is also consistent with ongoing reductions in Pb emissions (particularly from gasoline use) from Europe and North America. A very small increase in the Ni flux occurs at Hundvatn in sediment younger than 1890 but older than about 1924. The smelter in Nikel, midway between Hundvatn and Shuonijärvi commenced operation in 1932 (Dauvalter, 1994). The appearance of Ni enrichment in sediment older than the age of the Ni smelter activity may result from downward migration of Ni in the sediment, slight errors in dating (no more than a few year error), or Ni emission sources existing before the Nikel smelter. A dramatic increase in Ni has occurred since 1944, consistent with the history of smelting at Nikel. The two cores, obtained approximately upwind (Shuonijärvi) and downwind (Hundvatn) indicate a skewed deposition of emissions related to the Ni smelter, as seen by Dauvalter (1994) in surface sediments and short undated cores. The modest enrichment in Co (the last 20 to 30 years), Cu (the last 50 years), Zn (only in Hundvatn, the last 10+ years), and Cd (only in Hundvatn, since World War II) all suggest preferential deposition of pollutants to the northeast, relative to the southwest, consistent with the findings of Dauvalter (1994).

Analysis of flux data leads to several important conclusions. Based on the spatial distribution of the higher fluxes for the same element, it is clear that the Nikel, Russia smelter is a major source of metals (Cd, Co, Cu, Ni, and Zn) to lake environments, particularly to the north and east, the direction of prevailing winds. Consistent with the chemistry of the ores that are smelted there and consistent with the findings of Dauvalter (1994), the increased flux of Pb appears to be regional and if anything is attributable to dispersed sources to the west. The degree to which the measured sediment flux values mimic the atmospheric deposition is not well established because of the difficulty of measuring atmospheric deposition (wet and dry), the extent to which metals are delivered to lakes (and ultimately the sediment) from watersheds or bypass the lake sediments because of flow-through of particulates, mechanisms of incorporation of metals into the sediment column, and mobilization of metals because of changing water chemistry. Nonetheless, the chronology of major changes in sediment chemistry and the direction of change probably are correct within the resolution of the sediment sampling.

Steinnes (*in* Traaen et al., 1994) has analyzed undated peat cores from four ombrotrophic bogs in the Nikel region and finds much greater relative enrichment of Cu and Ni (more than two orders of magnitude). This greater enrichment is attributable to a much lower background value for both elements. With the existing data it is not possible to compare fluxes nor the timing of the increases in concentrations for Ni and Cu at the bog in close proximity to Shuonijärvi. However, the proportional increase in Ni and Cu is comparable to that found in Shuonijärvi and Hundvatn.

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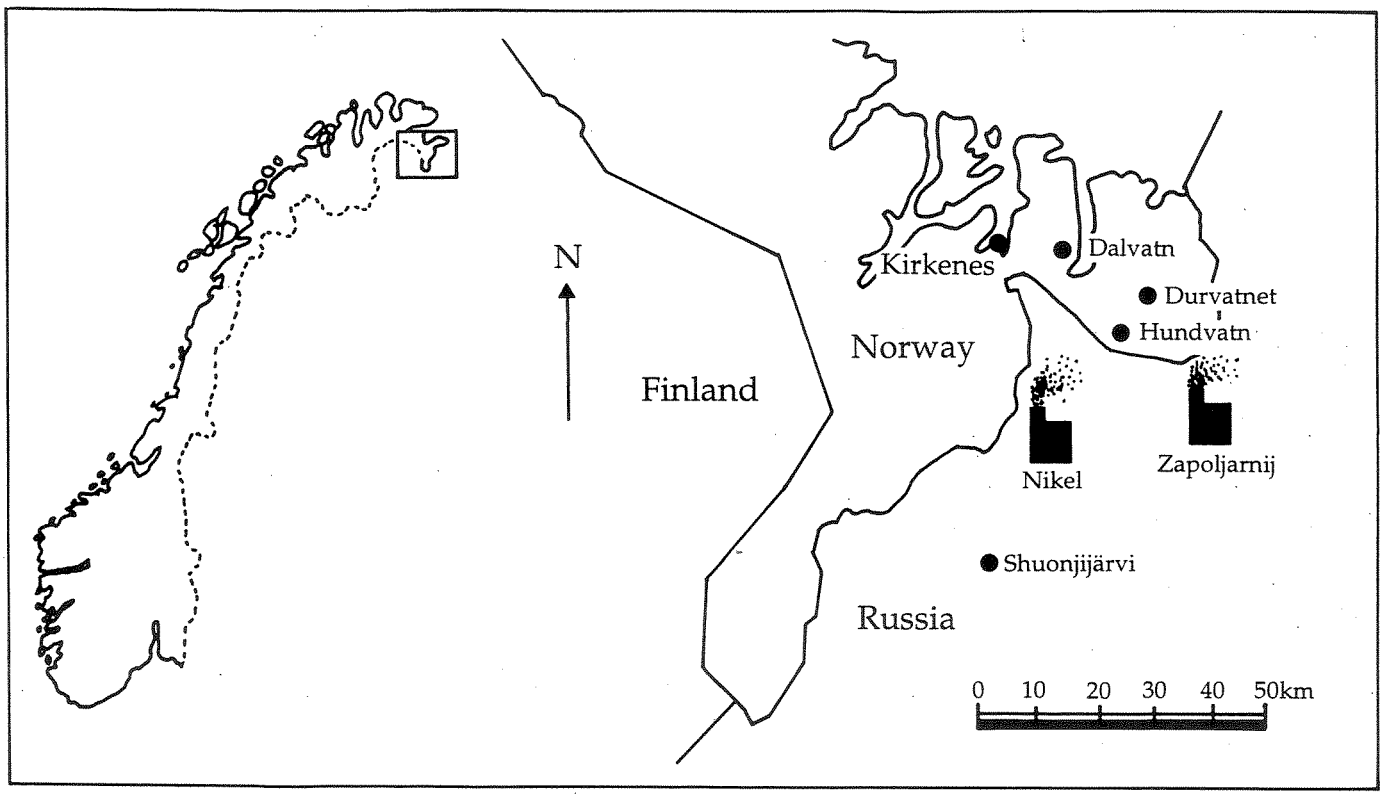

Figure 1. Location of lakes reported on in this report (Shuonijärvi and Hundvatn) and Dalvatn and Durvatn (Norton et al., 1992).

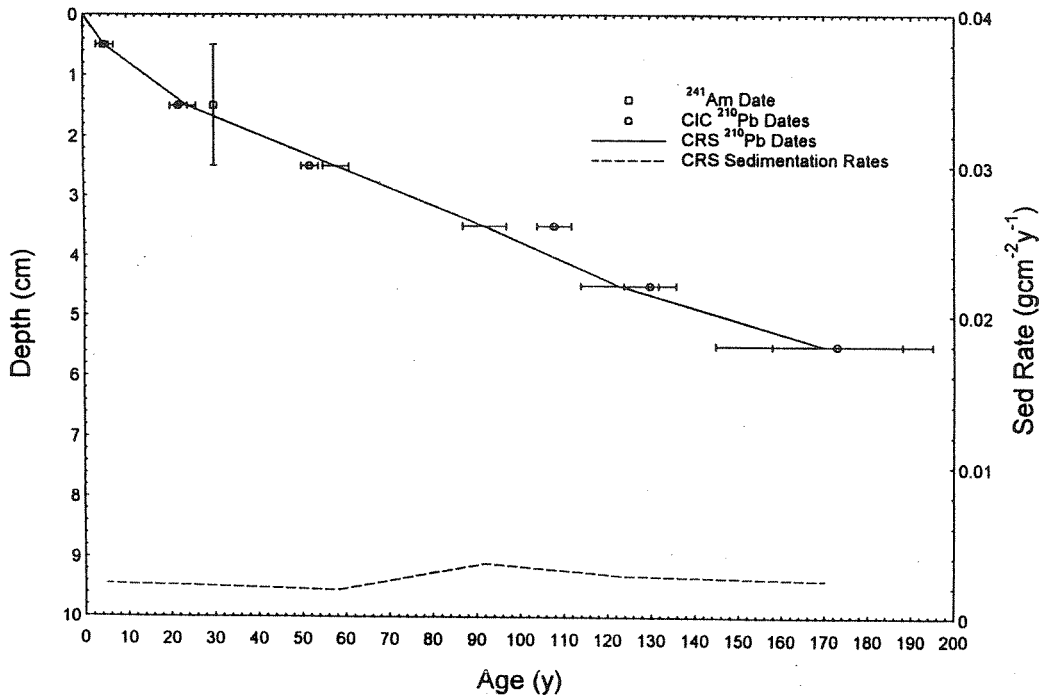

Figure 2. Depth versus age, Shuonijärvi, Core C-1.

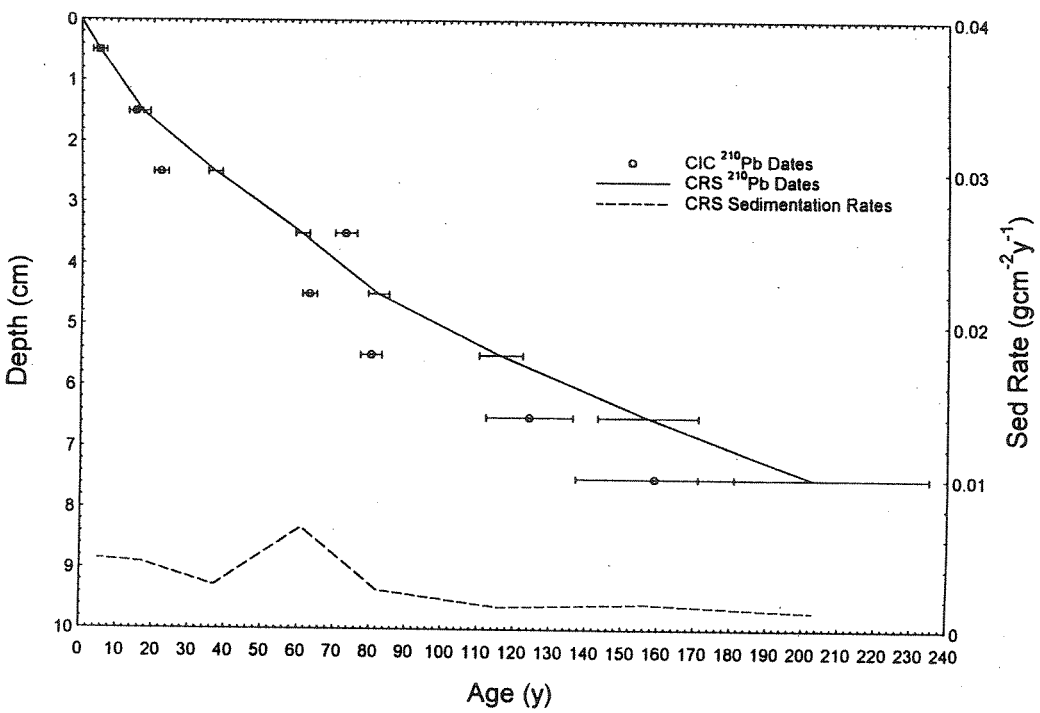

Figure 3. Depth versus age, Hundvatn, Core C-2.

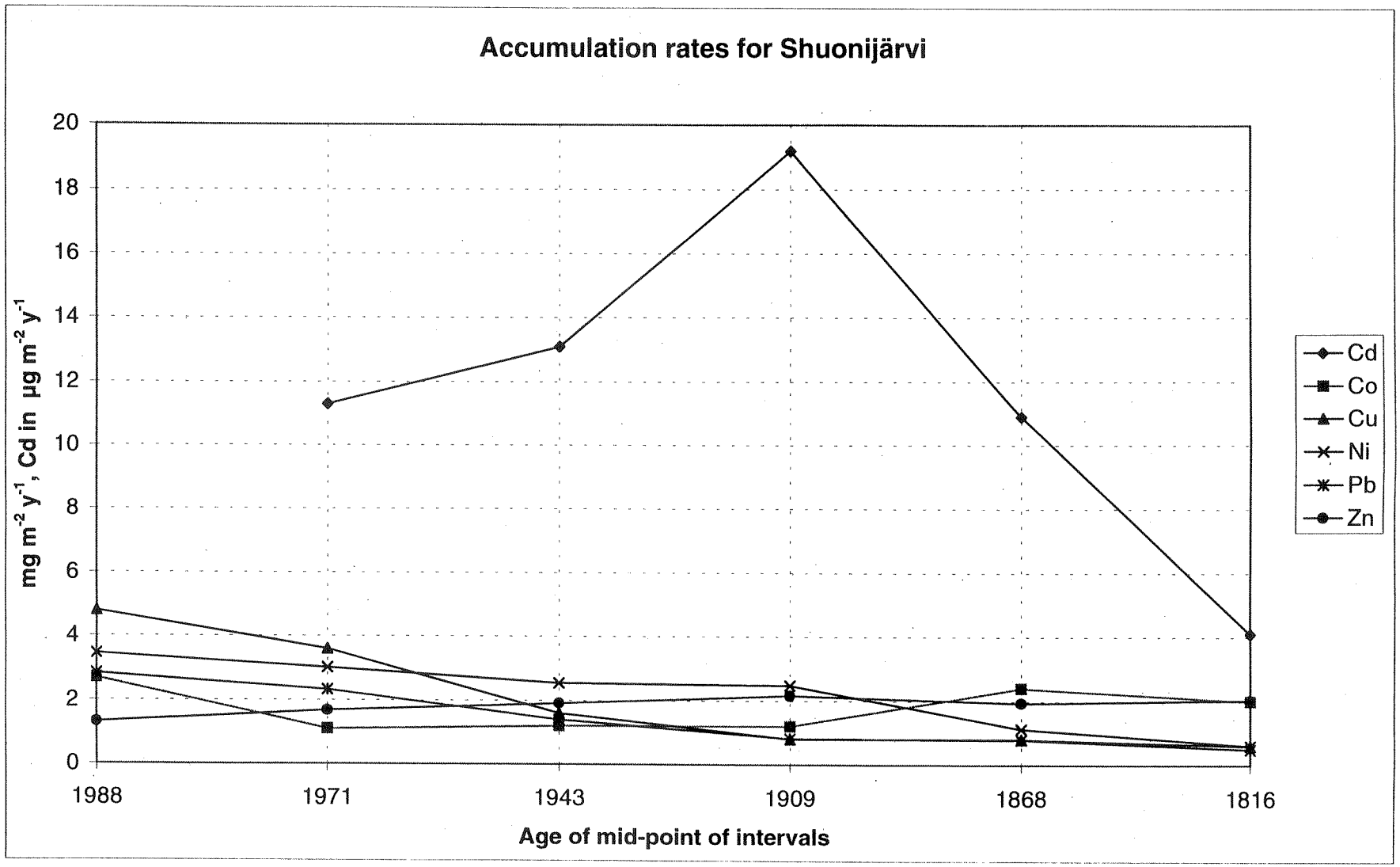

Figure 4. Accumulation rates of trace metals, Shuonijärvi.

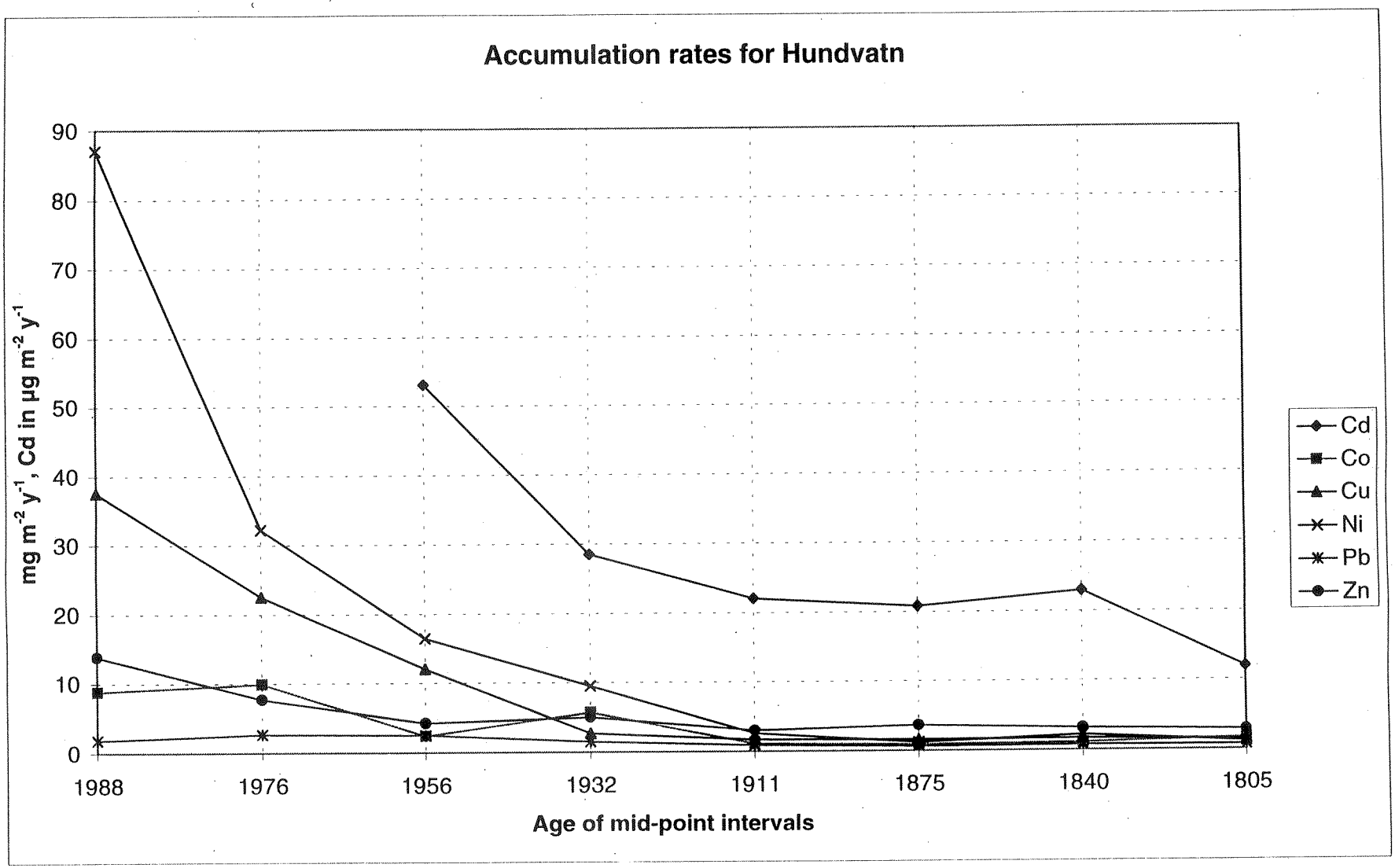

Figure 5. Accumulation rates of trace metals, Hundvatn.

Table 1. ^{210}Pb data for (a) Shuonijärvi and (b) Hundvatn.

(a) Shuonijarvi (Core C-1)

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Concentration	
		Total		Unsupp			
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.50	0.011	2242.4	55.0	2229.9	55.4	12.5	6.3
1.50	0.052	1321.8	33.9	1309.1	34.1	12.7	4.2
2.50	0.119	542.3	26.6	523.7	26.9	18.6	4.1
3.50	0.201	119.6	8.5	90.3	8.7	29.3	1.9
4.50	0.300	112.3	7.2	45.0	7.4	67.3	1.8
5.50	0.424	49.4	5.3	11.8	5.5	37.6	1.4
6.50	0.588	26.0	3.8	1.0	4.0	25.0	1.2
7.50	0.752	24.5	4.1	2.1	4.2	22.4	1.2
8.50	0.949	30.7	5.5	8.5	5.7	22.2	1.4
10.50	1.264	24.6	6.3	0.2	6.4	24.4	1.4
12.50	1.519	18.7	4.0	-0.1	4.1	18.8	0.9
14.50	1.780	21.4	5.7	-4.6	5.9	26.0	1.3

(b) Hundvatten (Core C-2)

Depth	Dry Mass	^{210}Pb Concentration				^{226}Ra Concentration	
		Total		Unsupp			
cm	gcm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.50	0.021	2109.8	55.3	1942.6	54.9	167.2	8.4
1.50	0.075	1670.8	39.9	1401.1	40.6	269.7	7.5
2.50	0.151	1217.7	23.7	1124.0	24.0	93.7	3.5
3.50	0.246	353.7	13.7	234.3	14.0	119.4	3.0
4.50	0.336	408.0	16.5	318.4	16.8	89.6	3.5
5.50	0.405	274.5	14.0	185.6	14.4	88.9	3.5
6.50	0.470	167.1	16.7	47.2	17.3	119.9	4.8
7.50	0.537	103.0	10.3	15.9	10.6	87.1	2.6
9.50	0.693	76.6	7.1	-9.3	7.4	85.9	2.1
11.50	0.859	100.2	9.5	15.6	9.8	84.6	2.4
13.50	1.015	79.9	7.4	-1.0	7.7	80.9	2.0

Table 2. ^{137}Cs, ^{134}Cs, and ^{241}Am data for (a) Shuonijärvi and (b) Hundvatn.

(a) Shuonijarvi (Core C-1)

Depth	^{137}Cs Conc		^{134}Cs Conc		^{241}Am Conc	
cm	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.50	963.0	18.4	115.5	36.2	3.5	1.4
1.50	658.6	11.4	94.8	42.3	6.1	1.4
2.50	365.0	10.4	0.0	0.0	2.1	0.9
3.50	159.0	3.6	0.0	0.0	0.0	0.0
4.50	100.3	2.4	0.0	0.0	0.0	0.0
5.50	49.4	1.8	0.0	0.0	0.0	0.0
6.50	17.8	1.4	0.0	0.0	0.0	0.0
7.50	15.3	1.5	0.0	0.0	0.0	0.0
8.50	13.6	1.7	0.0	0.0	0.0	0.0
10.50	5.4	1.2	0.0	0.0	0.0	0.0
12.50	1.3	0.7	0.0	0.0	0.0	0.0
14.50	0.0	0.0	0.0	0.0	0.0	0.0

(b) Hundvatten (Core C-2)

Depth	^{137}Cs Conc		^{134}Cs Conc		^{241}Am Conc	
cm	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.50	451.3	36.1	0.0	0.0	5.2	1.8
1.50	325.4	9.5	0.0	0.0	3.6	1.3
2.50	181.3	5.1	0.0	0.0	2.8	0.9
3.50	60.3	3.0	0.0	0.0	0.0	0.0
4.50	80.4	4.2	0.0	0.0	0.0	0.0
5.50	71.7	4.1	0.0	0.0	0.0	0.0
6.50	44.9	5.4	0.0	0.0	0.0	0.0
7.50	48.9	2.5	0.0	0.0	0.0	0.0
9.50	20.6	1.9	0.0	0.0	0.0	0.0
11.50	17.8	1.9	0.0	0.0	0.0	0.0
13.50	9.2	1.4	0.0	0.0	0.0	0.0

Table 3. Radiometric parameters for Shuonijärvi and Hundvatn.
(a) Sediment characteristics. (b) Fallout parameters.

(a) Sediment characteristics

	Mean core values				Surficial value
	^{226}Ra	^{238}U	^{40}K	Dry Wt	^{210}Pb
	$Bqkg^{-1}$	$Bqkg^{-1}$	$Bqkg^{-1}$	gcm^{-3}	$Bqkg^{-1}$
Shuonijarvi (C-1)	29	64	125	0.12	2242
Hundvatten (C-2)	94	324	101	0.074	2110

(b) Fallout parameters

	Unsupported ^{210}Pb						^{137}Cs			
	Max. Act.		Invent.		Flux		Max. Act.		Invent.	
	$Bq\ kg^{-1}$	±	$Bq\ m^{-2}$	±	$Bqm^{-2}y^{-1}$	±	$Bq\ kg^{-1}$	±	$Bq\ m^{-2}$	±
Shuonijarvi	2230	55	1860	62	58	2	963	18	1374	31
Hundvatten	1943	54	3348	92	104	3	451	14	916	21

Table 4. ^{210}Pb chronology and sedimentation rates for (a) Shuonijärvi (CRS = CIC Model) and (b) Hundvatn (CRS and CIC Model).

(a) Shuonijarvi (Core C-1)

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	gcm^{-2}	AD	yr	±	$gcm^{-2}yr^{-1}$	$cmyr^{-1}$	± (%)
0.00	0.000	1993	0				
0.50	0.011	1988	5	1			
1.00	0.032	1980	13	2			
1.50	0.052	1971	22	3			
2.00	0.086	1957	36	5			
2.50	0.119	1943	50	6			
3.00	0.160	1926	67	8	0.0024	0.032	12.5
3.50	0.201	1909	84	11			
4.00	0.250	1889	104	13			
4.50	0.300	1868	125	16			
5.00	0.362	1842	151	19			
5.50	0.424	1816	177	22			

(b) Hundvatten (Core C-2)

(i) CRS Model

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	gcm^{-2}	AD	yr	±	$gcm^{-2}yr^{-1}$	$cmyr^{-1}$	± (%)
0.00	0.000	1993	0				
0.50	0.021	1988	5	2	0.0046	0.092	4.1
1.00	0.048	1982	11	2	0.0045	0.080	4.3
1.50	0.075	1976	17	2	0.0044	0.068	4.5
2.00	0.113	1966	27	2	0.0037	0.051	4.6
2.50	0.151	1956	37	2	0.0029	0.034	4.8
3.00	0.198	1944	49	2	0.0048	0.054	6.4
3.50	0.246	1932	61	2	0.0067	0.073	8.0
4.00	0.291	1922	71	3	0.0047	0.053	8.7
4.50	0.336	1911	82	3	0.0026	0.032	9.4
5.00	0.370	1893	100	4			
5.50	0.405	1875	118	7			
6.00	0.438	1857	136	9	0.0019	0.028	15.8
6.50	0.470	1840	153	11			
7.00	0.504	1822	171	14			
7.50	0.537	1805	188	17			

(ii) CIC Model

Depth	Dry Mass	Date	Age		Sedimentation Rate		
cm	gcm^{-2}	AD	yr	±	$gcm^{-2}yr^{-1}$	$cmyr^{-1}$	± (%)
0.00	0.000	1993	0				
0.50	0.021	1990	3	1			
1.00	0.048	1986	7	2			
1.50	0.075	1983	10	2	0.0074	0.11	9.5
2.00	0.113	1978	15	2			
2.50	0.151	1973	20	2			
3.00	0.198	1966	27	3			
3.50	0.246				slump layer?		
4.00	0.291	1960	33	3			
4.50	0.336	1936	57	5			
5.00	0.370	1918	75	8			
5.50	0.405	1900	93	10	0.0019	0.028	15.8
6.00	0.438	1882	111	12			
6.50	0.470	1865	128	15			
7.00	0.504	1847	146	18			
7.50	0.537	1830	163	21			

Table 5. Sediment chemistry for Hundvatn, Norway. Concentrations based on ashed weight.

Sediment chemistry for Hundvatten																					
Depth	H2O	Organic	Beq/kg	Beq/kg	Beq/kg	Beq/kg	Beq/kg		Fe	Mn	Al	Ca	Mg	Na	K	Cd	Co	Cu	Ni	Pb	Zn
	%	%	Cs 137	Cs134	Am241	Pb210	Ra226		%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm
0 to 1	95.88	20	451	0	5.2	2110	167										240	1020	2363	50	375
1 to 2	93.66	20	325	0	3.6	1671	270										280	640	915	75	219
2 to 3	91.92	18.74	181	0	2.8	1218	94		34.9	1.66	1.55	0.736	0.369	0.086	0.075	2.25	100	510	696	105	180
3 to 4	90.08	15.31	60	0	0	354	119		39.5	1.26	1.12	0.653	0.223	0.065	0.054	0.75	150	70	251	39	132
4 to 5	93		80	0	0	408	90		20.6	0.853	2.49	0.844	0.388	0.546	0.126	1.02	50	80	121	41	140
5 to 6	93.63		72	0	0	274	89		18.2	0.758	2.93	0.9	0.41	0.855	0.14	1.34	60	100	77	41	236
6 to 7	93.83	19.89	45	0	0	167	120		24.1	0.924	3.11	0.985	0.447	0.198	0.138	1.49	70	110	142	48	208
7 to 8	93.34		49	0	0	103	87		16.4	0.655	2.97	0.908	0.385	0.539	0.139	0.78	110	100	78	46	188
8 to 9	92.29	19.17							17.7	0.663	3.47	1.139	0.505	0.292	0.174	1.59	70	120	50	34	232
9 to 10	92.45		21	0	0	77	86		15.3	0.524	3.3	1.033	0.429			0.61	90	90	50	19	232
10 to 11	91.89	19.64							10.3	0.46	3.66	1.215	0.542	0.415	0.203	1.55	130	100	53	20	264
11 to 12	92.19		18	0	0	100	85		8.1	0.389	3.21	1.067	0.649	0.362	0.181	0.59	120	110	82	14	264
12 to 13	92.85	21.52							11.1	0.525	3.76	1.243	0.741	0.334	0.192	1.4	150	120	70	17	204
13 to 14	92.18		9	0	0	80	81														
14 to 15	93	15.94							18.2	0.513	3.41	1.145	0.672	0.347	0.186	0.96	100	100	44	14	212
15 to 16	92.79	20.45							15.7	0.556	3.82	1.324	0.754	0.419	0.204	1.36	110	130	75	21	236
16 to 17	92.8	20.11							15.7	0.607	3.85	1.234	0.696	0.331	0.185	1.41	110	130	65	19	212
17 to 18	92.75	21.69							17.4	0.617	3.62	1.183	0.639	0.272	0.172	1.27	170	140	75	24	248
18 to 19	92.14	20.57							13.1	0.549	3.42	1.148	0.625	0.262	0.167	1.42	100	130	56	17	192
19 to 20	93.1	20.76							15	0.575	3.71	1.173	0.65	0.26	0.171	1.42	100	140	72	13	208
20 to 22	92.8	21.06							14.8	0.589	3.89	1.291	0.671	0.29	0.193	1.44	70	140	75	11	224
22 to 24	92.33	20.95							13.9	0.559	3.71	1.232	0.69	0.308	0.195	1.4	100	150	100	6	252
24 to 26	92.46	17.76							17.5	0.529	3.45	1.058	0.635	0.267	0.161	1.17	70	130	75	6	224
26 to 28	92.5	19.44							12.1	0.532	4.09	1.326	0.78	0.427	0.195	1.46	120	150	103	5	264
28 to 30	91.45	18.54							16.7	0.532	3.33	1.058	0.622	0.25	0.158	1.25	80	120	53	3	236
30 to 32	92.32	18.59							16.4	0.563	3.44	1.076	0.624	0.252	0.146	1.17	60	120	86	3	220
32 to 34	92.32	20.08							15.5	0.578	4.02	1.294	0.766	0.37	0.189	1.47	130	160	85	9	252
34 to 36	91.73	18.9							12.7	0.553	3.83	1.273	0.744	0.356	0.19	1.38	100	160	89	7	236
36 to 38	91.98	20.47							13.1	0.545	3.75	1.181	0.708	0.296	0.175	1.48	120	150	71	12	254
50 to 51									7.5	0.076	3.78	0.988	0.617	0.26	0.237	0.51	60	80	37	4	122
Organic concentration estimated for 0-1 and																					

Table 6. Sediment chemistry for Shuonijärvi, Russia. Concentrations based on ashed weight.

Sediment chemistry for Shuonijarvi																					
Depth	H2O	Organic	Cs 137	Cs134	Am241	Pb210	Ra226		Fe	Mn	Al	Ca	Mg	Na	K	Cd	Co	Cu	Ni	Pb	Zn
	%	%	Beq/kg	Beq/kg	Beq/kg	Beq/kg	Beq/kg		%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm
0 to 1	97.82	20	963	115.5	3.5	2242	12.5										140	250	180	148	69
1 to 2	94.19	20.3	659	94.8	6.1	1322	12.7		4.34	0.11	2.99	0.989	0.58	0.243	0.197	0.59	60	190	158	122	88
2 to 3	93	18.77	365	0	2.1	542	18.6		5.59	0.633	3.11	1.027	0.57	0.267	0.243	0.67	60	80	131	72	98
3 to 4	91.38	16.61	159	0	0	120	29.3		5.99	2.55	3.07	0.985	0.54	0.272	0.232	0.96	120	40	124	41	108
4 to 5	90.04	15.99	100	0	0	112	67.3		10.18	2.78	2.8	0.867	0.504	0.225	0.201	0.54	120	40	56	39	96
5 to 6	86.87	15.07	49.4	0	0	49	37.6		24.81	0.638	2.36	0.76	0.372	0.193	0.165	0.2	100	30	30	24	100
6 to 7	83.46	17.09	17.8	0	0	26	25		34.52	0.372	1.84	0.648	0.293	0.105	0.098	0.09	70	10	26	21	96
7 to 8	86.69	16.14	15.3	0	0	25	22.4		17.26	0.176	2.92	0.889	0.494	0.212	0.165	0.37	50	30	33	29	96
8 to 9	78.45	15.96	13.6	0	0	31	22.2		10.66	0.139	3.48	1.021	0.614	0.313	0.221	0.2	40	40	36	20	88
9 to 10	88.29	15.96							11.44	0.142	3.65	1.09	0.637	0.346	0.24	0.82	80	30	52	21	140
10 to 11	88.03	14.97	5.4	0	0	25	24.4		3.07	0.092	3.23	0.993	0.562	0.299	0.223	0.49	30	30	36	13	100
11 to 12	88.06	14.74							6.44	0.115	3.34	0.942	0.557	0.27	0.22	0.32	60	30	42	10	105
12 to 13	88.53	19.04	1.3	0	0	19	18.8		39	0.258	3.54	0.798	0.425	0.153	0.143	0.16	100	30	41	12	124
13 to 14	87.63	15.1							8.64	0.117	3.32	0.922	0.549	0.257	0.222	0.62	80	20	53	5	168
14 to 15	87.92	15.65	0	0	0	21	26		7.57	0.115	3.82	1.076	0.674	0.363	0.278	0.38	40	20	50	6	112
15 to 16	87.11	13.9							5.35	0.092	3.19	0.914	0.574	0.259	0.213	0.49	50	30	43	4	144
16 to 17	87.22	14.7							7.45	0.103	3.38	0.986	0.6	0.28	0.219	0.39	140	20	42	6	96
17 to 18	88.43	17.27							12.18	0.134	4.19	1.053	0.636	0.328	0.243	0.58	90	40	54	10	172
18 to 19	88.31	16.89							9.7	0.12	4.07	1.094	0.668	0.359	0.251	0.7	60	30	46	13	104
19 to 20	87.67	15.55							8.63	0.107	4.22	1.106	0.658	0.381	0.264	0.46	90	50	46	11	108
20 to 22	87.16	15.71							10.12	0.107	4.15	1.119	0.668	0.415	0.276	0.61	70	60	43	10	128
22 to 24	86.56	14.31							8.29	0.092	4.16	1.102	0.687	0.412	0.279	0.39	40	60	37	8	156
24 to 26	87.69	16.66							9.8	0.101	4.31	1.12	0.722	0.406	0.292	0.85	60	70	34	9	120
26 to 28	87.39	16.12							9.08	0.094	4.24	1.134	0.703	0.377	0.269	0.62	50	60	33	11	172
28 to 30	86.81	15.06							8.14	0.089	4.49	1.101	0.699	0.364	0.266	0.61	40	60	34	7	140
30 to 32	87.9	18.79							10.86	0.099	4.43	1.096	0.679	0.346	0.282	0.71	40	70	46	7	136
32 to 34	87.02	16.72							9.68	0.084	3.97	0.99	0.586	0.261	0.241	0.53	50	60	35	7	144
34 to 36	87.21	17.77							8.42	0.08	3.91	0.98	0.582	0.275	0.233	0.37	70	60	47	3	148
36 to 38	86.62	16.46							8.32	0.079	4.03	1.058	0.604	0.353	0.252	0.32	70	70	42	7	152
38 to 40	86.9	17.75							8.66	0.082	4.12	1.052	0.623	0.301	0.225	0.31	40	80	47	6	136
45 to 46	87.11	17.46							8.71	0.079	4.14	1.014	0.576	0.265	0.226	0.35	50	80	43	5	
50 to 51	87.23	17.79							7.5	0.076	4.07	0.996	0.564	0.271	0.217	0.7	50	70	37	4	144
Concentration of organic matter in 0-1 cm is estimated																					

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