Recent sedimentation rates across the Norwegian Trough

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From the systematic sampling of 20 stations of the Norwegian part of the Skagerrak in 1993, six cores were chosen for determination of recent sedimentation rates by the lead-210 method and verifications by Cs-137 depth distributions. By using the gamma-spectrometric variant of the method, both natural and anthropogenic radioisotopes are simultaneously measured in the samples.

The highest average linear sedimentation rate (4.7 mm/year) was found for a core (NC-84) from station 67, on the southern lowermost slope of the Norwegian Trough; a relatively high average sedimentation rate (2.3 mm/year) was also deduced from the measured data for the core (NC-13) from station 56, taken in its central (deepest) part. The cores from the northwestern part of the trough, from stations 69 (NC-97) and 74 (NC-134), showed rates that were close to or somewhat higher than 1 mm/year, while cores from stations 65B (NC-71) and 71 (NC-113) showed significantly disturbed depth profiles.

Using unsupported lead-210 intensities and the physical data on the cores (water content, dry weight and bulk density of the core slices) it was possible to reconstruct the sedimentation history of the cores. When the modelling (constant rate of supply) is applied to the Cs data, it is obvious that Cs-137 distributions with depth can most likely be explained by three superimposed anthropogenic events: Chernobyl accident, Sellafield release and nuclear bomb testing, with the Sellafield release being the most dominating feature observed in the investigated cores.

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Introduction

The systematic investigations in the Norwegian part of the Skagerrak and the transitional area to the North Sea by the Geological Survey of Norway and the University of Bergen also aim at the evaluation of sediment geochemical features which hitherto have not been published in the form of geochemical maps. Relying on the distribution of chemical elements along a sediment core requires, however, that the core has been checked for discontinuities in sediment deposition, i.e. for bioturbation or physical mixing by currents, slides or human activity. If this had not been done, most of the geochemical data would be more or less worthless for the following reasons.

Supposing that the along-core chemical data suggest an accumulation or/and depletion of elements in the upper few cm of the core, the question then arises whether this is by normal diagenetic changes, caused by pollution or by redox mobilisation, respectively. The observed chemical pattern, however, could also be caused by a disturbance in sediment deposition at some point in time. These processes have been studied in great detail over the past years and the results of such studies have been discussed in numerous publications. In any case, a procedure to determine sudden or long-lasting changes in the sediment deposition pattern is needed and, furthermore, chemical depth profiles in recent sediments need to have a time scale to evalute whether anthropogenic input is increasing from a certain period of time or whether there is a significant pollution decrease caused by public law initiatives, as exemplified by the chemical data. In other words, the chemical studies of sediments strongly need some sort of dating tool.

Many of the pre-1990 sediment core geochemical data were published without application of any dating tool, largely because of the timely and expensive dating methods available in the past. Most of them were checked for disturbances by experienced sedimentologists but since many disturbed sediment cores show no macro- or microscopic features which provide information on these disturbances, a convincing depositional check of the sediment cores is lacking.

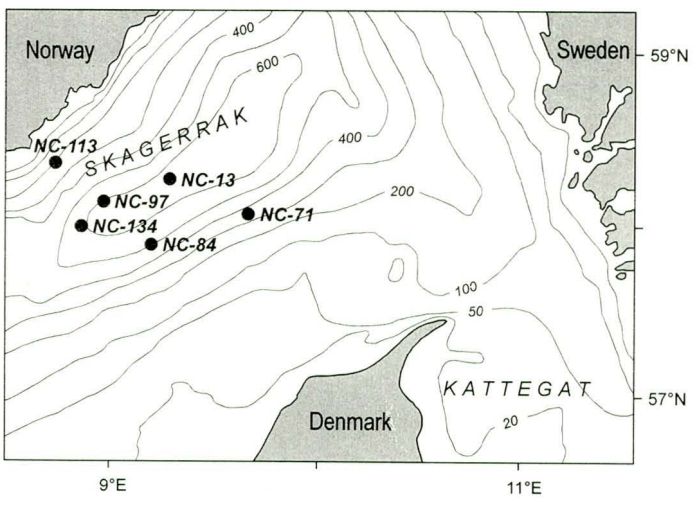

Fig. 1. Investigated area in the Norwegian part of the Skagerrak showing positions of sediment cores used for lead-210 dating.

The only available radiometric dating method for recent sediments is based on lead-210, which has a half-life of 22.3 years. This radioisotope has been applied indirectly for dating purposes over the past few decades through its daughter isotope Po-210. Because the physical method for the determination of this radioisotope is by alpha-spectrometry, total dissolution of samples has to be carried out (e.g., Robbins & Edgington 1975, Robbins 1978, Madsen & Sørensen 1979, Christensen 1982). Since the mid-eighties a more direct technique for lead-210 dating has been developed, where the lead radioisotope is determined directly in an untreated sediment sample by gamma-ray spectrometry (e.g., Joshi et al. 1988), and application of the technique to Kattegat sediments has also been reported (Christiansen et al. 1993).

In the present paper we report on the dating of six Skagerrak cores by the new technique. We concentrate on the data interpretation of the samples and use simultaneously generated Cs-137 data to verify the dating. Average linear sedimentation rates and mass accumulation rates have been estimated. For the cores that were dated, the contents and changes in some chemical elements with depth are also briefly discussed.

Geological setting

The Skagerrak area is at present one of the focal areas when studying anthropogenic chemical fluxes on the sea floor. The hydrographical setting of the area has been discussed by, e.g., Svansson (1975), Rohde (1987) and Hognestad (1987).

The sediment cores were taken during a cruise in 1993 by R/V 'Håkon Mosby' as part of a systematic investigation of marine sediments in the Norwegian Skagerrak area. This project includes both systematic geophysical and geological work. Starting at the easternmost part of the Norwegian Skagerrak, the project is presently continuing along the southwestern coastal area of Norway. The positions of the dated cores are given in Table 1 and plotted in Fig. 1.

All of the cores were taken by Niemistö coring equipment, recovering up to 0.6 m long cores of diameter 56 mm directly in an PVC cylinder. Parallel cores were taken at all stations except for station 65B. From each station, one core was usually X-rayed and a sedimentological description of the core was carried out.

Table 1. Coring stations and sediment core characteristics.

Core No	Station	Position	Water depth (m)
NC-13	56	58.1548° N 9.2896 ° E	252
NC-71	65B	58.0556° N 9.6673 ° E	340
NC-84	67	57.9695 ° N 9.1888 ° E	483
NC-97	69	58.0861 ° N 8.9498 ° E	640
NC-113	71	58.2016 ° N 8.7063 ° E	307
NC-134	74	58.023 ° N 8.8335° E	594

In the deeper parts of the Skagerrak, the sediments are generally very fine-grained with a clay content exceeding 50% (Bøe et al. this volume). Above 300 m water depth on the Danish slope, sandy sediments prevail and along the Norwegian coast they vary from clays to tills. All the cores show significant, but generally very moderate bioturbation.

Core NC-113 (station 71), close to the Norwegian coast, had a clay content of 50-60% throughout the core. The upper 15 cm seemed to be severely disturbed (Bøe 1994). Cores NC-13, NC-97 and NC-134 (stations, 56, 69 and 74, respectively) are from the more central parts of the Skagerrak Deep (Fig. 1), where the thickness of Holocene sediments varies between 10 and 20 m (Rise et al. this volume). The upper 5 to 10 cm (2.5 Y3/2) are usually very soft, and the cores are moderately bioturbated. Core NC-97 is more fine-grained than the other two cores from the deep parts and is characterised by clay contents of more than 70% throughout the core. Core NC-84 (station 67 is from the lower part of the Danish slope, where the Holocene sediments are between 40 and 50 m thick (Rise et al. this volume). The sand content is nearly zero and the silt content increases to 60% at a depth of 30 cm, which indicates a change in the sedimentary environment.

Methods

The sediment cores were cut into slices of 5 to 10 mm thickness (the thinner slices were used for near-surface sediments). Wet sediments were weighed and dried, and the dry weight was then determined. Through this procedure, both the water content of the sediment disk and its bulk density (Rhobulk =dry weight/wet volume) could be calculated.

Dried sediment material (10 to 30 g) was then filled into aluminium containers with thin plastic foil bottoms and tops. The containers were sealed by tape and then stored for at least 14 days to restore secular equilibrium which may be disturbed due to radon escape. However, this routine operation is regarded as of minor importance because the marine sediments in general already suffer from chemical separations in sea water which usually leads to significant radioactive disequilibrium.

The sample container area of 72 mm diameter is relatively large, 4072 mm^2, which reduces physical radiation interferences caused by varying particle grain sizes. As a rule, more or less the same amount of sample material of slices from a core were used for counting. In this way, possible self-absorption effects in the sample are reduced considerably. This is not always necessary, however, because experience has shown that there is a limited density variation of sedimented material over the relatively short time spans involved (several hundreds of

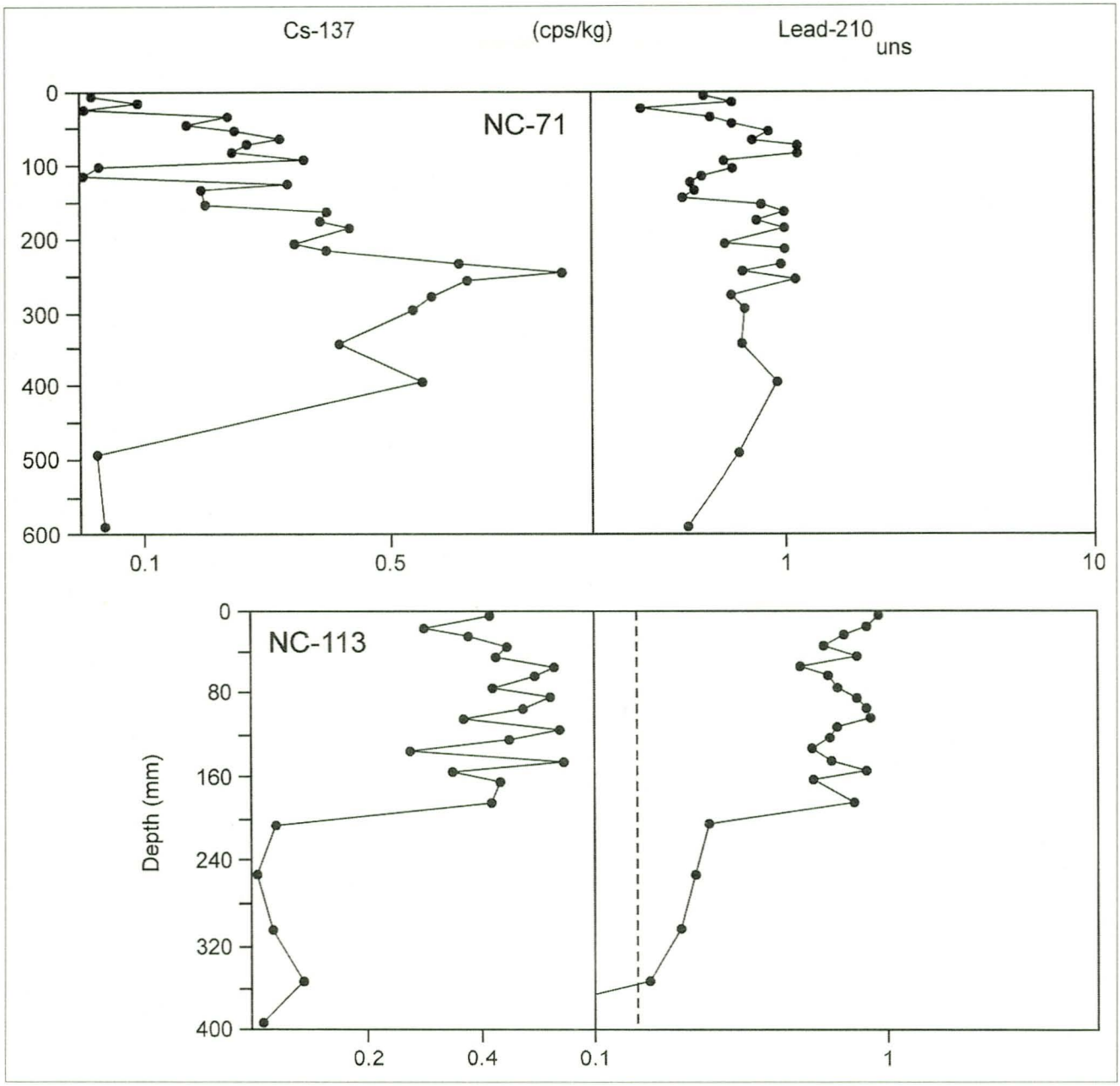

Fig. 2. Depth profiles of Cs-137 and unsupported lead-210 of cores NC-71 and NC-113. The stippled line in the figure indicates the level for an inferred background. Both cores were excluded from the dating because of possible sediment deposition disturbances.

years).

For gamma-spectrometric purposes, the containers were then measured in a low-level radiation counting facility. A reverse-electrode coaxial Ge detector (10% rel. efficiency) with energy resolution values of 640 eV and 1.7 KeV at 5.9 KeV and 1332 KeV, respectively, was used. The gamma-ray spectra from the samples were collected by means of a normal nuclear counting apparatus (standard counting electronics and multichannel analyser).

To reduce the background radiation, the counting system was shielded by at least 100 mm Pb around the detector head. Because the present Risø counting facility is positioned in a normal laboratory building, background counts could not be reduced to values lower than about 5.8 counts per second (for the range 0 to 680 keV). In general, background variations with time, obtained from repeated measurements were usually below the 10 per cent level. However, it should be mentioned that the actual background level for a sample consisting of 0-20 g sample material of varying physical and chemical composition is difficult to determine. This is because background depends on the composition of the sample matrix material; hence, the background obtained from an empty sample container is usually too high because of the lack of an absorbing sample layer of the same height as the actual sample.

Table 2. Estimated sedimentation (R) and sediment accumulation (w) rates for the Skagerrak cores.

Core No	Depth range (mm)	R (mm year -1)	Mass depth range (g cm-2)	W (g m-2 year-1)
NC-13	15-155	2.3±0.4	0.5-3	449±81
NC-71	-	-	-	-
NC-84	25-95	4.7±1.8	1-5	843±198
NC-97	5-95	1.1±0.1	0.2-2.5	278±34
NC-113	-	-	-	-
NC-134	5-95	1.5±0.1	0.2-2.5	365±37

All the lead-210 intensities (cps/kg dry weight) were calculated directly from the counting rate of the 46.5 keV peak. Cs-137 was determined from its 661.6 keV peak. A number of other natural decay series and anthropogenic radioisotope intensities were also determined, partly to check the equilibrium status of the sediment disks or to discriminate against pollution of the sediments. Counting times were usually in excess of 80000 s. At such counting intervals, counting errors for lead-210 were usually below 10% but were greater (10 to 20%) for sediments taken at depth.

The intensity of unsupported lead-210 was calculated by first subtracting a constant background (data from an empty sample container used) and then the equivalent supported Pb-210 intensity. Using an empty sample container for background subtraction is not the correct way to obtain net intensities because it is the non-radioactive matrix that determines the amount of background radiation reaching the detector. However, as a first approximation, this calculation strategy is sufficient. The supported lead-210 intensity is generally assumed to be proportional to that of Ra-226 or Bi-214 or any other radioisotope observed in the decay series. The gamma-spectrometric method allows the direct determination of Ra-226 by its 185 keV, although some interference from U-235 may occur. An experimentally determined fraction of these radioisotopes from a rock sample in certificated radioactive equilibrium was subtracted from the total lead-210 activity, and the remaining activity is named the unsupported lead-210. By doing this, the gamma-spectrometric method must be regarded superior to the conventional alpha-spectrometric technique because it also gives values for the supported lead-210 directly from the measurement of some other radioisotopes, e.g, Ra-226 or Bi-214.

A possible problem with self-absorption, due to the low-energy radiation of lead-210, can be handled by using similar sample size and filling grade for all of the sample containers, i.e. keeping these parameters constant within ±5%. An internal density-check procedure, however, is presently being described (Kunzendorf, 1996) which involves the use, for correction purposes, of other, simultaneously determined gamma-radiation also present in the sediments.

Results and discussion

Lead-210 dating

Unsupported lead-210 and Cs-137 data are plotted vs. depth in Figures 2 and 3. The dating results are given in Table 2. From Fig. 2 it can be seen that cores NC-71 (station 65B) and NC-113 (station 71) are difficult to use for age calculations. While the latter core is clearly disturbed down to 200 mm depth, there is some trend in the Cs-137 data of core NC-71, which both show a peak at depth (ca. 250 mm) and generally high intensities. If one argues that the elevated Cs-137 is due to Sellafield releases peaking in the mid-seventies, a relatively high sedimentation rate, close to 10 mm/year, would apply. If this were the case, sediment data in excess of 600 mm depth are needed to determine the rate by lead-210 data. The core history evaluations were therefore not carried out for these cores.

All the other cores show very clear depth profiles for both radioisotopes (Fig. 3). The curves for unsupported lead-210 (Fig. 3) suggest that there is some variation in sedimentation rate in the Norwegian Trough. When using the constant initial concentration model (CIC) (e.g., Robbins 1978), average sedimentation rates for cores NC-13, NC-84, NC-97 and NC-134 (stations 56, 67, 69 and 74, respectively) are 2.3, 4.7, 1.1 and 1.5 mm/year, respectively (Table 2). A variation of sedimentation rates is expected because the thickness of the Holocene deposits is quite variable in this area (Rise et al. this volume). Some of the above rates, especially those from the central parts of the trough, e.g. cores NC-13 and NC-134, are in good agreement with the findings of van Weering et al. (1987, core 11 and 24, respectively). These authors also reported a number of varying rates in the Skagerrak area (van Weering et al. 1993). A major feature of their lead-210 depth profiles was that sediment mixing in the upper few tens of cm was deduced, because constant unsupported lead values were observed in the uppermost sediment layers. An important finding was that their data also suggested that sedimentation rates in the Skagerrak increase eastwards. However, to depict the sedimentation pattern in the Skagerrak area it is clear that much more closely spaced undisturbed sediment data are needed to evaluate the pertinent hydrographic regime in space and time.

Incorporating the bulk sediment density data along the cores (r_{bulk} = dry weight/wet volume), average sediment accumulation rates can also be calculated from the constant initial concentration model. These data for cores NC-13, NC-84, NC-97 and NC-134 were estimated to be 449, 843, 278 and 365 g m^{-2} $year^{-1}$, respectively. Again, these values are varying considerably and they require an explanation of the basic sediment transport system in the Skagerrak and the adjacent water masses (North Sea, Kattegat). However, the accumulation rate of especially core NC-13 agrees with that presented by Paetzel et al. (1994, core A).

By using the constant rate of supply model (CRS) for

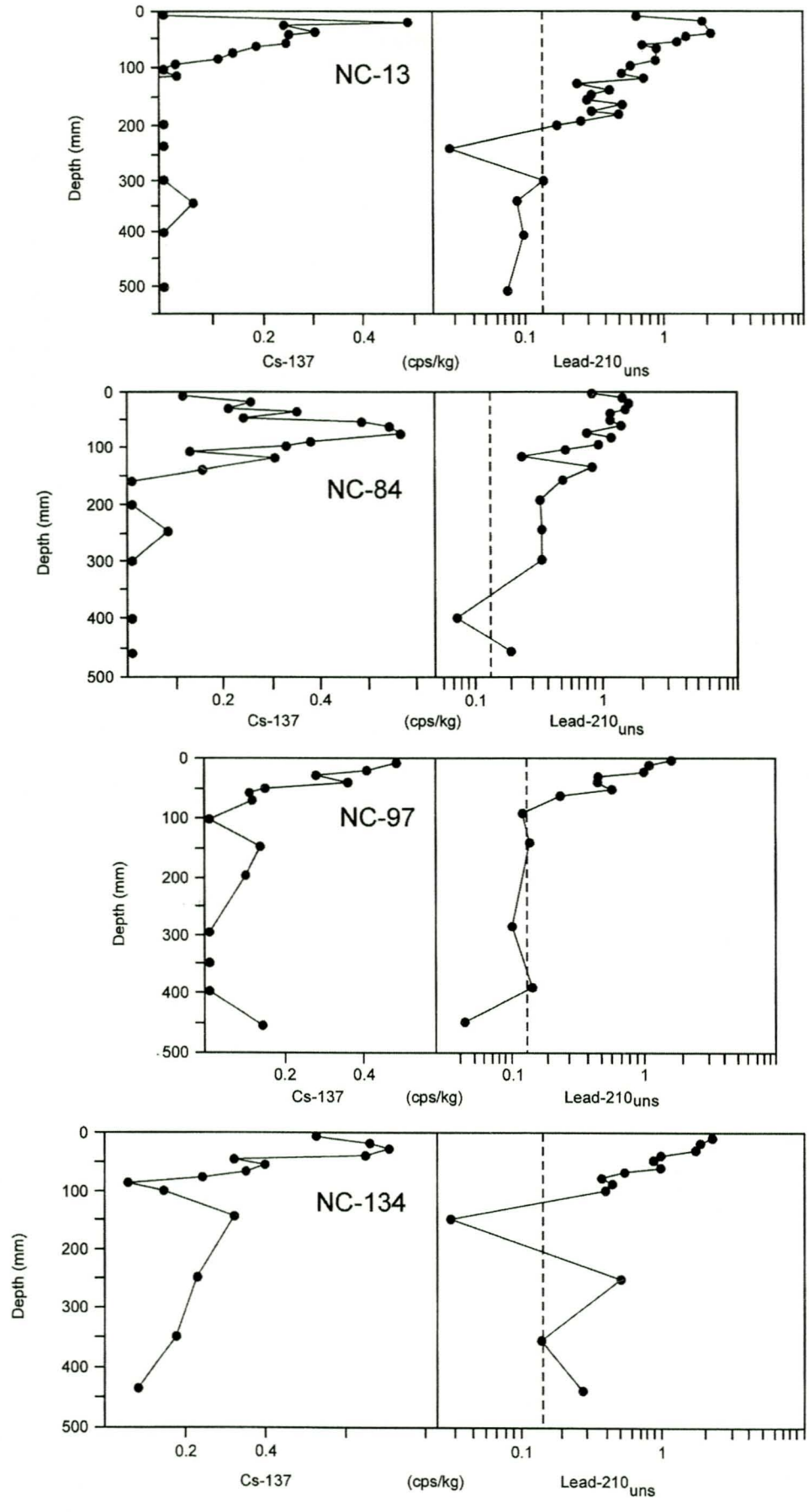

Fig. 3. Depth profiles of Cs-137 and unsupported lead-210 of cores NC-13, NC-84, NC-97 and NC-134 showing clear activity decreases with depth for lead-210.

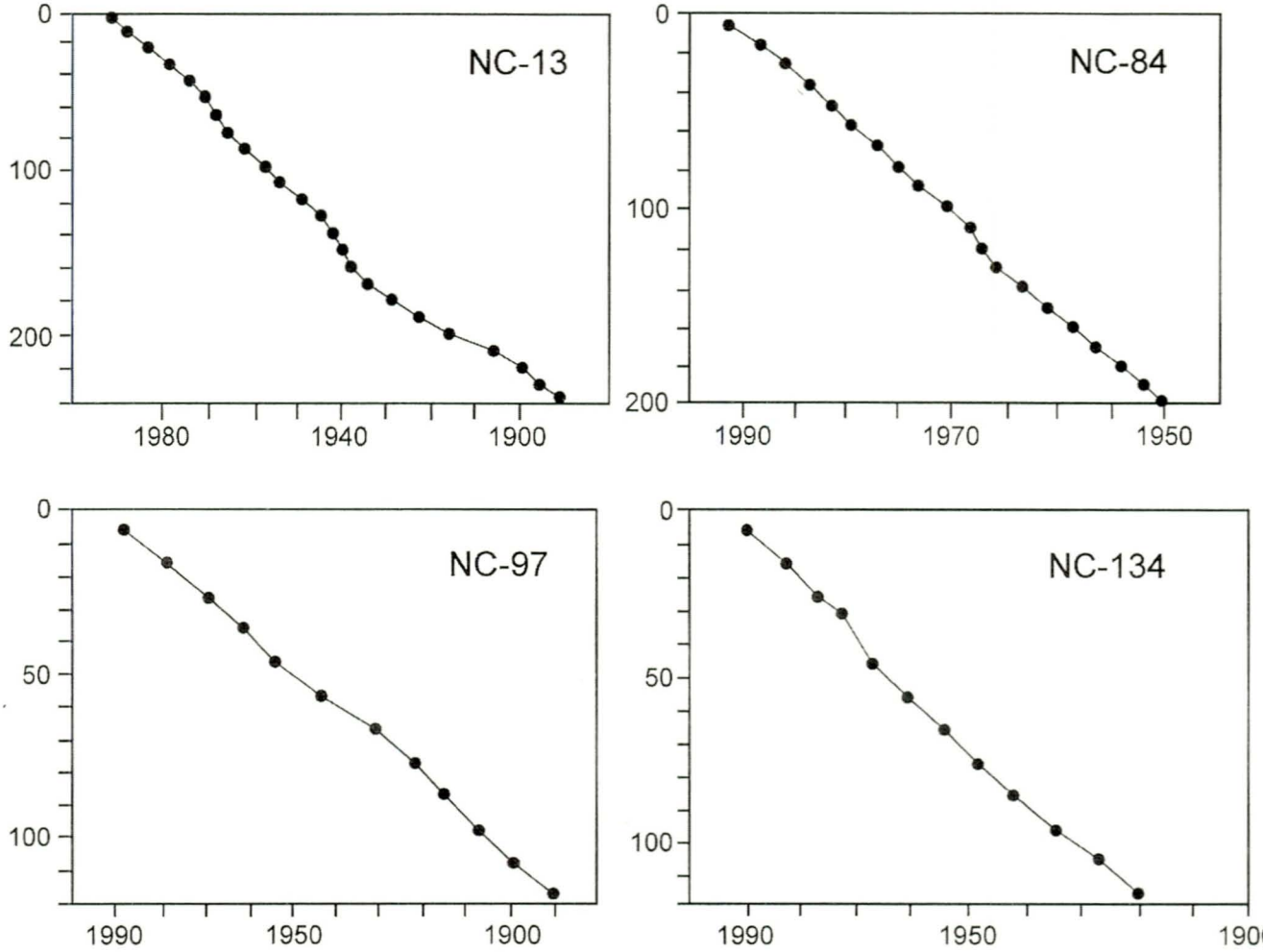

Fig. 4. Results of age estimation using the CRS model for cores NC-13, NC-84, NC-97 and NC-134.

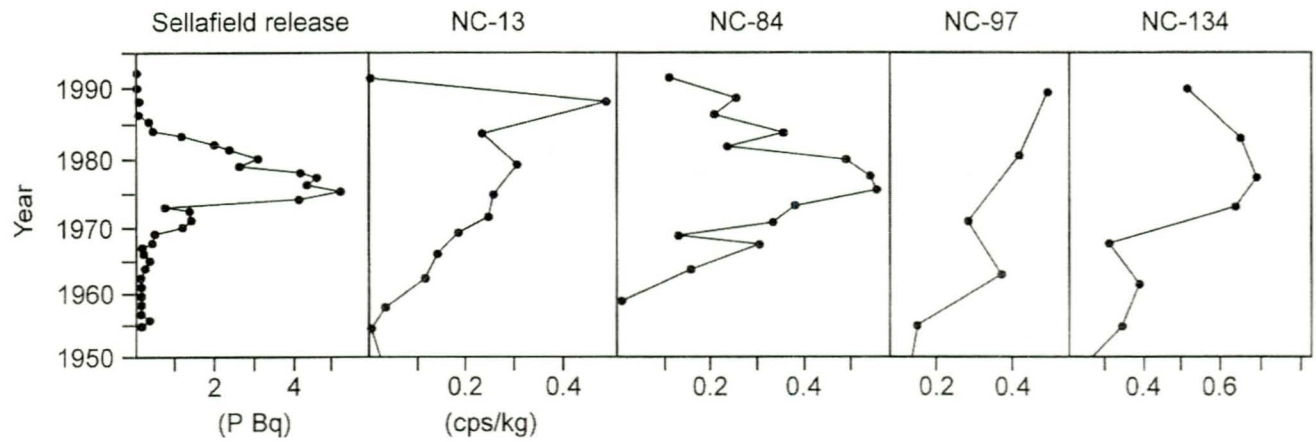

Fig. 5. Dated depth profiles of Cs-137 of cores NC-13, NC-84, NC97 and NC-134.

the Pb-210 dating (e.g., Robbins 1978), the sediment histories of the four cores can be estimated (Fig. 4). These data were gathered by applying the measured unsupported Pb-210 intensities to a core depth where background levels were reached. At depth, lead-210 data from the CIC fit were used. The age of a sediment at any depth can then be calculated from the equation $t(x_i) = l^{-1} \ln (A_{total}/A(x_i))$ where l is the Pb-210 decay constant (year^{-1}), A_{total} the total Pb-210 activity along the core (in 10^{-3} cps cm^{-2}) and $A(x_i)$ is the activity below sediment depth x_i. A problem that often arises when constructing the sedimentation history is that of the lack of bulk density data

Table 3. Observed Cs-137 intensities in the Skagerrak cores ascribed to the influence of different events.

Core No	Chernobyl 1986	Sellafield releases max. 1975	Bomb testing max. 1963
NC-13	+	+	(+)
NC-71	disturbed		
NC-84	(+)	+	(+)
NC-97	(+)	(+)	(+)
NC-113	disturbed		
NC-134	(+)	+	+

at depth. This is because core length, in many cases, is about 300 mm which is too short for dating purposes for a sediment deposition with rates exceeding about 4 mm/year. This problem did not, however, play a role in the evaluation of the present cores which all exeeded 450 mm.

Cs-137 data

After the reconstruction of the recent sedimentation history by the CRS model, a date can be ascribed to each mid-point of a sediment core section. Replotting the Cs-137 data (Fig. 5) permits the assignment of Cs-137 to one of the three known events, i.e. Chernobyl, Sellafield or nuclear weapons testing. Data for these events based on monitoring are also shown in the Figure.

From Fig. 5 it appears that there is a clear Sellafield component in the Cs-137 curves observed for cores NC-13, NC-84 and NC-134. It can also be argued that there is a contribution of Chernobyl derived Cs in these cores. Due to the relatively low sedimentation rate, the depth distribution of Cs-137 for core NC-134 is somewhat broader than for the other cores. The contribution from Sellafield releases, however, seems to be higher because of the high Cs-137 values. In this respect, the sequence of Sellafield release influence is NC-134, NC-84 and NC-13, which may be related to the distance to the North Sea pathways. It is also worthwhile to note that, in general, the cores also suggest the accumulation of Cs-137 from nuclear bomb testing, peaking in 1963.

Dated chemical profiles

Selected chemical profiles along the dated cores (NC-13, NC-84, NC-97 and NC-134) are given in Fig. 6. These data were generated by a semiquantitative, automatic, energy-dispersive, X-ray fluorescence spectrometer (e.g., Kunzendorf 1979).

Although it is not within the scope of this paper to discuss the geochemistry in detail, the most striking observation is that only three of the four dated sediment cores show a very clear diagenetic Mn enrichment in the upper sediments. The manganese profile of core NC-84 from the SE flank of the Norwegian Trough displays a different diagenetic imprint. The well-known chemical behaviour of Mn and Fe in marine sediments described elsewhere in

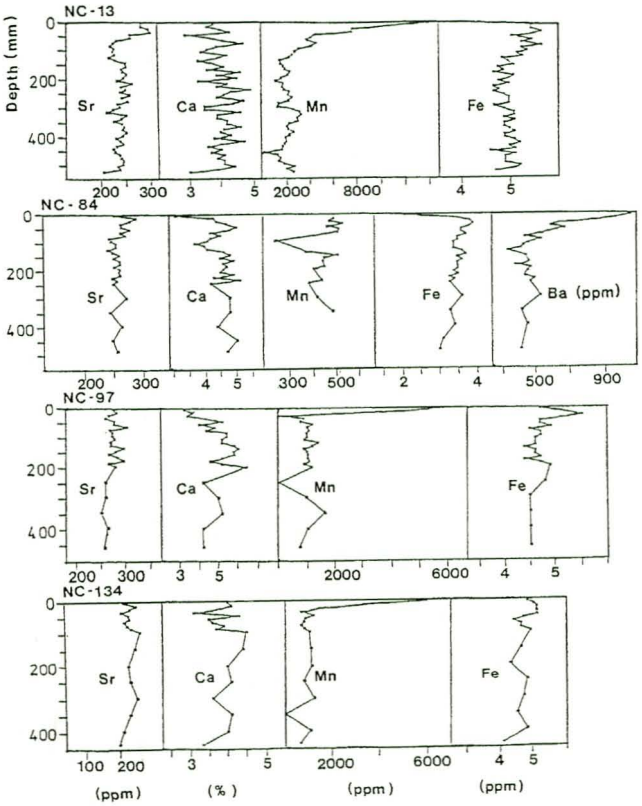

Fig. 6. Profiles of Sr, Ca, Mn, and Fe with depth from cores NC-13, NC-84, NC-97 and NC-134. For core NC-84, the profile of Ba with depth is also shown.

the literature leads to the following explanation of the observed Mn and Fe profiles of the cores. It is assumed that, below the redox boundary of about 50 mm (cores NC-97 and NC-134), manganese and iron phases in the sediments are dissolved and the solutions migrate upwards. When reaching the oxic sediment zone (< 50 mm), Mn is precipitated preferentially from these solutions in the form of fine oxyhydroxide particles leading to a significant enrichment of this metal towards the bottom/seawater transition zone. Iron is also enriched in the oxic zone, but iron diagenesis is less pronounced. Interestingly, the highest concentrations of Mn, both at depth (2000 compared to 1000 ppm) and in the surface layers (up to 1.4% compared to 6000), are found in core NC-13 from the central part of the trough. These mechanisms are here displayed on well-dated sediments and therefore increase the significance of interpretation.

While there are generally relatively low Mn concentrations in the sediments of core NC-84, the main characteristic is a significant enrichment of Ba in the upper 100 mm with the highest values at the sediment/seawater interface. Enrichment of Ba starts at some time after 1970 and one could argue that core NC-84 is within a sediment material transport channel transporting North Sea materials to the Norwegian Trough. Barium could then be ascribed to hydrocarbon exploration and exploitation activities which have increased significantly since the

mid-seventies. This is also verified by the observed high sedimentation rate (4.7 mm/year) and a strong Sellafield release imprint in the sediments. However, other processes of Ba enrichment in the surface sediments may have been operating.

Conclusions

The dating of six sediment cores from the Norwegian Trough by the Pb-210 method suggests the following:

1) Average linear sedimentation rates vary between 1.1 and 4.7 mm/year, with the highest sedimentation found in core NC-84 (station 67). Average mass accumulation rates were found to vary between 278 and 843 g cm^{-2} $year^{-1}$. A sedimentation history was constructed for these cores by applying the constant rate of supply model.
2) For cores NC-71 (station 65B) and NC-113 (station 71), the Pb-210 and the Cs-137 activity depth profiles showed no significant variations, suggesting that these core are greatly disturbed.
3) By assigning actual dates to the cores with significant Cs-137 profiles it appears that the profiles can be explained by three superimposed anthropogenic events, namely the Chernobyl accident, the Sellafield releases and the nuclear bomb testings. It appears that the Sellafield releases in the late seventies had a major effect on Skagerrak sediment deposition.

In general, our investigations also suggest that the lead-210 dating technique based on recording gamma radiation activity with depth of several radioisotopes instead of the conventional alpha-spectrometry is a promising technique in high-resolution marine geochemical studies of recent sediments. Because lead-210 data may give erroneous results, the Cs-137 recorded at the same time usually confirms and strengthens the data obtained from lead-210. Although counting times are comparable to conventional techniques (alpha spectrometry), ease of operation and the possibility of repeated non-destructive measurements are the main advantages of the gamma-spectrometric technique. Most of the physical effects (e.g. self-absorption) can also be controlled.

The increasing demand for elucidating the pollution history and the recent environmental changes in depositional marine basins favours the use of radiometric profiling as a basic tool in marine environmental studies dealing with chemical element fluxes.

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