

Heavy metal (Zn, Cu, Pb) accumulation in the Barnesfjord: Western Norway

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Two gravity cores and two box cores from the inner and outer basins of the anoxic Barnesfjord were dated by radiocesium of the 1986 Chernobyl accident and of earlier Pacific nuclear weapon tests in 1963 and 1959. Sedimentation rates in the inner and outer basin are >0.4 to 2.0 cm/year over the last 200 years. The concentration and accumulation rates of three heavy metals in the surficial sediments are Zn 72–144, Pb 27–51 and Cu 17–31 ppm; their accumulation rates are Zn 0.28–0.39, Pb 0.13–0.25 and Cu 0.06–0.11 g/m²/year. The accumulation rates for sediments deposited during the last 10 years are similar to those deposited before AD 1900. The values are equal to or even higher than those reported from other Norwegian fjords subject to industrial pollution.

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Heavy metal pollution caused by periodic industrial release is a major problem in many Norwegian fjords, for instance the inner Oslofjord (Agerup 1984), Bunnefjord (Egeberg 1983; Skei & Melson 1982), Sandebukta (Nagy & Alve 1987), Sunndalsfjord (Næs & Rygg 1988), Sørfjord (Skei 1981; Skei et al. 1972), Trondheimsfjord (Skei 1983) and Ranafjord (Skei & Paus 1979). The assessment of the environmental impact of this periodic pollution is frequently carried out by determining the amounts of heavy metals in surficial sediments taken from fjord bottoms. The nature of periodic and non-constant dumping of industrial waste waters into fjords prohibits a quantification of the degree of pollution by analysis of fjord waters taken at one time.

Sediments accumulating in fjords are excellent recorders of both natural- and human-induced impact. Prerequisites that must be met when assessing magnitudes of pollution using concentrations of heavy metals in sediments include: (1) the sediments must accumulate undisturbed and in situ; (2) sediment sampling must be recovered near surface sediments that are no older than 10 years; and (3) sedimentation rates must be accurately determined in order to convert component concentration into specific accumulation rates that can be used for comparison with other areas.

Sedimentation rates can be determined by different methods. The 1986 accident at the Soviet nuclear power plant at Chernobyl, which caused the atmospheric transport of radio-isotopic material and its subsequent fallout over wide areas, has provided us with a short-lived 'golden spike' in oceanic, freshwater and fjord sedimentary environments which lay in the pathway of the radiocesium containing cloud. This 'spike' is an extremely useful stratigraphic tool with which to determine recovery of near surface sediments and to determine sediment accumulation rates after 1986.

The 1986 Chernobyl accident is one reliable marker, others further back in time include: (1) the peak of

worldwide fallout of Pacific nuclear bomb testings in 1963 and 1959; (2) well-documented historical events that left traces in the sedimentary record, such as catastrophic floods and major slide and slump events.

Using well-constrained events of known age in the sedimentary record, such as those listed above, to calculate accurate sedimentation rates has the advantage over the traditionally used ²¹⁰Pb decay curve by providing absolute dated tie points in the sedimentary column.

Environmental setting

The Barnesfjord in western Norway is a NE-trending tributary of Sogndalsfjord, which is connected to Sognefjord to the south (Fig. 1). The Barnesfjord consists of two shallow basins (Fig. 2). The outer one (75 m deep) stretches from the town of Sogndal in the south to the peninsulas of Barsnes and Kvam about 2 km further north. The inner basin (62 m deep) stretches from Barsnes ca. 2.5 km to the east, where the river Årøy flows into the fjord. Both basins have a smooth and flat bottom. They are separated by a 29 m shallow sill. A second shallow sill (7.5 m deep) separates the outer basin from Sogndalsfjord.

Dissolved oxygen concentrations of the surface water in the outer basin are uniform at 11 to 14 ml O₂/l throughout the year. The bottom water (at 60 m water depth) is characterized by a lack of oxygen in winter (December–February) and dissolved oxygen values of 2 to 5 ml O₂/l throughout the rest of the year. The dissolved oxygen concentrations of the inner basin bottom water may be less than those of the outer basin (Hovgaard 1985). The deeper parts of both basins are periodically (the outer basin) and permanently anoxic (the inner basin), resulting in the accumulation of relatively undisturbed sedimentary records (Paetzel 1990).

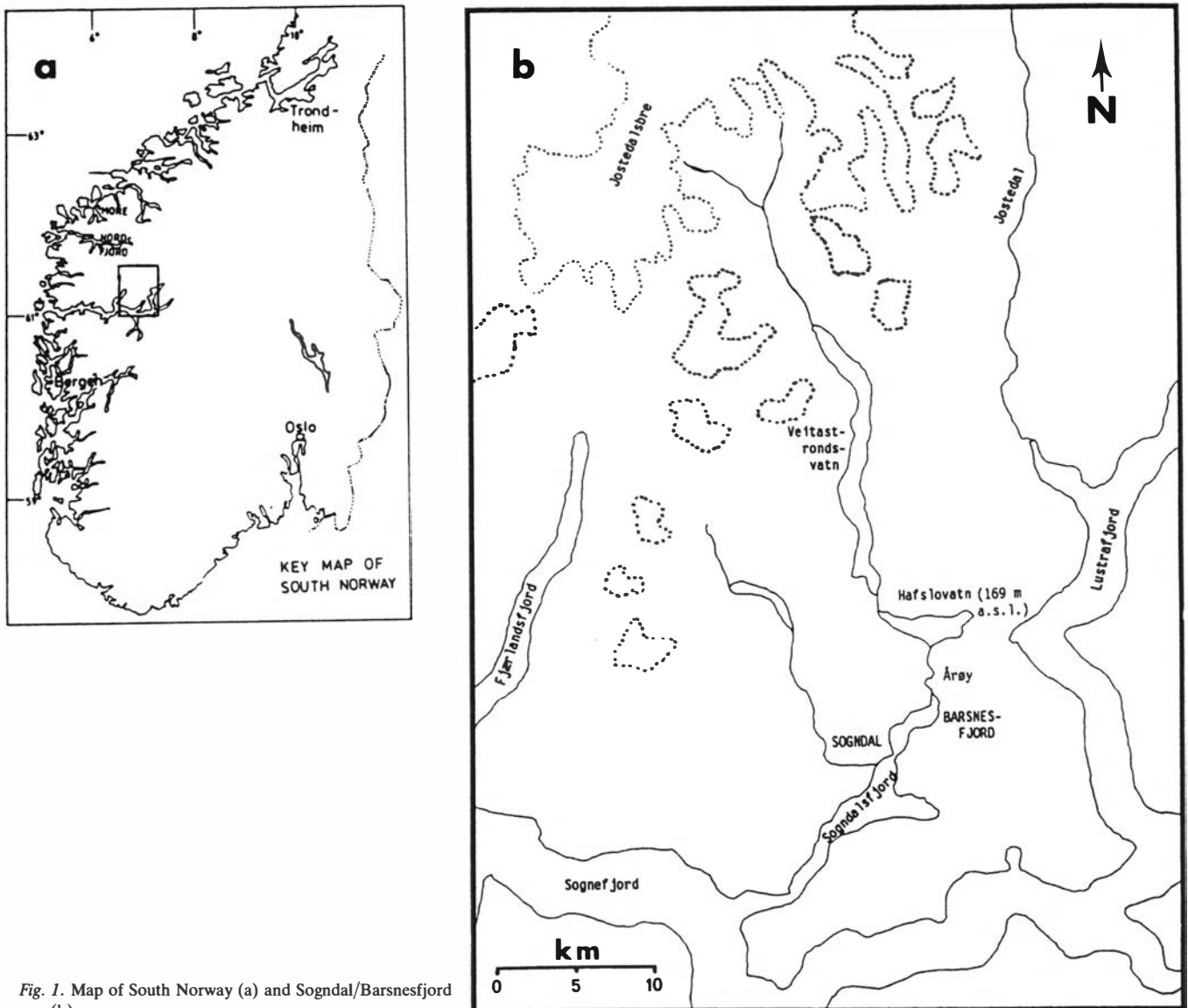


Fig. 1. Map of South Norway (a) and Sogndal/Barsnesfjord area (b).

Methods

Two undisturbed box cores (BC-74-1, BC-74-3) and two gravity cores (GC-74-1, GC-74-3; for location and water depth, see Table 1 and Fig. 2) were retrieved in the summer of 1988. The gravity corer (Oregon State University, College of Oceanography design) consisted of a weighted 2 m long plastic barrel (inert thick-walled drain pipe, 15 cm diameter) with a brass lemon core catcher. A Smøgen box corer with 30 × 30 × 50 cm stainless steel boxes was used to retrieve short <50 cm long cores. Box cores were subsampled by pushing inert plastic tubes

(1.5 cm thick walls, 7.5 cm diameter) into the recovered sediment column. Great care was taken not to contaminate any samples. Since metal concentrations in the upper 50 cm were similar in both the gravity corer with a brass core catcher and in the open vented box corer, it is assumed that no metal contamination by the brass core catcher occurred.

Subsamples of either 10 or 20 cm³ volume were taken from the box cores by pushing one-way syringes with cut-off heads into the cleaned sediment column immediately after core recovery. These samples were extruded into clean plastic bags and stored under refrigerated conditions. After return from the cruise these samples were analysed immediately for wet bulk density and water content (Table 2).

Box core subcores and gravity cores were stored vertically under refrigerated conditions until they were either horizontally subsampled or longitudinally split into an archive and working half.

Table 1. Position, water depth and coring instruments used during cruise 74 in Barsnesfjord. BC = box core and GC = gravity core.

Station	Latitude	Longitude	Water depth	Instrument
74-1	61°14'17"	07°07'50"	75 m	BC, GC
74-3	61°15'22"	07°08'31"	62 m	BC, GC

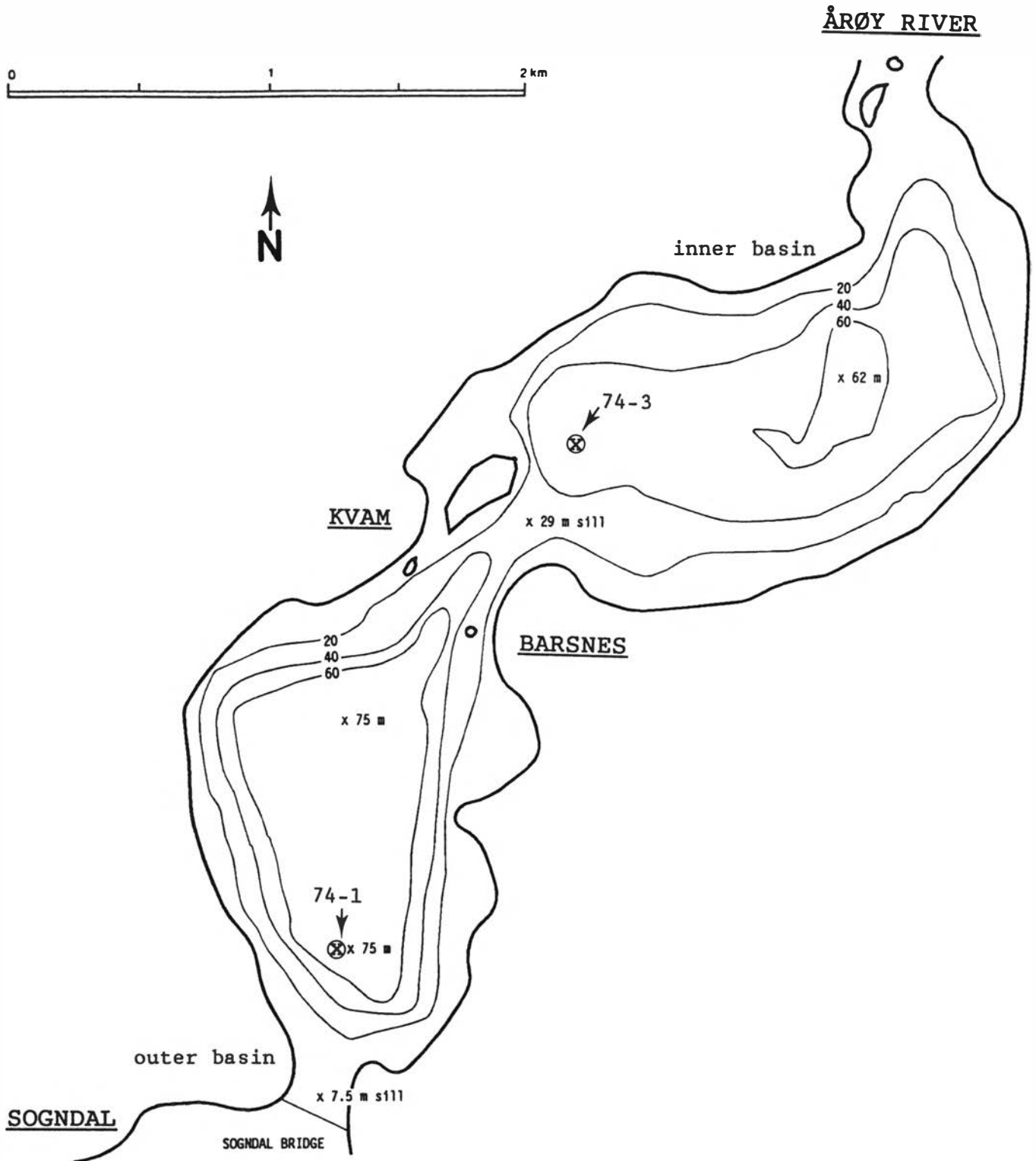


Fig. 2. Bathymetric map of Barsnesfjord. Equidistance is 20 m. Stations 71-1 and 74-3 are marked by arrows.

A CANBERRA-Omega 1 Multichannel Analyzer model 4100 and a PHILIPS-Counter PW 4123/00 were used for β -activity counts of millimetre sliced subsamples. These subsamples were taken continuously every 4 mm downcore and placed in clean, weighted one-way plastic petri dishes, which are neutral to radioactivity. They were oven dried (at 60°C) and their dry weight was determined.

The background level of the β -activity counting detector was determined by measuring the activities of empty clean petri dishes. Counts of ^{137}Cs were measured in cpm/g (counts per minute per gram, Table 3).

The organic carbon fraction of the subsampled sediment was burned off at 900°C for XRF analysis. The organic carbon-free samples were then pressed into 2-

Table 2. Physical properties of cores: d(w) = wet bulk density; W = water content; m(w) = mass wet sample; m(d) = mass dry sample; m(W) = water mass; V(w) = volume of wet sample; org C = organic carbon

Core no.	Depth cm	d(w) g/ccm	W %	m(w) g	m(d) g	m(W) g	V(w) ccm	org C %
BC-74-1	0.0	1.027	78.0	19.3	4.3	15.1	18.8	2.29
	6.5	1.121	76.6	22.4	5.3	17.2	20.0	3.12
	11.5	1.151	71.3	23.0	6.6	16.4	20.0	2.76
	16.5	1.173	71.1	23.5	6.8	16.7	20.0	2.96
	21.5	1.272	60.4	25.4	10.1	15.4	20.0	2.35
	26.5	1.272	68.6	25.4	8.0	17.4	20.0	2.18
	31.5	1.218	66.1	24.4	8.3	16.1	20.0	2.24
GC-74-1	200.0	1.251	59.6	12.5	5.1	7.3	10.0	1.87
BC-74-3	5.5	1.060	84.4	21.2	3.3	17.9	20.0	3.45
	10.5	1.121	77.1	22.4	5.1	17.3	20.0	2.69
	15.5	1.102	79.5	22.0	4.5	17.5	20.0	2.93
	20.5	1.097	78.2	21.9	4.8	17.2	20.0	2.39
	25.5	1.120	77.0	22.4	5.2	17.2	20.0	2.64
	30.5	1.129	75.5	22.6	5.5	17.0	20.0	2.27
	35.5	1.184	69.3	23.7	7.3	16.4	20.0	2.02
	40.5	1.213	68.1	24.3	7.7	16.5	20.0	1.71
GC-74-3	200.0	1.069	60.9	10.7	4.2	6.5	10.0	2.17

3 mm thick tablets, dried and analysed for heavy metal concentrations (BC/GC-74-1, Table 4) on a PHILIPS X-ray generator (PW 1730/10). Govindaraju's (1984) recommended certified US standards (G-2-granite, Nim-G-granite, AGV-andesite, GSP-granodiorite, BCR-basalt, Nim-N-norite, W-2-diabas and BHVO-1-basalt) were used as XRF reference material for marine sediments. Heavy metal concentrations and accumulation rates (Tables 4, 5 and 6) are presented in both bulk sediment and organic carbon-free sediment.

Concentrated HNO₃ was added to the sediment samples (5 g sample and 20 ml acid) used for ICP analysis (GC/BC-74-3, Table 4). Undissolved residues were removed by filtering. The remaining concentrate was diluted to 50 ml with double distilled H₂O. A 20 ml subsample was taken from this solution and diluted to 100 ml with double distilled H₂O. ICP analysis was done at the laboratories of Norsk Hydro, Department of Petrology, Bergen/Norway. The ICP analysis was obtained in order to verify concentrations of selected metals from the XRF analysis.

Organic carbon content (Table 4) was determined on a LECO Carbon Determinator E-C 12.

Accumulation rates (Table 5) were calculated by using averaged individual values over the interval 0–32 cm of box core BC-74-1 and over the interval 0–10 cm of box core BC-74-3. These sediments were deposited later than AD 1940 and represent heavy metal sedimentation in industrial times.

Gravity cores GC-74-1 and GC-74-3 were sampled at the 200 cm level to determine pre-industrial accumulation rates (Table 5). These sediments were deposited around AD 1700 and represent natural heavy metal sedimentation.

The following formulas were used for wet bulk density

(ρ_{wet} in g/cm³) and water content (W in %):

$$(I) \rho_{\text{wet}} = m_{\text{wet sample}} / V_{\text{wet sample}}$$

$$(II) W = (m_{\text{water}} / m_{\text{wet sample}}) \times 100$$

where: m = weight (g); m_{water} = m_{wet sample} - m_{dry sample}; V = volume (cm³).

The formula of Dymond & Veeh (1975) was used for calculating accumulation rates:

$$(III) AR = CP \times SR \times \rho_{\text{wet}}(100-W)/100 \times 10^4$$

where: AR = accumulation rate of component (g/m²/year); CP = component concentration (%); SR = sedimentation rate (cm/year); ρ_{wet} = wet bulk density of the sediment (g/cm³); W = water content (%).

The β -activity measurement of ¹³⁷Cs (in cpm/g = counts per minute per gram) followed the procedure described by Augustson et al. (1978):

$$(IV) (C_1-B_1)/(C_2/B_2)/t/m = {}^{137}\text{Cs (cpm/g)}$$

Table 3. ¹³⁷Cs counts and dry weights of ¹³⁷Cs subsamples in box core BC-74-3; cpm/g are averaged counts per minute per gram (n = 3, or more for measurements near the background level); depth scale indicates upper boundary of subsequent 4 mm sediment slices. Numbered capital letters refer to sediment horizons described in Fig. 3 and text.

Depth (cm)	Dry weight (g)	Counts (cpm/g)	Depth (cm)	Dry weight (g)	Counts (cpm/g)
0.0	3.21	16.08 $\bar{A}1$	16.0	4.52	0.35
0.4	4.41	7.25	16.4	4.55	0.45
0.8	5.06	3.52	16.8	4.84	0.39
1.2	5.97	1.76	17.2	4.76	0.42
1.6	7.58	0.79 $\bar{C}1$	17.6	4.89	0.47
2.0	7.48	0.86	18.0	5.17	0.33
2.4	5.90	1.13 $\bar{B}1$	18.4	5.31	0.41
2.8	4.16	1.50	18.8	5.48	0.34
3.2	3.47	1.22	19.2	5.41	0.67 $\bar{A}2$
3.6	3.21	1.36	19.6	5.35	0.65
4.0	3.38	1.21	20.0	5.31	0.46 $\bar{D}2$
4.4	3.45	1.59	20.4	5.43	0.50
4.8	3.46	1.35	20.8	5.52	0.46
5.2	3.76	1.46	21.2	5.44	0.43
5.6	4.02	1.40	21.6	5.39	0.40
6.0	3.96	1.34	22.0	4.64	0.59 $\bar{A}3$
6.4	4.41	0.81 $\bar{B}2$	22.4	5.46	0.34 $\bar{D}3$
6.8	4.47	0.65	22.8	5.36	0.39
7.2	4.58	0.94	23.2	5.48	0.29
7.6	4.57	0.87	23.6	5.32	0.36
8.0	4.77	0.71	24.0	5.39	0.27
8.4	4.60	0.87	24.4	5.50	0.50
8.8	5.93	0.69	24.8	5.34	0.52
9.2	6.12	0.42 $\bar{C}2$	25.2	5.59	0.51
9.6	6.08	0.24	25.6	5.91	0.34
10.0	5.04	0.38	26.0	5.84	0.41
10.4	5.03	0.36	26.4	6.14	0.38
10.8	4.92	0.36	26.8	6.32	0.47
11.2	4.59	0.75 $\bar{B}3$	27.2	5.62	0.33
11.6	4.60	0.78	27.6	5.76	0.39
12.0	4.60	0.52	28.0	5.90	0.46
12.4	4.47	0.70	28.4	5.91	0.32
12.8	4.50	0.71	28.8	5.96	0.38
13.2	4.50	0.82	29.2	6.26	0.23
13.6	4.77	0.57	29.6	6.51	0.52
14.0	4.59	0.78	30.0	6.70	0.26
14.4	4.63	0.43 $\bar{D}1$	30.4	6.94	0.45
14.8	4.58	0.38	30.8	7.18	0.39
15.2	4.65	0.44	31.2	6.59	0.37
15.6	5.22	0.38			

Table 4. Zn, Pb, Cu and organic carbon (org C) concentrations of box (BC) and gravity (GC) core samples. Heavy metal values are on an organic carbon-free basis in column A; they are for bulk sediment in column B in BC/GC-74-1. Heavy metal values in BC/GC-74-3 are determined by ICP. The interval 0–0.8 cm in BC-74-1 is influenced by minerogenic slide material and is not included in the averaged heavy metal concentrations of that core.

Core no.	Depth cm	Zn ppm		Pb ppm		Cu ppm		org C %
		A	B	A	B	A	B	
BC-74-1	0.0	107	105	29	28	21	21	2.29
	0.4	74	72	28	27	17	17	2.29
	0.8	86	84	28	27	20	20	2.29
	2.0	97	94	31	30	19	18	3.12
	4.4	96	93	—	—	18	17	3.12
	5.6	95	92	46	45	21	20	3.12
	6.8	96	93	44	43	19	18	3.12
	8.0	117	114	36	35	26	25	2.76
	9.2	98	95	35	34	18	18	2.76
	10.4	91	88	39	38	18	18	2.76
	11.6	92	89	37	36	17	17	2.76
	12.8	94	91	43	42	21	20	2.96
	14.0	87	84	42	41	22	21	2.96
	15.2	80	78	41	40	19	18	2.96
	16.4	78	76	39	38	20	19	2.96
	17.6	117	114	43	42	29	28	2.35
	18.8	111	108	51	50	31	30	2.35
	20.0	105	103	48	47	31	30	2.35
	21.2	106	104	45	44	31	30	2.35
	22.4	109	107	38	37	31	30	2.18
23.6	107	105	44	43	28	27	2.18	
24.8	106	104	43	42	28	27	2.18	
26.0	115	112	38	37	28	27	2.18	
28.4	129	126	36	35	32	31	2.24	
29.6	103	101	37	36	25	24	2.24	
30.8	116	113	35	34	29	28	2.24	
32.0	120	117	31	30	26	25	2.24	
Average:		103	100	40	39	24	24	
GC-74-1	200.0	83	81	52	51	23	23	1.87
BC-74-3	0–10	—	144	—	—	—	30	3.07
GC-74-3	200.0	—	137	—	—	—	27	2.17

where: C_1 = counts of ^{137}Cs area; C_2 = counts of a control area; B_1 = background counts of ^{137}Cs area; B_2 = background counts of the control area; t = counting time in minutes; m = dry weight of sample in g.

Results

Sedimentation rates were calculated by dating the sediment surface of box cores BC-74-1 and BC-74-3 to 1986 (^{137}Cs from Chernobyl) and then measuring the distance to the next ^{137}Cs peak from the 1963 and 1959 nuclear weapon testings. That peak (1963) occurred in box core BC-74-3 at 20 cm depth (Fig. 3). The ^{137}Cs levels of 1986 are quite high and thus easy to recognize (sequence A1, Fig. 3). The 1963 and 1959 events on the other hand were more difficult to locate. Four different sediment characteristics and β -activities were used to identify the 1963 and 1959 ^{137}Cs horizons (Fig. 3).

Horizon (A) is an organic-rich silty clay with either consistently high amounts of ^{137}Cs counts (A1) or constant counts of ^{137}Cs that lie well above the background levels

Table 5. Average sediment concentration and accumulation rates of Zn, Pb and Cu in two box cores of Barsnesfjord in industrial times (ca. AD 1940–1986; $n = 24$ over the interval of 2–32 cm in BC-74-1, and $n = 1$ over the interval of the upper 0–10 cm in BC-74-3), and in two gravity cores in pre-industrial time (ca. AD 1700, $n = 1$). Pb was not analysed in BC/GC-74-3. Values in column A are on an organic carbon-free basis; in column B they are for bulk sediment.

Core no.	Time interval	Zn AR		Pb AR		Cu AR	
		A	B	A	B	A	B
BC-74-1	1986–1940	0.35	0.34	0.13	0.13	0.08	0.08
GC-74-1	ca. 1700	0.40	0.39	0.25	0.25	0.11	0.11
BC-74-3	1986–1940	—	0.28	—	—	—	0.06
GC-74-3	ca. 1700	—	0.33	—	—	—	0.07

(A2 to A3). The low counts within intervals A2 (with ^{137}Cs from 1963) and A3 (with ^{137}Cs from 1959) are due to the age of this interval (the half-life time of ^{137}Cs is 26 years) and substantially lower initial inputs of radio-caesium than the Chernobyl event.

Horizons B1 to B3 mark a sequence of homogeneous mud with successive lower ^{137}Cs content. This ^{137}Cs originates from the Chernobyl accident and may be the result of downcore migration of soluble ^{137}Cs (Buesseler 1987) through the watery sediment section (Table 2).

Horizons C1 to C2 represent intervals with larger grain size (silt) and/or decreased organic matter content. These two horizons are deposits of the 1982 and 1975 slump events (Schrader & Paetzel 1991). Radioactive caesium in the sediment is bound either to organic material (Buesseler 1987; Erlenkeuser & Balzer 1987) or to fine, minerogenic grains (Andersen et al. 1987; Augustson et al. 1978). Thus the relative low counts of ^{137}Cs within C1 and C2 that lie within areas of definitive ^{137}Cs content (B1 to B3) can be explained by lithological sequences (Fig. 3) that do not permit permanent storage of ^{137}Cs .

Horizon (D) represents the background level in the homogeneous muds with no detectable ^{137}Cs content (D1 to D3). Count values vary greatly in this interval. The few relatively high counts below 22 cm (D3) represent repeated averaged measurements (three or more repetitive counts of same sample) with usually low but erratically high activities.

Net sedimentation rates (that is, after subtracting identified slide and slump horizons from the 1959 to 1986 interval, Fig. 3) are 0.78 cm/year.

The ^{137}Cs based sedimentation rates are confirmed by two other dating methods: (1) Sedimentation rates determined over those intervals that contain seasonal laminae, i.e. 0–1 and 2.5–4 cm in BC-74-3 (Fig. 3); (2) sedimentation rates determined using historically documented slide events as fix points (Schrader & Paetzel 1991). Sedimentation rates for both coring stations are approximately 0.75 cm/year.

The sediment surface of two box cores (0–35 cm of BC-74-1 and 0–10 cm of BC-74-3) and two gravity core reference samples (sampled at 2 m core depth) were analysed for zinc, lead and copper. Variations in

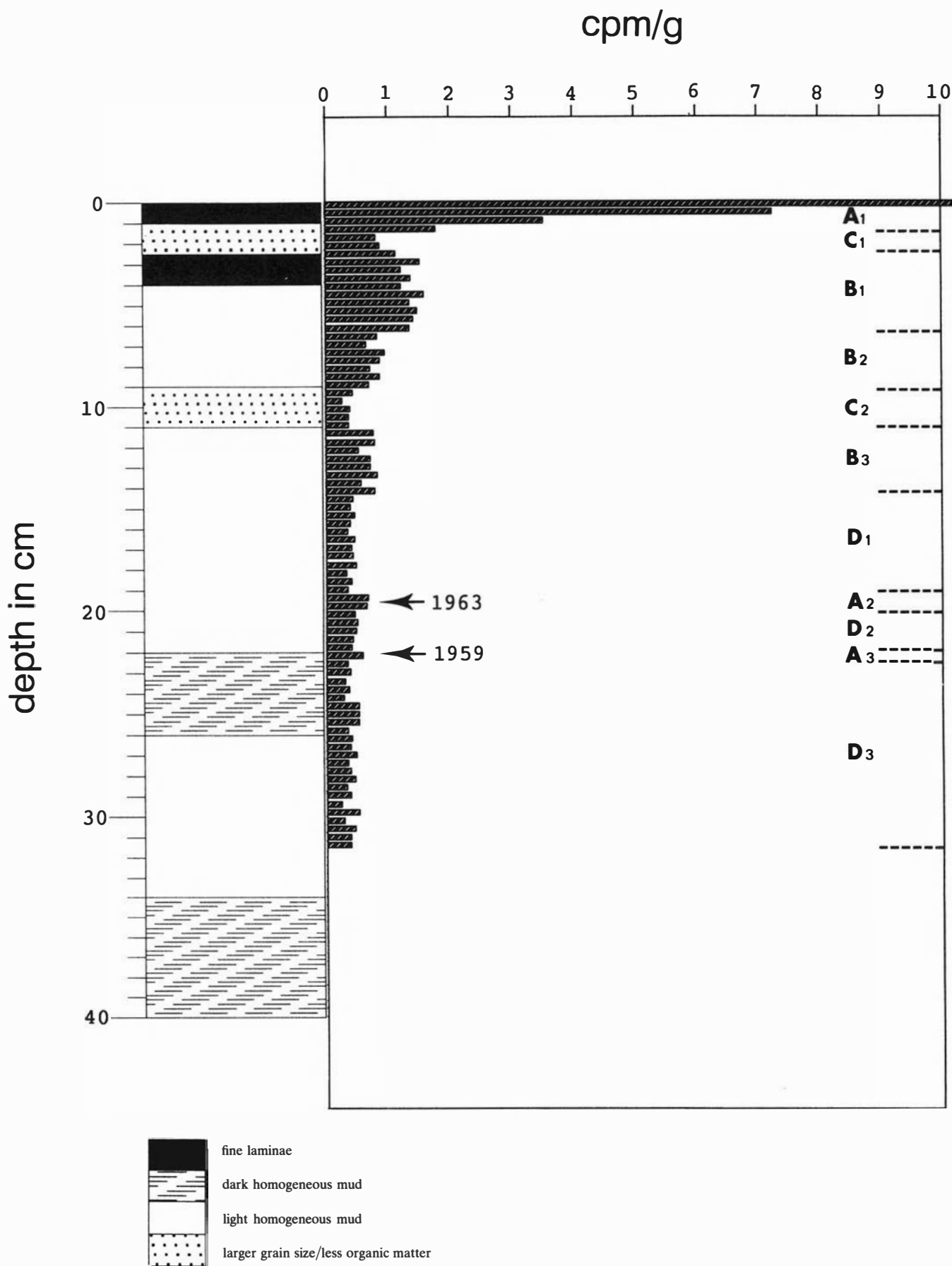


Fig. 3. ¹³⁷Cs counts versus depth and lithology of BC-74-3. Numbered capital letters and numbers (A1 to D3) indicate the different sediment horizons that affect the ¹³⁷Cs distribution in the core as described in the text.

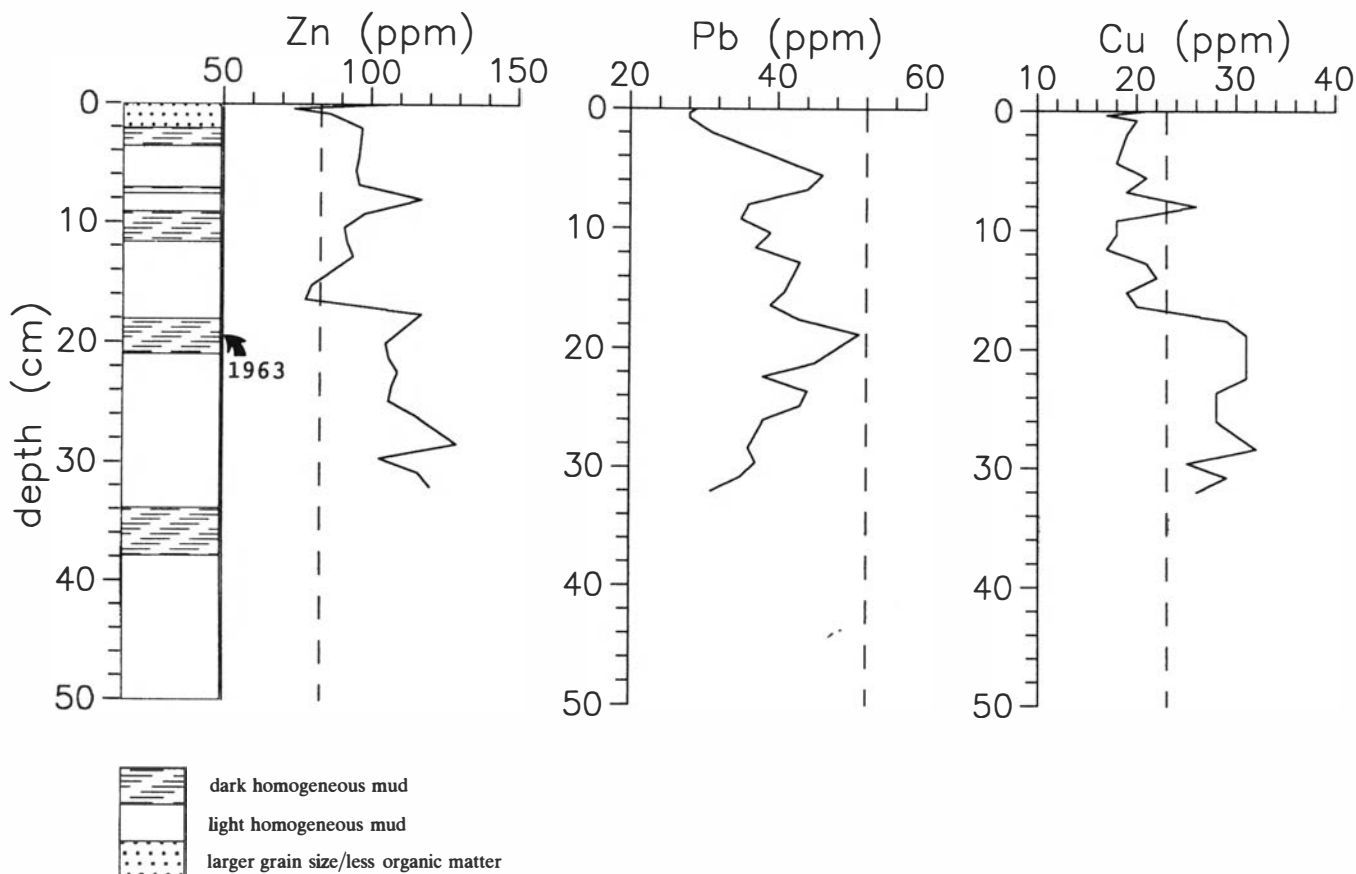


Fig. 4. Concentrations of Zn, Pb and Cu on an organic carbon-free basis of BC-74-1 versus depth and lithology. Stippled lines represent the reference value ($n = 1$) from 200 cm depth of gravity core GC-74-1 (pre-industrial time). ¹³⁷Cs from 1963 is indicated at 19 cm (adopted from BC-74-3).

concentration in BC-74-1 are for Zn 72 to 144, for Pb 27 to 51 and for Cu 17–31 ppm (Table 4). The low concentration over the interval 0–2 cm coincides with a major change in mineralogy (Fig. 4). Concentrations in BC-74-3 do not vary significantly from those in BC-74-1.

Wet bulk densities are 1.027 to 1.272 g/cm³ and water contents vary between 70 and 80% for both cores (Table 2). These values, together with high sedimentation rates, resulted in accumulation rates during industrial times (sediments that were deposited after AD 1940) and during pre-industrial times (sediments that were deposited before AD 1700) as presented in Table 5. The pre-industrial accumulation rates were calculated using just one sample from both gravity cores. Heavy metal accumulation rates (in g/m²/year) are nearly constant over the 200 cm long column and show only a decreasing trend for lead towards the sediment surface at both locations. Concentrations of heavy metals, on the other hand, are more variable: zinc increases, lead decreases and copper remains constant over the 200 cm sediment column.

Discussion

The Barsnesfjord is an active sedimenting fjord environment with high primary production (Hovgaard 1985;

Wassmann 1984). Two shallow sills effectively limit water circulation and exchange of bottom waters, leaving bottom waters frequently starved of dissolved oxygen. A high percentage of organic matter reaches the fjord bottom and because of sluggish bottom water exchanges and partial oxidation of this organic matter, anoxic bottom conditions prevail periodically in the outer, and more permanently in the inner, Barsnesfjord basin. These anoxic bottom water conditions are responsible for the continuous and undisturbed sedimentation of both terrigenous and biogenous particles occasionally interrupted by occurrences of slumps and slide events.

Similar anoxic land-locked fjord environments were first analysed by Strøm (1936 and 1937) and are described from several places in Norway: Maurangerfjord (Pedersen 1974); Lindåspollene (Wassmann 1983); Nordåsvannet (Wassmann 1985); Kviturdvickpollen and Vågsbøpollen (Wassmann & Aadnesen 1984).

Sedimentation rates in Barsnesfjord are high compared with oxic fjord environments and the open ocean, reaching 1 cm/year over the last 150 to 200 years. These rates are typical for young sediments accumulating in such anaerobic bottom environments, varying from 0.3 to 1.2 cm/year in the above-mentioned fjords. Sedimentation rates in oxic fjords, on the other hand, are usually smaller; they range from <0.1 to 0.2 cm/year, i.e. the

Vestfjord (Doff 1969), the Ranafjord (Skei & Paus 1979) and the Fjærlandsfjord (Vangsnes 1981).

The Chernobyl ^{137}Cs from 1986 has been found worldwide in surficial sediments from the deep Black Sea (Buesseler 1987); and surface sediments from the Norwegian Sea continental margin (Erlenkeuser & Balzer 1987) to mention two examples. Even the worldwide 1959 and 1963 peaks of radiocesium derived from Pacific nuclear weapon testings, with one half-life time gone, can still be recognized in high sedimentation rate environments such as Canadian lakes (Andersen et al. 1987), Norwegian lakes (Augustson et al. 1978), British lakes (Pennington et al. 1973), in marine sediments from the Gulf of California (Juillet-Leclerc & Schrader 1987; Juillet-Leclerc et al. unpublished) and the Adriatic Sea (together with Chernobyl cesium; Pušarić et al. 1990).

In order to quantify and to assess magnitudes of pollution by anthropogenic influence it is essential to determine the sedimentary flux and sedimentary accumulation rates of components of interest. Here we have concentrated on only a few indicators of pollution, namely the heavy metals zinc, copper and lead. High concentration and high accumulation rates of heavy metals are 'normally' considered to be indicators of pollution. We found low concentrations of heavy metals in surficial sediments and in sediments that were deposited in pre-industrial times. Barsnesfjord heavy metal concentrations are lower than those found in other Norwegian fjords which have been classified as being polluted. Table 5 presents heavy metal concentrations and accumulation rates for some Norwegian fjords. A comparison reveals that heavy metal concentrations of Barsnesfjord sediments are lower in comparison with other 'polluted' fjords. Within this group Sørfjord, Ranafjord and Vestfjord represent well-ventilated fjords with oxygenated bottom conditions. Oslofjord (only those regions

analysed by Doff 1969), Singlefjord, Ørstadfjord, Bunnefjord and Mofjord are characterized by sluggish exchange of bottom waters and by seasonal or permanent anoxic bottom conditions.

The zinc, copper and lead concentrations of the bulk Barsnesfjord sediments (Table 6) lie below those values that are reported from so-called unpolluted Norwegian fjord sediments. This classification was suggested by Sæther & Larsen (1989). No data of the oxygen concentration of bottom waters are available from these fjords, though.

Converting the metal concentrations of the Barsnesfjord sediments into accumulation rates, unexpectedly high accumulation rates of these metals arise over the 2 m sediment column representing sedimentation of the last 200 years (Table 6). Accumulation rates of Zn, Cu and Pb exceed values that are reported from other fjords. Due to the general lack of reliable sedimentation rates and physical properties from other Norwegian fjords that are unpolluted, no direct comparison with these can be made. These Barsnesfjord values, taken without further interpretation, appear to indicate that this environment is strongly under the influence of heavy metal pollution, but just the opposite is true.

Comparison of present heavy metal accumulation rates in Barsnesfjord (Table 5) with those of pre-industrial times shows that the post-industrial rates are equal to or lower than the pre-industrial rates. These similar rates are a strong indication for the insignificance of human, including industrial, activity on the distribution of copper, zinc and lead in the Barsnesfjord area. Therefore, the high accumulation rates are solely due to natural processes leaching the metals from local source rocks and transporting them into the Barsnesfjord. Henriksen (pers. comm. 1990) found horizons of galena (PbS) and

Table 6. Bulk Zn, Pb and Cu sediment concentrations (in ppm) and their bulk sediment accumulation rates (in $\text{g}/\text{m}^2/\text{year}$) in Barsnesfjord compared to other 'polluted and unpolluted' Norwegian fjords. Barsnesfjord values are for bulk sediment, including organic matter, averaged over the two box cores (AD 1940–1986) and the two gravity cores (<AD 1700). Reference numbers are: (1) Doff (1969), (2) Skei (1981), Skei et al. (1972), (3) Bergan (1983), (4) Skei & Paus (1979), (5) Egeberg (1983), (6) Skei et al. (1972), (7) and (8) Sæther and Larsen (1989).

Region	Concentration bulk			Accumulation rates bulk		
	Zn	Pb	Cu	Zn	Pb	Cu
<i>Polluted</i>						
(1) Oslofjord	346	104	66			
(2) Sørfjord	>1000	>1000	>1000			
(3) Singlefjord	540	—	190			
(4) Ranafjord	234	83	45	0.27	0.09	0.05
(5) Bunnefjord	663	195	205	0.20	0.06	0.07
Vestfjord	336	110	59	0.10	0.03	0.02
<i>Unpolluted</i>						
(6) Mofjord	130	56	25			
(7) Ørstadfjord	112	33	52			
(8) Norwegian fjords (mean)	<150	<40	<50			
<i>This study</i>						
1940–1986	122	39	27	0.31	0.13	0.07
ca. 1700	109	51	25	0.36	0.25	0.09

chalcopyrite (CuFeS₂) in a coarse-grained monzonite around the river Årøy. Zinc usually occurs together with lead in these rocks.

Conclusion

The Barsnesfjord is a highly productive fjord with a sluggish bottom water exchange and therefore has seasonal or permanent anoxic bottom water conditions. 'Recent' sedimentation rates are in the order of 1 cm/year.

Recent sediments have been dated by different methods. These are ¹³⁷Cs peaks from both the Chernobyl accident and from the 1963 and 1959 nuclear weapon testings in the Pacific, the occurrence of well-documented sedimentary records of slide and slump events and the occasional occurrence of seasonally deposited sediment layers. Heavy metal surficial sediment concentrations have been converted into accumulation rates using direct physical property measurements of undisturbed cores, combined with the absolute dating of sediment horizons.

High Zn, Cu and Pb accumulation rates in Barsnesfjord are not caused by industrial pollution, by city waste water disposal, or by increased land-use, since the values are equally high for pre- and post-industrial times. Thus the high accumulation rates of heavy metals originate from natural sources. These sources of Pb, Zn and Cu in Barsnesfjord are rocks from areas surrounding the river Årøy.

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