Recent sediment accumulation in the Norwegian Channel, North Sea

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In the Norwegian Channel 35 box cores were taken for sedimentological analysis, and ^{210}Po α- and ^{137}Cs γ-spectroscopy to determine sedimentation rates. Grain sizes were determined and X-ray photographs of the cores were made. In addition, penetrating echo sounding lines covering a length of more than 5500 km were studied. Sediments enter the Norwegian Channel from the south and the west as suspended load. The dry bulk densities of these generally fine-grained sediments (silty clays - silts) range from 0.35 to 1.79 gxcm^{-3}. Most of the cores show a surface mixed layer of less than 2 cm. The sedimentation rates measured in the Norwegian Channel range from 30 to 280 mmx100 yr^{-1}. Highest sedimentation rates are found in the northern part of the research area. The total recent dry bulk sediment accumulation in the Norwegian Channel is calculated to be 28x10^{6} tons^{x}yr^{-1}. Penetrating echosounder data reveal that sedimentation occurs in the deeper parts and in small protected basins along the flanks of the Norwegian Channel. The contrast between the present-day relatively high sedimentation rates and the thin Holocene sedimentary unit is explained by a change in the depositional system sometime during the Holocene.

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Introduction

The Norwegian Channel is one of the largest and deepest recent sedimentary basins of the North Sea and forms a major sink for fine-grained material in the North Sea (Eisma 1981, van Weering 1981, Eisma & Kalf 1987, van Weering et al. 1987, 1993). Sediments enter the North Sea (Fig. 1) from the Atlantic Ocean in the north, through the English Channel, from the Baltic Sea and from river input. Furthermore, sea floor erosion, coastal erosion, primary production and atmospheric input contribute to the sediment load of the North Sea. The sediments in the North Sea are transported by an anticlockwise residual circulation (Otto et al. 1990). Recent sediment accumulation occurs mainly along the eastern margin of the North Sea (the Wadden Sea, the German Bight, the Skagerrak, the Kattegat and the Norwegian Channel) (McCave 1973, Eisma 1981, Eisma & Kalf 1987).

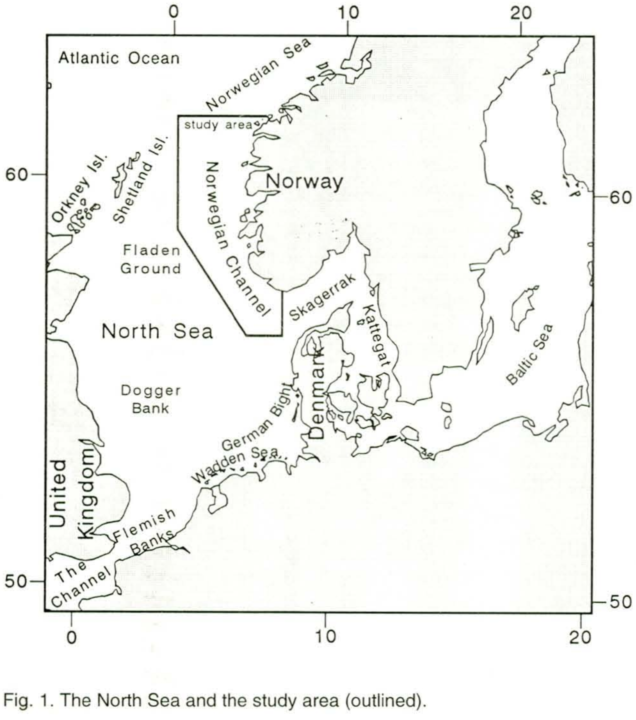

Fig. 1. The North Sea and the study area (outlined).

In recent years, application of ^{210}Pb geochronology has been used to calculate sedimentation and/or accumulation rates of recent sediments in the depositional sinks of the North Sea (van Weering et al. 1987, 1993, Zuo et al. 1989, Jørgensen et al. 1990, Dennegård et al. 1992a). Other methods have also been used, such as pollen studies (Zagwijn & Veenstra 1966, van Weering 1982, Henningmoen & Høeg 1985, Long et al. 1988), mass budget calculations of suspended sediments (Eisma 1981), ^{14}C (Long et al. 1988, Moodley & van Weering 1993), dinoflagellates (Long et al. 1986), stable isotopes (Erlenkeuser 1985) and foraminifera (van Weering 1982, van Weering & Qvale 1983, Qvale & van Weering 1985).

In this paper we report on sedimentation and sediment accumulation rates in the Norwegian Channel based on data collected during a cruise with the R.V. 'Aurelia' in 1988 and two cruises with the R.V. ' Pelagia' in 1991 and 1993 (ENAM93) to the Norwegian Channel, and on data from the literature. This study has aimed at determining the total amount of sediment being deposited in the Norwegian Channel, and to explain the major sedimentary processes.

Methods

A total of 35 box cores were collected in the Norwegian Channel with the R.V. 'Aurelia' (1988) and with the R.V. '

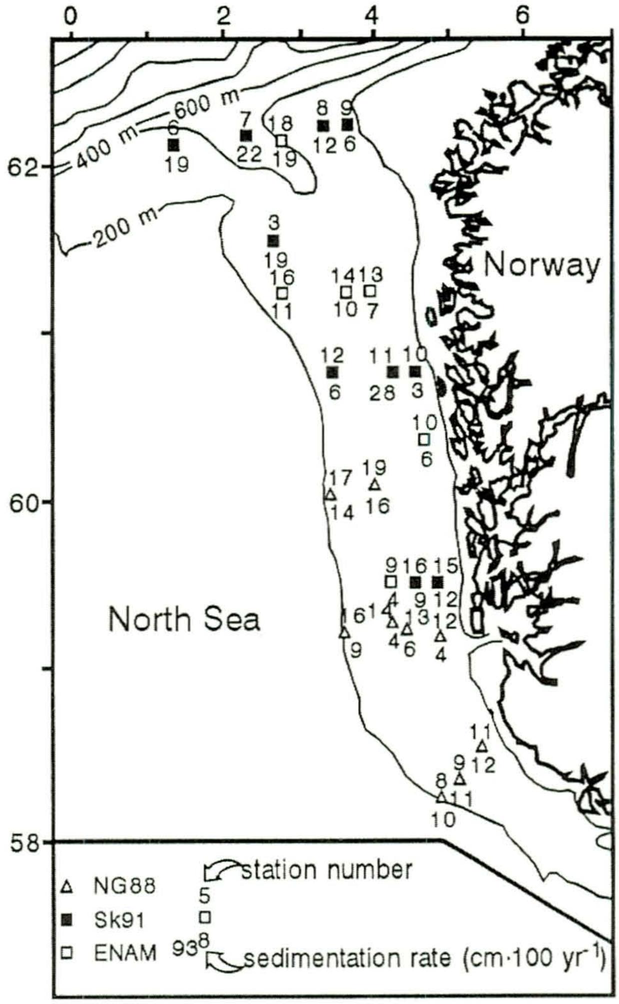

Fig. 2. Locations and sedimentation rates for the stations where sedimentation rates have been determined.

Pelagia' (1991 and 1993). Immediately after retrieval of the cores the overlying bottom water was siphoned off and subsamples were made by inserting wet PVC liners (Ø: 9 cm) into the box cores. The liners were closed with plastic caps and sealed with tape. After sampling, the liners were stored upright at 4° C. Sedimentation rates were determined using α- and γ-spectrometry. ^{210}Pb was measured via its α-particles emitting granddaughter ^{210}Po, which is assumed to be in equilibrium with ^{210}Pb. The sedimentation rates were calculated according to the CIC (Constant Initial Concentration) method. The method used is described in more detail by van Weering et al. (1987). ^{137}Cs activity was measured using Aptec and Canberra germanium γ-ray detectors on 1 cm-thick sediment slices with 35-65 g dry weight, depending on the porosity of the sediment. ^{210}Pb and ^{137}Cs analyses were performed on the selected cores at 1 cm depth intervals. The counting time for the α- and γ- measurements was 24 hours and 1 to 2 weeks, respectively.

X-radiographs of the split cores were made using a Hewlett-Packard 43805N X-ray system Faxitron. The radiographs were used to check the cores for bioturbation and other possible disturbances. Sedimentation rates were determined only from cores not disturbed by bioturbation or by sampling and/or storage. Twenty-five cores were considered suitable for sedimentation rate determination (Fig. 2). Grain-size analyses were performed at the University of Utrecht using a Malvern Particle Sizer model 2600D capable of measuring grain sizes within a range of 0.5-188 mm. Dry bulk densities were determined by taking subsamples of 5 cm^3 of wet sediment which were dried at 60-70°C for 72 hours and afterwards weighed on a Mettler P1200N balance. Sedimentation rates and dry bulk densities were corrected for compaction during subsampling and storage of the samples. This was done by measuring the compaction of the sediments in the liners and assuming a linear compaction over the whole sediment column. Accumulation rates were calculated using sedimentation rates and dry bulk densities.

3.5 kHz penetrating echosounder lines recorded in 1973, 1974, 1975, 1976 and 1993, and data from the literature were used to determine where in the Norwegian Channel recent sedimentation and erosion/non-deposition occurs.

Geological setting, hydrography and sediment transport

The present morphology of the Norwegian Channel is the product of glacial erosion followed by sedimentation during the Pleistocene and Holocene (van Weering 1975, Otto et al. 1990, Pedersen et al. 1991, Holtedahl 1993, Pederstad et al. 1993). At ~59°30'N the Norwegian Channel shallows to 280 m at a saddle point. Further south, the Norwegian Channel deepens to more than 700 m in the Skagerrak (Otto et al. 1990).

An overview of the dominant circulation pattern in the northern North Sea is given by Otto et al. (1990). Atlantic water enters the North Sea mainly along the western slope of the Norwegian Channel and through the Orkney-Shetland inflow. This water mass enters the Skagerrak along the southern slope as the Atlantic Shelf Edge Current. Water coming from the southern North Sea enters the Skagerrak along the southern slope and partly flows into the Kattegat. The remainder mixes with water coming from the Baltic Sea, and the Atlantic Shelf Edge Current. This water mass leaves the Skagerrak as the less saline Norwegian Coastal Current, which flows to the north through the Norwegian Channel and finally into the Norwegian Sea. Seasonal variations in this pattern are the result of differences in water temperature and wind stress (Otto et al. 1990). The fraction of the sediments which does not settle in the Skagerrak is transported out of the Skagerrak into the Norwegian Channel by the Norwegian Coastal Current as suspended load. Some of this material settles in the Norwegian Channel and the remainder is transported into the Norwegian Sea (Eisma 1981, van Weering 1982).

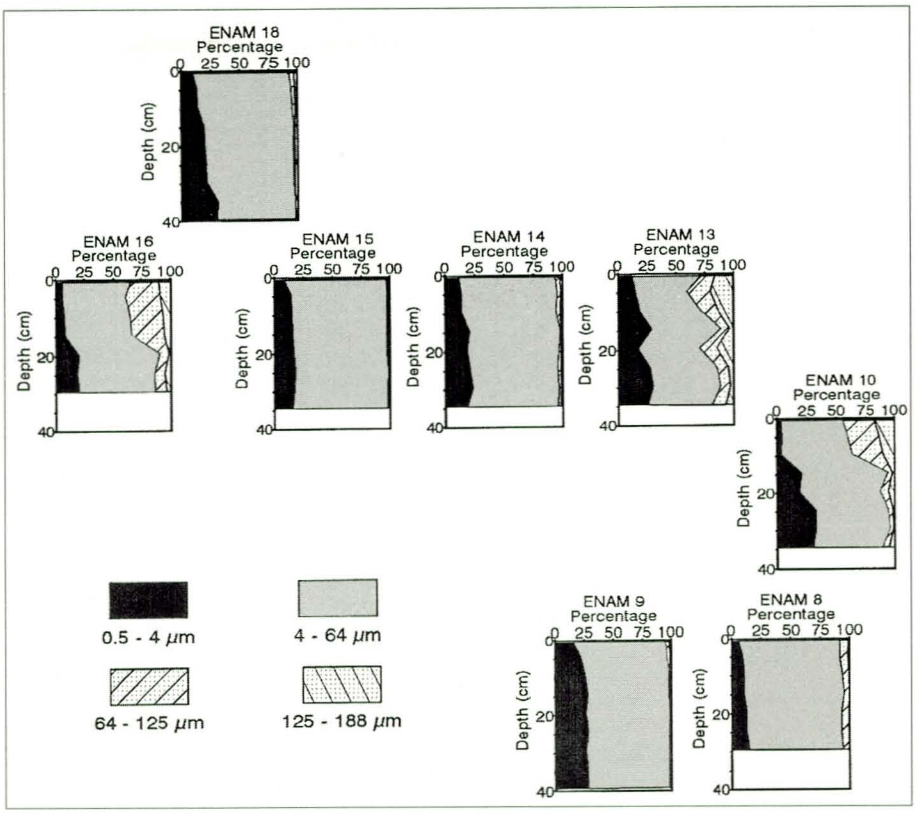

Fig. 3. Results of the grain-size analyses of the ENAM cores. Position of the graphs relative to the geographical location of the cores.

Results

Sediments

Description

The sediments in the Norwegian Channel consist mainly of brownish, greenish and greyish silty clays. Some cores show a few cm thick sandy intervals (e.g. Sk91-4), while others are sandy throughout the core (e.g. Sk91-6). Core Sk91-2, taken high upon the western slope of the Norwegian Channel, consists of medium to coarse sand. Sometimes gravel is found (core NG88-6). Shells, shell fragments and echinoid spines are common. Macroscopically the cores are homogeneous and lack almost completely primary sedimentary structures. X-radiographs of the cores also show very few primary sedimentary structures. Coarse-grained intervals, quartz and clay pebbles, and dark and light intervals caused by differences in mineralogy can be recognised on the X-radiographs. Macroscopic burrows can be recognised in most of the cores and on the X-ray images. The burrows have diameters ranging from 0.5 mm to more than 10 mm. In many cases only a few narrow (Ø=0.5 mm) or wider (Ø ±10 mm) burrows are present, leaving the few primary sedimentary structures and the light and dark intervals intact, i.e., the sediments are more or less undisturbed. In other cores the primary structures and colour banding are clearly disturbed, indicating strong bioturbation (cores ENAM93-8, Sk91-13 and Sk91-14). Several box cores showed worm tubes at the sediment surface. The brownish colours of most of the top sediments of the cores indicate a well oxygenated environment.

Grain-size analysis and dry bulk density

The grain sizes have only been determined on the ENAM93 samples (Fig. 3). Most of these cores consist of clayey silts, the percentage of clay being usually less than 25%. In most of the cores the amount of very fine to fine sand is 5% or less. Cores ENAM93-10, 13 and 16 are relatively coarse, and the amount of sandy material sometimes exceeds 40% (top of ENAM93-10). The finest-grained sediments are found in the central part of the Norwegian Channel. The grain-size distribution of the surface sediments is in agreement with the data provided by Qvale & van Weering (1985).

Dry bulk densities vary from 0.35 to 1.79 gxcm^{-3} depending on the depth in the core and the grain-size distribution.

^{210}Pb and ^{137}Cs measurements and sedimentation rates

The locations of the individual stations and the sedimentation rates measured are given in Table 1. Cores ENAM93-8, ENAM93-15, NG88-6, NG88-7, NG88-10, NG88-15, Sk91-13 and Sk91-14 were not used for interpretations, because they are strongly bioturbated. Core

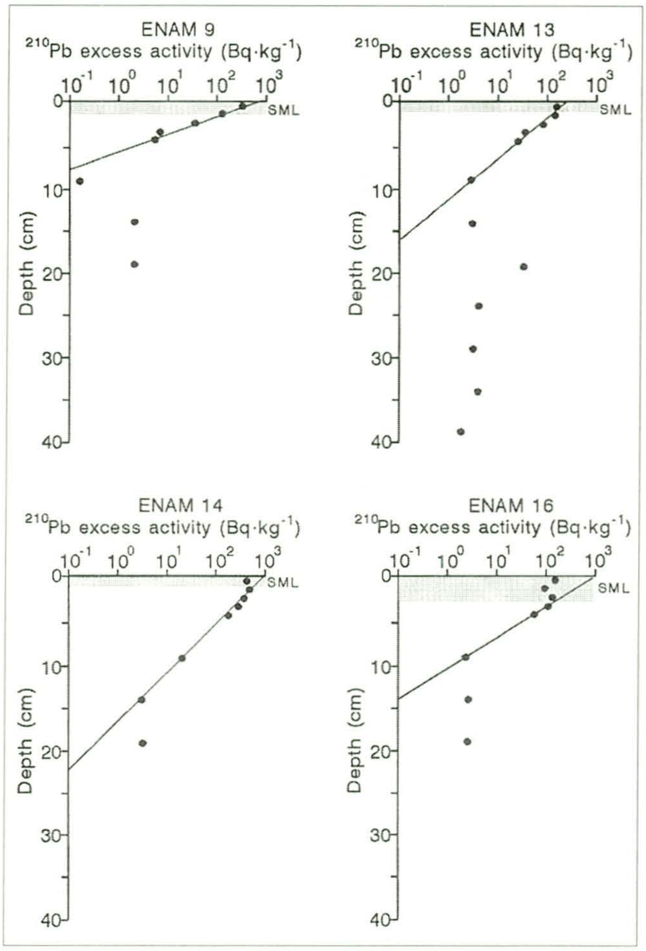

Fig. 4. Selected results of the ^{210}Pb measurements. Grey interval indicates thickness of the surface mixed layer (SML). See text for more details.

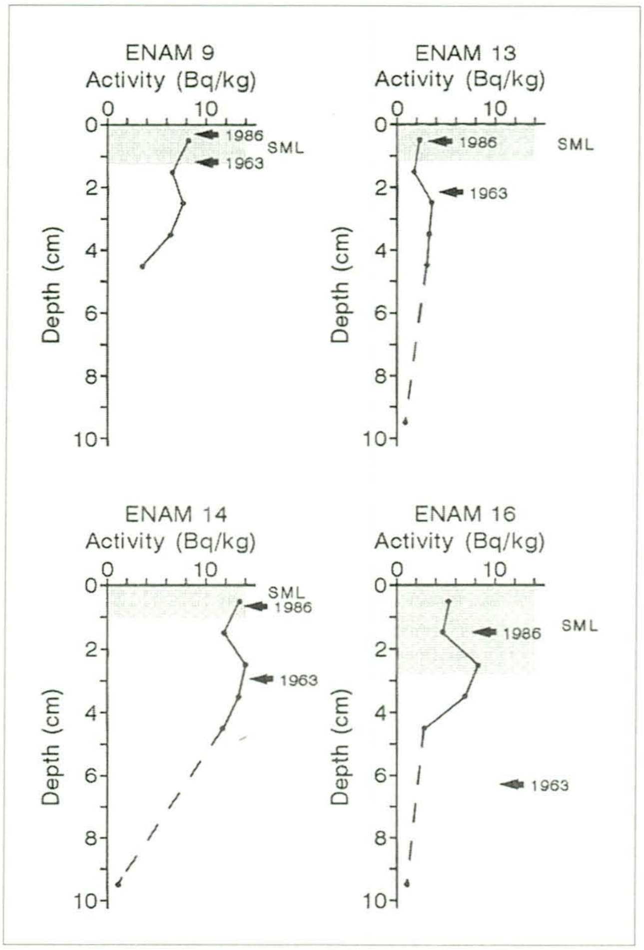

Fig. 5. Results of ^{137}Cs measurements of ENAM 1993 cores. Grey interval indicates thickness of the surface mixed layer (SML). Arrows indicate expected depth of 1963 and 1986 activity peaks.

Sk91-2 was only 5 cm long and therefore too short to be of any use. Core Sk91-4 showed a compaction of 53% during sampling and storage, and is therefore possibly too disturbed to allow a reliable determination of the sedimentation rate. Fig. 4 shows some of the results of the ^{210}Pb measurements. In general, the logarithmic excess ^{210}Pb activity plotted versus core depth shows a straight line below the surface mixed layer (SML). Usually the SML is very thin. In most cores the thickness does not exceed 2 cm (Fig. 4). In some cores, however, (ENAM93-8 and 15) the SML reaches a thickness of 15 cm or more. Some of the ^{210}Pb plots show anomalously high or low ^{210}Pb values deeper in the core (ENAM93-13, Fig. 4). These are thought to be the result of local burrowing below the SML, which resulted in the transport and subsequent mixing of older or younger sediment. This explanation is supported by the X-radiographs which show some major burrows at the depths concerned, and by grain-size analyses showing a variance in grain size at these specific depths.

Fig. 5 shows ^{137}Cs-activity profiles of some of the ENAM93 cores. The 1963 nuclear bomb testing and the 1986 Chernobyl ^{137}Cs-activity peaks in core ENAM93-9 fall within the bioturbated upper layer of the sediment and are therefore not clearly visible in the profile. The 1986 peaks in cores ENAM93-13 and 14 are within the bioturbated layer, but small increases in ^{137}Cs-activity are visible. Both these cores show a maximum in activity resulting from the 1963 nuclear bomb testing. The peak at the base of the bioturbated layer of core ENAM93-16 might be the result of the burial of 1986 sediments due to bioturbation. This causes a pre-1986 ^{137}Cs-activity peak which is located too deep in the core. The high activity in the 3-4 cm interval just below the bioturbated layer may be the result of the increased Sellafield releases which peaked around 1975 to 1980 (Kunzendorf et al. this volume). The sedimentation rates were determined from the ^{210}Pb and ^{137}Cs measurements. The sedimentation rates in the Norwegian Channel range from 30 to 280 mmx100 yr^{-1}. Highest sedimentation rates were found in the northern part of the Norwegian Channel (Fig. 2).

From the literature it is known that on the Fladen Ground, on the plateau northwest of the Norwegian Channel and the upper western slope of the Norwegian Channel, there is little sedimentation, and possibly erosion (Johnson & Elkins 1979, Rise & Rokoengen 1984). On

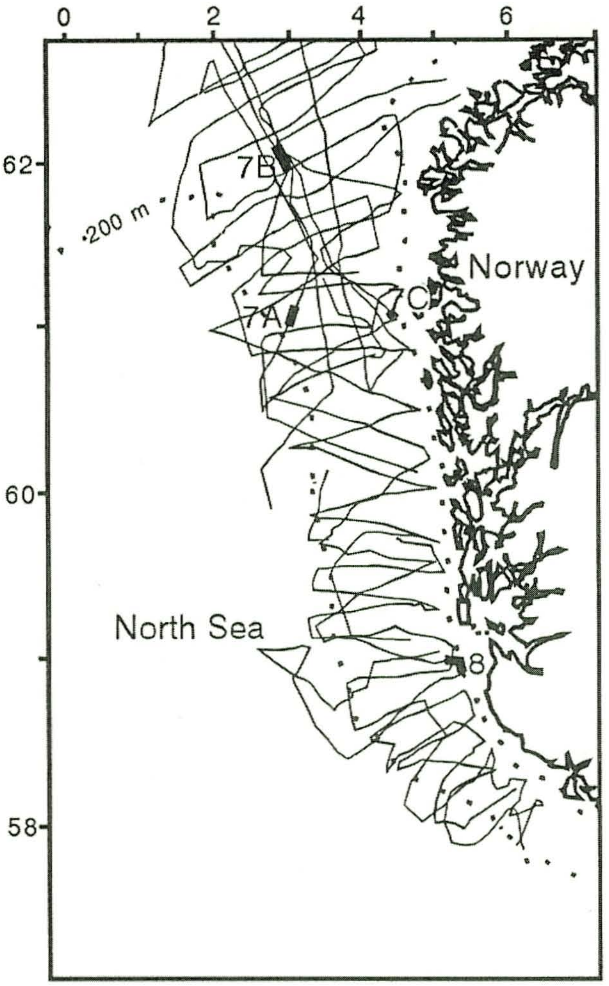

Fig. 6. Location map of the acoustical reflection profiles used in this study. Numbers 7A to 8 indicate the position of the profiles shown in Figs 7A to 8, respectively.

the eastern slope of the Norwegian Channel, towards the mainland, crystalline bedrock extending from land is locally exposed, which indicates that non-depositional conditions prevail there (Holtedahl 1993, Rise & Rokoengen 1984), but isolated, ponded Holocene is likely to be present. On the western slope of the channel the local effect of erosion on the platform is noticed in the presence and amount of older, reworked foraminifera in Norwegian Channel sediments (Qvale & van Weering 1985).

Acoustical data

In the period 1973-1976, 3.5 kHz echo-sounding lines were recorded across the Norwegian Channel between 58° and 63°N. Lines located north of 60°N are discussed in van Weering (1983). In 1993, some additional lines were recorded using a Datasonics Chirp echosounder. Together these lines cover a length of more than 5500 km (Fig. 6).

North of 60°N van Weering (1983) identified four sedimentary units reflecting depositional events during and after the last glaciation. These units can be traced in the area south of 60°N. The upper unit (unit 1) represents Holocene fine-grained sediments which overlie Weichselian glacial marine deposits (unit 2) (van Weering 1983, Holtedahl 1993). The Holocene and glacial marine sediments are not equally thick throughout the area. The average thickness of the combined units in the central part of the Norwegian Channel is about 10-20 m. Datings of a core from the central part of the Norwegian Channel show that here the base of the Weichselian glacial marine unit lies at about 23 m, and the base of the Holocene at 3.75 m depth (core Troll 3.1, Lehman et al. 1991, Lehman & Keigwin 1992). In the southern part of the Norwegian

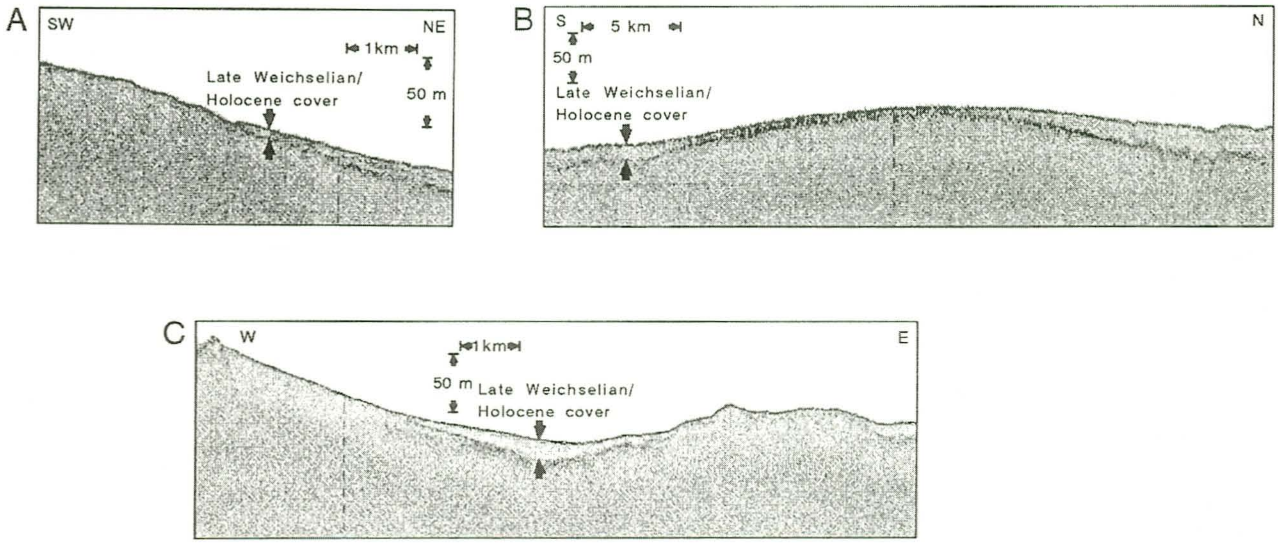

Fig. 7. 3.5 kHz penetrating echosounder profiles from the Norwegian Channel. Dashed lines in subsurface are time markers. A) Profile showing the pinching out of the Holocene sediments on the western slope of the Norwegian Channel. Water depth 320-390 m, vertical exaggeration 20x. B) Profile showing thin Holocene sedimentary cover on a topographic high in the central part of the Norwegian Channel. Water depth 400-440 m, vertical exaggeration 50x. C) Profile showing a small local basin on the eastern slope of the Norwegian Channel. Water depth 340-420 m, vertical exaggeration 20x.

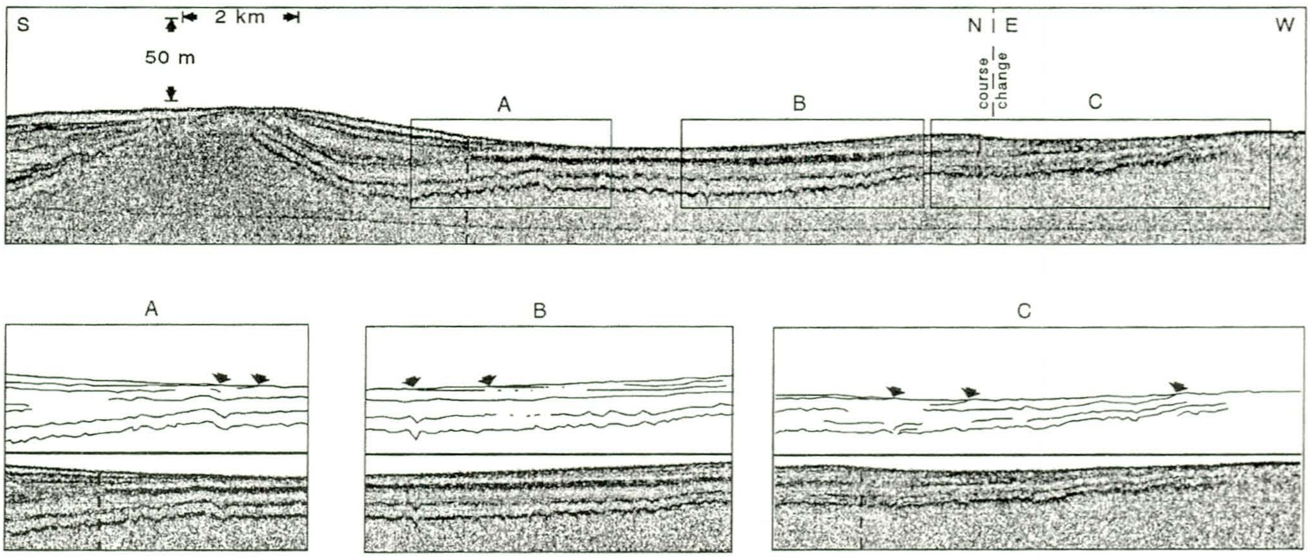

Fig. 8. Penetrating echo sounder profile showing the truncation of internal reflectors at the sea floor, for details see blow ups A to C. Arrows indicate the truncation of internal reflectors by the sea-floor reflector. Water depth 240-260 m, vertical exaggeration 30x.

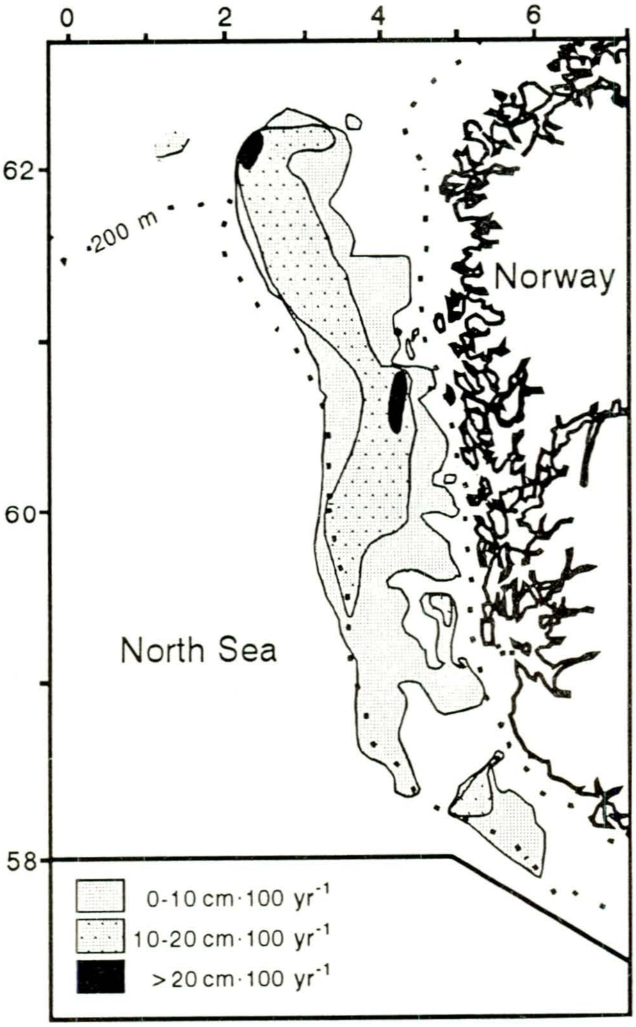

Fig. 9. Geographical distribution of recent sedimentation areas in the Norwegian Channel.

Channel these layers can be thicker, but the boundary between the Holocene sediments and the Weichselian glacial marine sediments beneath (van Weering 1983, unit 2) can be very unclear. The thickness of the Holocene cover can therefore not always be determined accurately. Units 1 and 2 pinch out towards the margins of the Norwegian Channel and towards the south and the north (Fig. 7A). On topographic highs the Weichselian and Holocene sedimentary cover is sometimes extremely thin (Fig. 7B). Local depressions of the sea bed act as sedimentary basins in which increased sedimentation occurs. Especially along the eastern flank of the Norwegian Channel the pronounced topography results in the presence of small local basins (Fig. 7C). In some cases the internal reflectors of earlier deposited sediments appear to be truncated at the sea floor (Fig. 8).

Accumulation rates

Based on the acoustical data, the maximum surface area of that part of the Norwegian Channel in which recent sedimentation occurs is calculated to be 33,900 km^2 (Fig. 9). Using three intervals of sedimentation rates (0-100, 100-200 and >200 mmx100 yr^{-1}) and calculating average sedimentation rates and average dry bulk densities for each of these intervals, the maximum total yearly dry bulk accumulation rate in this part of the Norwegian Channel is calculated to be $28x10^6$ tons.

Discussion

Although the X-radiographs clearly show the effect of bioturbation, the sedimentation rates calculated from

Table 1. List of stations and ^{210}Pb sedimentation rates (n.d.=not determined).

Station No.	Position North	East	Sedimentation rate (mm/100 yr)
Sk91-2	61°20.45′	2° 00.70′	n.d.
Sk91-3	61°30.79′	2° 33.42′	190
Sk91-4	61°39.20′	3° 24.90′	n.d.
Sk91-6	62°07.00′	1° 19.78′	190
Sk91-7	62°09.83′	2° 18.83′	220
Sk91-8	62°12.28′	3° 17.75′	120
Sk91-9	62°12.81′	3° 38.05′	60
Sk91-10	60°43.50′	4° 29.70′	30
Sk91-11	60°42.71′	4° 10.28′	280
Sk91-12	60°43.49′	3° 20.89′	60
Sk91-13	60°42.62′	3° 10.24′	n.d.
Sk91-14	60°43.30′	3° 13.08′	n.d.
Sk91-15	59°30.60′	4° 46.50′	120
Sk91-16	59°29.99′	4° 27.30′	90
NG88-6	58°10.47′	4° 37.61′	n.d.
NG88-7	58°12.43′	4° 40.25′	n.d.
NG88-8	58°15.73′	4° 52.12′	100
NG88-9	58°24.18′	5° 07.83′	110
NG88-10	58°28.61′	5° 18.92′	n.d.
NG88-11	58°36.68′	5° 24.71′	120
NG88-12	59°11.92′	4° 51.39′	40
NG88-13	59°13.81′	4° 26.94′	60
NG88-14	59°15.47′	4° 08.85′	40
NG88-15	59°12.70′	3° 42.88′	n.d.
NG88-16	59°13.07′	3° 30.46′	90
NG88-17	59°59.45′	3° 17.80′	140
NG88-19	60°01.72′	3° 55.14′	160
ENAM 8	59°30.10′	3° 41.25′	n.d.
ENAM 9	59°30.03′	4° 05.29′	40
ENAM 10	60°20.60′	4° 39.32′	60
ENAM 11	60°19.98′	3° 22.06′	n.d.
ENAM 13	61°19.94′	3° 52.17′	70
ENAM 14	61°19.77′	3° 35.58′	100
ENAM 15	61°19.25′	3° 15.87′	n.d.
ENAM 16	61°19.96′	2° 34.64′	110
ENAM 18	62°03.69′	2° 55.58′	190

downcore ^{210}Pb profiles are considered to reflect the real sedimentation rates. This assumption is based on the work of Nittrouer et al. (1984), who concluded that sedimentation rates on the Washington shelf can be calculated from the ^{210}Pb profile below the surface mixed layer. Furthermore, the maxima in the ^{137}Cs-activity profiles coincide well with the expected depths of the 1963 nuclear bomb test and 1986 Chernobyl accident peaks, thus supporting the sedimentation rates determined by the ^{210}Pb method.

The thin Holocene sedimentary cover in the central part of the northern Norwegian Channel, in the order of 4 m or less, and the even thinner layer near the flanks of the Norwegian Channel do not correspond with the extrapolated recent sedimentation rates measured by the ^{210}Pb method, which are in the order of 100-200 mmx100 yr^{-1}. The relatively thin Holocene sedimentary cover in relation to the high recent sedimentation rates in the northern part of the area cannot be explained by a stronger compaction of the sediments. The contrast between the present-day sedimentation rates and the thin Holocene sedimentary cover can, however, be explained by a change in sedimentary regime sometime during the Holocene. This explanation is supported by the grain-size distribution in two piston cores taken about 30 miles NNW (station ENAM93-15, Table 1) and 45 miles SSW (ENAM93-11, Table 1) of core Troll 3.1 described by Lehman et al. (1991) and Lehman & Keigwin (1992). In these two cores a coarsening upwards starts at ~1 m and ~2 m core depth, respectively. In both ENAM cores the grain size increases from clayey silt to coarse silt - very fine sandy silt. Echo-sounding lines located very near the three cores mentioned, do suggest that on the locations where the two ENAM93 cores and core Troll 3.1 were taken, similar sedimentary processes took place during the Late Weichselian and Holocene. The only difference is found in the total thickness of the sedimentary unit. In the south (near ENAM93-11), the unit is about 1.5 times as thick as on the location of core Troll 3.1. In the north, near station ENAM93-15, the thickness is just slightly less than near core Troll 3.1. The mechanism behind this change in depositional regime and possible related change in hydrological conditions is not yet known. Further study of the piston cores will most probably give the answer to this question.

Van Weering (1983) concluded that in the northern part of the Norwegian Channel the deposition of the Holocene deposits (unit 1) ceased around 8000 BP. The results of the ^{210}Pb measurements presented here clearly show that this is not the case, as was already suggested by Nagy & Ofstad (1980). The absence of present-day sedimentation along the eastern flank of the Norwegian Channel, as concluded on the basis of the echo-sounding data (Fig. 8), is supported by the work of Nagy & Ofstad (1980) who studied foraminifera along two transects across the Norwegian Channel.

Several authors have reported erosion and redistribution of sediments on the shallow sea floor of the North Sea. Erosion of the Flemish Banks (southern North Sea) was reported by Eisma & Kalf (1987). The tidal current near the Dogger Bank is not strong enough to transport sea-floor sediments. Sea-floor erosion and sediment transport in this area, however, do occur during storms (von Haugwitz & Wong 1988). Sea-floor photographs of the Norwegian sector of the North Sea indicate local present-day sea-floor erosion (Rise & Rokoengen 1984, NIOZ unpublished data). Foraminiferal studies also point to local erosion and reworking of sediments (Qvale & van Weering 1985). Sediments removed from the sea floor of the southern North Sea are transported northwards by the residual current (Eisma & Kalf 1987). Erlenkeuser & Pederstad (1984) found fine-grained sediment from a southern origin (southern North Sea and the Baltic Sea) in the Skagerrak. Hass (1993) concluded that the sedimentation pattern in the Skagerrak is influenced by short-term climatic changes. He showed that the average sedimentation rates in a core in the Skagerrak clearly increased during the stormy ' Little Ice Age' (1550-1890 A.D.) compared to the four centuries before the Little Ice Age and the present-day situation. An increased frequency of winds influenced the bottom currents and therefore erosion and transport of sediments. The sediments in the Norwegian Channel are transported and supplied by the Jutland Current, the Baltic Current, and also by the Norwegian rivers and fjords (Björklund et al. 1985); thus sediments eroded from the North Sea sea floor and sediments transported out of the Baltic Sea may be deposited in the Norwegian Channel. In the Norwegian Channel, where current velocities are lower and wave activity less pronounced, the sediments settle out of suspension and in the deeper parts of the Norwegian Channel the hydrological conditions favour permanent deposition of the sediments. This is clearly seen in Fig. 7A, which shows that deposition occurs only in the lower parts of the flanks. Another example is given in Fig. 7B, which shows that on local topographic highs in the deep central part of the study area the sedimentary cover is much thinner than in the surrounding deeper parts. Local depressions higher up the slopes provide enough shelter for sediments to settle permanently, as is clearly demonstrated in Fig. 7C. The truncation of reflectors within older deposits shown in Fig. 8 indicates that previously deposited sediments are eroded.

Conclusions

Downcore ^{210}Pb activity measurements allow the determination of recent sedimentation and mass accumulation rates in the Norwegian Channel. The recent sedimentation rates in the Norwegian Channel range from 30 to 280 mmx100 yr^{-1}. Highest sedimentation rates are found in the northern part of the Norwegian Channel. Sediments enter the Norwegian Channel from the south through the Skagerrak and from the west from the North Sea plateau, most probably as suspended load. In the Norwegian Channel, lower hydrodynamic activity allows the sediments to settle out of suspension. Recent deposition of sediments occurs in the deeper central part and in small protected basins higher up on the eastern flank of the channel. In the central northern Norwegian Channel the thickness of the Holocene sedimentary cover is generally ~4 m, and becomes thinner towards the flanks of the basin. In the southern part the Holocene deposits are thicker. The contrast between the thin Holocene cover and the relatively high present-day sedimentation rates is explained by a change in the hydrological and depositional regime in the Norwegian Channel sometime during the Holocene. In the Norwegian Channel 28x10^{6} tons of dry bulk sediment is deposited annually.

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