GEOCHEMICAL AND BIOLOGICAL RESEARCH AT THE NEA DUMPSITE FOR LOW-LEVEL RADIOACTIVE WASTE

Interim report of the dutch DORA program

by

M.M. RUTGERS VAN DER LOEFF & M.S.S. LAVALEYE
Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands.

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INTRODUCTION

Since 1967, the dumping of low level radioactive waste in the deep sea has normally taken place under the auspices of NEA, the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD). To further the objectives of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (the London Dumping Convention), the OECD Council established in 1977 a Multilateral Consultation and Surveillance Mechanism for Sea Dumping of Radioactive Waste. According to the terms of this Mechanism, NEA (1980) prepared a review of the suitability of the present dumpsite that has been in use since 1974. The Steering Committee for Nuclear Energy of the NEA considered in 1980 that, on the basis of the review, the existing site was suitable for continued dumping for the next five years. At the same time, the Steering Committee agreed on the need for developing a coordinated site-specific program to increase current knowledge of the processes controlling the transfer of radionuclides in the marine environment, so that future assessments could be based on more accurate and comprehensive scientific data.

An international Coordinated Research Project (CRESP) was then set up to yield the required information and build more site-specific models. Within CRESP, scientific experts from NEA member countries have discussed research priorities and devided research tasks. The Netherlands agreed to perform a biological and geochemical investigation of the dumping area. On behalf of the dutch government, the Netherlands Energy Research Foundation (ECN) asked the Netherlands Institute for Sea Research (NIOZ) to carry out this research.

The aim of the dutch contribution, which has been called the DORA project, is to supply additional information on those geochemical and biological characteristics of the dumpsite that can affect the transport of radionuclides once they have been released from the waste packages. The project started in May 1982. This report gives the results (up to December 1983) of analyses on samples that have been collected during the first expedition, in August-September 1982.

Acknowledgments.—We thank captain and crew of MS Tyro for their support during the expedition. The assistance from NIOZ technicians during preparations and during the actual expedition has been of great value. The enthousiasm of the swiss team contributed to the success of the expedition. Echosounder profiles were recorded by J. van Weereld. Much of the laboratory work was performed by D.A. Waijers and G.J. Zigterman and additional assistance was obtained during the cruise from J. Hegeman, B. van Megen and R.T.P. de Vries. X-ray diffraction analyses were performed by Sj. v.d. Gaast; X-ray fluorescence analyses by J. Kalf; G. Berger did the ^{210}Pb analyses shown in Fig. 11. We thank Dr F. Jansen for helpful discussions. H. Hobbelink and B. Verschuur took care of the illustrations. Neutron activation analyses were performed by Dr H. v.d. Sloot (ECN) and ^{14}C analyses by Prof. W.G. Mook (isotope physics laboratory, Groningen). ETS measurements would not have been possible without the help of Dr Miriam Sibuet, CNEXO, during our unplanned visit to Brest. The micropaleontological data of the

gravity cores are derived from a study by Drs Y. Coenegracht. The fishes caught with the trawl were identified with help of J.IJ. Witte. We further acknowledge the support obtained from Kristinebergs Marine Biological Station, Sweden, the Netherlands National Geologic Survey, the State Museum of Natural History (Leiden) and the Netherlands Council for Sea Research.

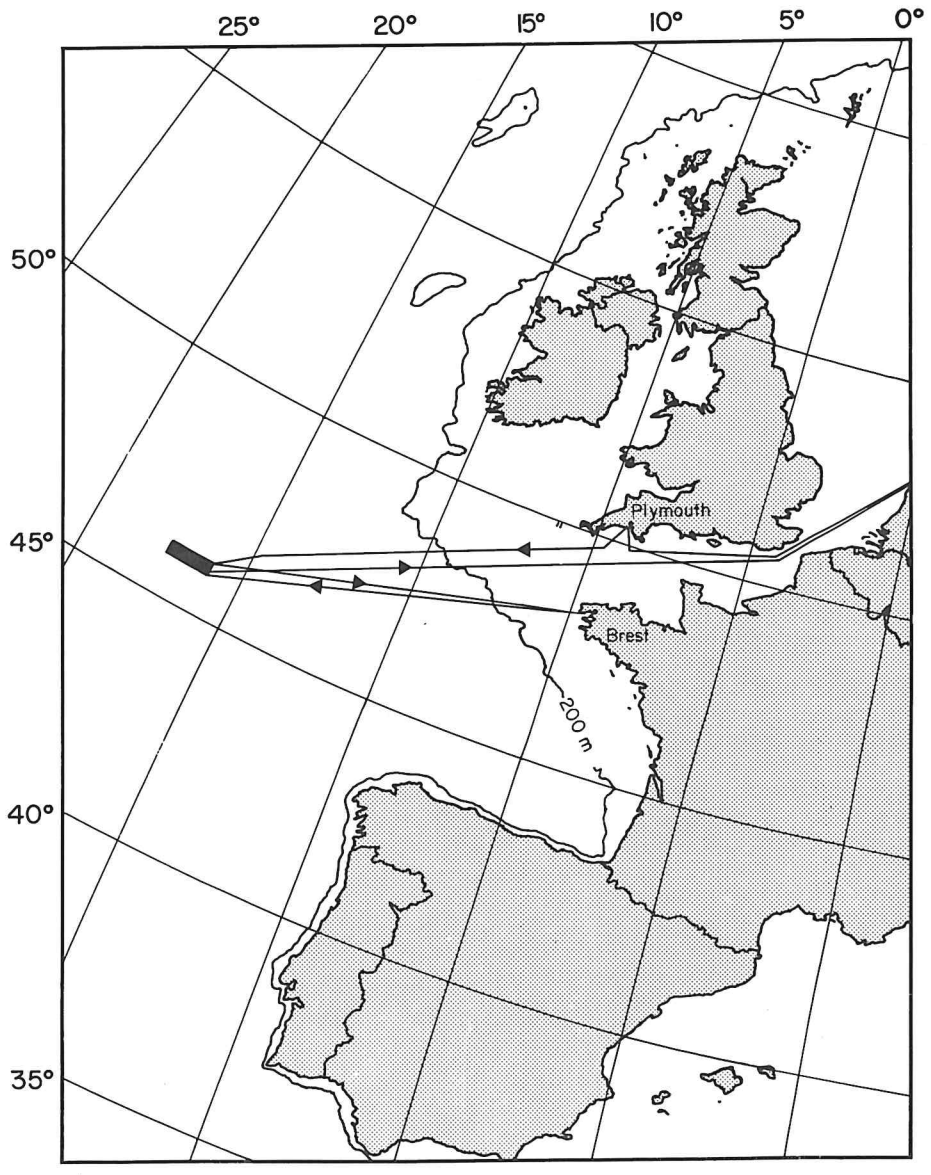


Fig.1. Cruise track of the TYRO expedition in 1982.

The project is financed by the Netherlands Energy Research Foundation, the dutch government (Ministry of Environment and Ministry of Economic Affairs), contributions from the swiss and belgian governments and through a contract with the Commission of the European Communities (No. BIO-B-509-NL (N)).

2. CRUISE TO THE DUMPSITE

A joint Swiss-Belgian-Dutch cruise was organized from 19 August to 13 September 1982 with MS Tyro. The position of the dumpsite and the cruise track are shown in Figs 1 and 2.

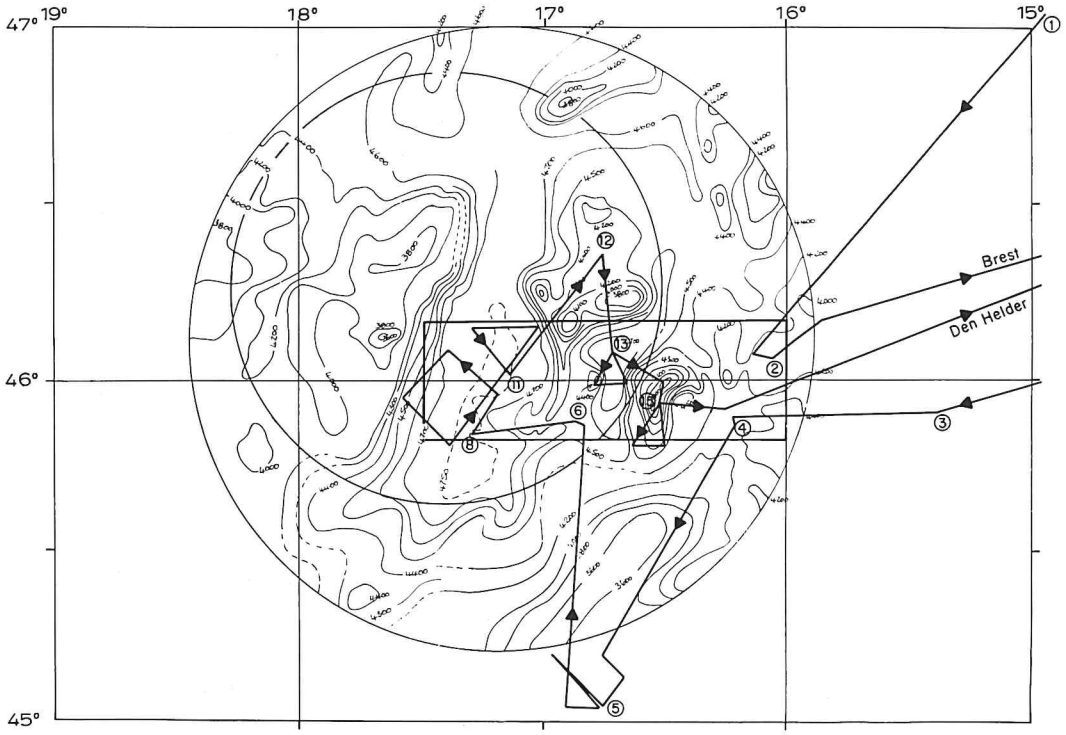
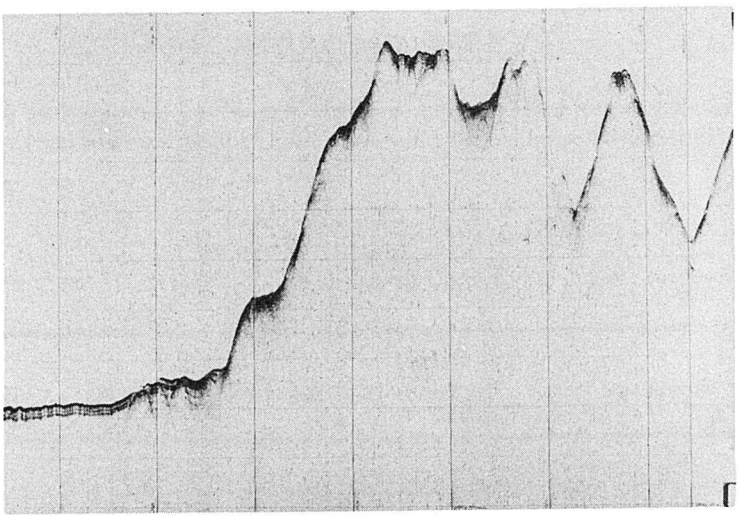


Fig.2. Dumpsite with cruise track and sampling stations.

Because the local bathymetry is not known in great detail, a 3.5 kHz echosounder was operated continuously during the cruise. The data were required for decisions on trawling and coring. Apart from depth and slope of the bottom (Fig.3), the reflections gave information on bottom hardness and layering (Figs 4 and 5).



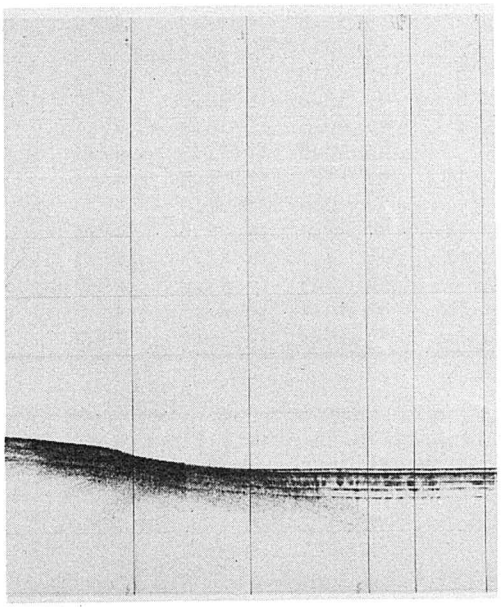


Fig.3. Echosounder reflection profile in E part of the dumpsite. Vertical range 4124-4875 m. Vertical scale exaggerated 50×.

Fig.4 (left). Echosounder reflection profile during coring at station 12, showing hard bottom, giving a second reflection. Vertical range 4125-4875 m.

Fig.5 (right). Echosounder reflection profile during coring at station 13, showing soft, layered sediment. Vertical range 4125-4875 m.

3. SAMPLING SCHEME

Table 1 shows the geographical position, the water depth and the sampling program at each of the stations visited. The following sampling techniques were used.

Table 1
Position, water depth (m) and sampling program at each of 11 stations visited.

station	position[1] N	W	depth[1] (echo)	CTD	boxcore	gravity core	trawl	PP
	° ,	° ,						
1	47 1.8	14 56.6	4800	x	x			
2	46 3.3	16 3.2	4200	x	x			x
3	45 59.3	15 9.2	4600				x	
4	45 51.6	16 13.3	4300	x	x			
	45 52.1	16 13.4	4000			2)		
5	45 3.3	16 45.3	4325		x		x	
6	45 53.6	16 52.0	4570	x	x			
8	45 50.5	17 16.1	4725	x	x		x	x
	45 48.8	17 17.3	4725			x		
11	46 1.1	17 8.9	4725	x	x		x	x
	46 0.9	17 7.9	4725			x		
12	46 22.1	16 42.8	4200	x	3)		x	
13	46 4.7	16 42.3	4700	x	x		x	
	46 5.3	16 43.0	4725			4)		
15	45 56.1	16 30.1	4000	x	x		x	
	45 54.9	16 31.5	4000			x		

1) ship position and water depth when core was taken.
2) only 15 cm penetration.
3) insufficient penetration due to hard bottom.
4) sediment rinsed out, probably due to very soft sediment.

CTD-rosette sampler.—11 Niskin bottles of 30 liter water content were mounted on a Rosette sampler. The CTD from the swiss team was equipped with a nephelometer and with an altitude sonar to measure height above the sea floor. The swiss team took samples for their study of the particulate material in the Benthic Nepheloid Layer (BNL) by Coulter counter methods and by EDAX analysis after filtration. Filtered samples were shipped to Dr V. Noshkin (Lawrence Livermore Laboratory, U.S.A.) for $^{239+240}Pu$ analysis. Nutrient and oxygen analyses were performed by NIOZ with standard techniques.

Boxcorer.—Undisturbed bottom samples with a surface area of 0.25 m^2 and 20 to 30 cm deep were obtained with a Mark III boxcorer. Up to 20 subsamples for chemical and

(micro)biological analyses were taken and the remaining sediment was sieved for the study of macrofauna. Boxcores are denoted by B.

Boxcorer, gravity corer and trawl were operated with a 16 mm synthetic (Kevlar) wire. As this material has negligible underwater weight, the bottom contact of the corers could be observed very easily from the wire tension, and the use of a pinger was not necessary.

Gravity corer.—Cores up to 3 m in length were obtained with a 125 mm diameter gravity corer. Gravity cores are denoted by G.

Trawl.—Macrofauna from the deep sea bottom was sampled with a 3.5 and a 5 m Agassiz trawl. The sampled trajectory was approximately 10 km long and real fishing time was 2 to 3 hours. The use of a light weight synthetic wire may have resulted in a poor bottom contact.

Primary production.—Primary production was measured three times with the ^{14}C incubation technique from dawn to noon.

4. GEOCHEMISTRY

4.1. INTRODUCTION

The sorption characteristics of marine sediments and diffusion within sediments of a variety of radionuclides has been studied extensively by Duursma (Duursma & Bosch, 1970; Duursma & Gross, 1971; Duursma, 1973; Duursma & Eisma, 1973). The concept of distribution coefficients (symbol K_d) is very useful in predicting the scavenging of radionuclides from the water column by sediment particles (Duursma & Gross, 1971). It has to be born in mind, however, that K_d values are no physical constants, but are related to sorption equilibria which can be highly dependent on chemical speciation of the radionuclides, the surface condition of the sediment particle, and the redox chemical state of the medium. These conditions are subject to changes as a result of diagenetic reactions in the sediment. Our understanding of diagenesis has improved substantially from studies of marine sedimentary pore waters (Hartmann *et al.*, 1976; Manheim, 1976; Suess, 1976; Froelich *et al.*, 1979; Berner, 1980; Sayles, 1979 and 1981). The complex of reactions involved in $CaCO_3$ dissolution and early diagenesis of organic material, accompanied with many remobilization and precipitation reactions (Bonatti *et al.*, 1971; Manheim & Sayles, 1974; Berner, 1980), reduces in marine sediments the applicability of the concept of constant distribution coefficients (Duursma & Gross, 1971; Nelson & Lovett, 1980; Sholkovitz *et al.*, 1982).

The geochemical study deals with those characteristics of the sediment at the NEA dumpsite that affect sorption of radionuclides and their subsequent redistribution within the sediment. These characteristics include elemental and mineralogical composition of the sediment, composition of the pore water, distribution equlibria of elements between sediment and pore water, physical-chemical state of the sediment (pH, Eh) and all parameters that can elucidate the role of bioturbation.

Boxcores (50 x 50 cm) boxcores were subsampled on deck with PVC tubes.

A rectangular subcore, 4 x 7 cm in cross-section, was cut in two 2-cm thick vertical slices for immediate X-ray and colour photography.

A 6 cm diameter subcore was sectioned and used for measurement of Electron Transport System (ETS) activity according to OLANCZUK-NEYMAN & VOSJAN (1977).

Two 7 cm diameter subcores were immediately frozen for later sectioning and analysis for ^{210}Pb and $^{239+240}Pu$ profiles.

One subcore (3 cm diameter) was stored frozen, sectioned upon thawing in the laboratory and analyzed for organic carbon by wet oxidation (MENZEL & VACCARO, 1964).

Two subcores were transported to a refrigerated laboratory-container for temperature equilibration at seafloor temperature (2 °C).

1) One 6 cm diameter subcore with polyethylene liner was opened in a nitrogen-filled glove bag for measurements of pH and Eh by directly introducing electrodes into the sediment, and of dissolved oxygen by flushing the electrode of a Radiometer blood gas analyser with wet sediment from a plastic syringe.

2) The second subcore, 12 cm in diameter, was extruded, sectioned and squeezed through 0.2 μm cellulose nitrate filters in squeezers with all-teflon inner parts. Nitrogen pressure up to 5 atm was applied on a rubber diaphragm covered with parafilm. No precautions were taken to exclude contact with atmospheric oxygen since oxygen had been shown to be present throughout all boxcores. The teflon inner parts, teflon filter supports, filters and polyethylene sample bottles used for trace metal analyses had all been thoroughly rinsed in 6 $mol \cdot l^{-1}$ hydrochloric acid and double distilled water before use.

Gravity cores were cut in 1 m lengths. These were cut in half and transferred to the refrigerated container. One half was photographed, sealed in plastic and stored at 4 °C for reference. The other half was analysed for pH and O_2 as described above. Sediment from selected depth horizons was transferred to squeezers inside a nitrogen filled glove bag and squeezed as described above. In some occasions the pressure was increased to 35 atm. Further treatment and analyses were identical to the ones described for boxcore samples.

Pore water analyses.—Samples for trace metal analyses were acidified with 1 $ml \cdot l^{-1}$ of 6 $mol \cdot l^{-1}$ HCl suprapur and stored at 4 °C. Mn was determined in the laboratory by Atomic Absorption Spectrometry using direct injection in the graphite furnace.

A 10 ml aliquot was used for nutrient analyses following HELDER & DE VRIES (1979) for ammonia and standard autoanalyzer techniques for the other nutrients. Silicate was determined within 24 hours on board ship. The samples for nitrate, nitrite, phosphate, ammonia and urea analyses were stored frozen and analyzed within one month.

Alkalinity was determined on board ship by potentiometric titration of a 10 ml aliquot filling a narrow mouth polytethylene bottle covered with parafilm. 1 $mol \cdot l^{-1}$ hydrochloric acid was added from a microburette and alkalinity was evaluated according to JOHANSSON & WEDBORG (1982).

Sediment analyses.—Squeezed sediment cakes were devided in two parts and sealed in polyethylene bags. One half was stored at 4 °C and used for analyses of

-Mineralogy. Carbonate was dissolved in an acetate buffer at pH >4.8. The bulk of the remaining fraction as well as an oriented sample of the size fraction <2 μm of it, were analysed with X-ray diffraction after saturation with Ca from calcium acetate.

-^{14}C-age of carbonate-carbon at the isotope physics laboratory, Groningen.

The other half of the sediment cake was stored frozen, lyophillized, homogenized and analysed for:

-The elements Na, K, Sc, Cr, Fe, Co, As, Br, Rb, Cs, La, Ce, Nd, Sm, Eu, Yb, Lu, Hf, and Th by neutron activation analysis at the Energy Research Foundation, Petten.

-The major elements Ca, Mg, Si, Al, Fe, Mn, Ti, K, and Na by X-ray fluorescence.

-Cation Exchange Capacity (CEC) by saturating 500 mg on a membrane filter with 1 mol·l^{-1} sodium acetate, rinsing with ethanol (96%), eluating with 1 mol·l^{-1} ammonium acetate and measuring Na in the eluate with Atomic Absorption Spectroscopy.

-Ca by dissolution of carbonates in 1 mol·l^{-1} HCl and titration with EGTA.

-Ca, Mg, Sr, Fe, Mn, Cu, Zn with Atomic Absorption Spectroscopy after a selective extraction procedure distinguishing the fractions:

1) easily leachable (exchangeable with a solution containing 1 mol·l^{-1} ammonium acetate and 1 mol·l^{-1} magnesium acetate).

2) carbonate-bound (soluble in acetate buffer at pH 4.8).

3) reducible (with hydroxyl ammonium chloride after 2).

4) soluble (in 1 mol·l^{-1} hydrochloric acid).

Since a consequent discrimination between fractions 2 and 3 turned out to be impossible, these fractions were summed.

4.3. RECENT SEDIMENTOLOGICAL HISTORY

The available published data on the sedimentary environment of the NEA dumpsite has been summarized by KIDD (1983). From the limited data available from sections in the hill areas, this author concluded that erosion or redeposition of sediment at these locations must be assumed to be minor, at least, not in the form of submarine slides or slumps. Any data about the occurrence of such processes in the trough area in the W part of the dumpsite was however lacking.

We have obtained box cores and 3 m gravity cores from both the hill area and the trough area. All 3 gravity cores show disturbed sedimentary records.

Fig. 6 shows $CaCO_3$ content, the abundance of planktonic Foraminifera and ^{14}C datings of core 11G (*i.e.* gravity core taken at station 11) taken in the valley in the western part of the site. Beds that appeared as dense layers on X-radiographs are also indicated. These beds were associated with inversed ^{14}C ages, and can probably be related to lateral transport (see also 4.4). From ^{14}C data in undisturbed beds an average sediment accumulation rate is estimated of about 7 cm·kyr^{-1} during the late Pleistocene (30-10 kyr BP). Holocene sediment accumulation rates are only 1 to 2 cm·kyr^{-1} (KERSHAW, personal communication).

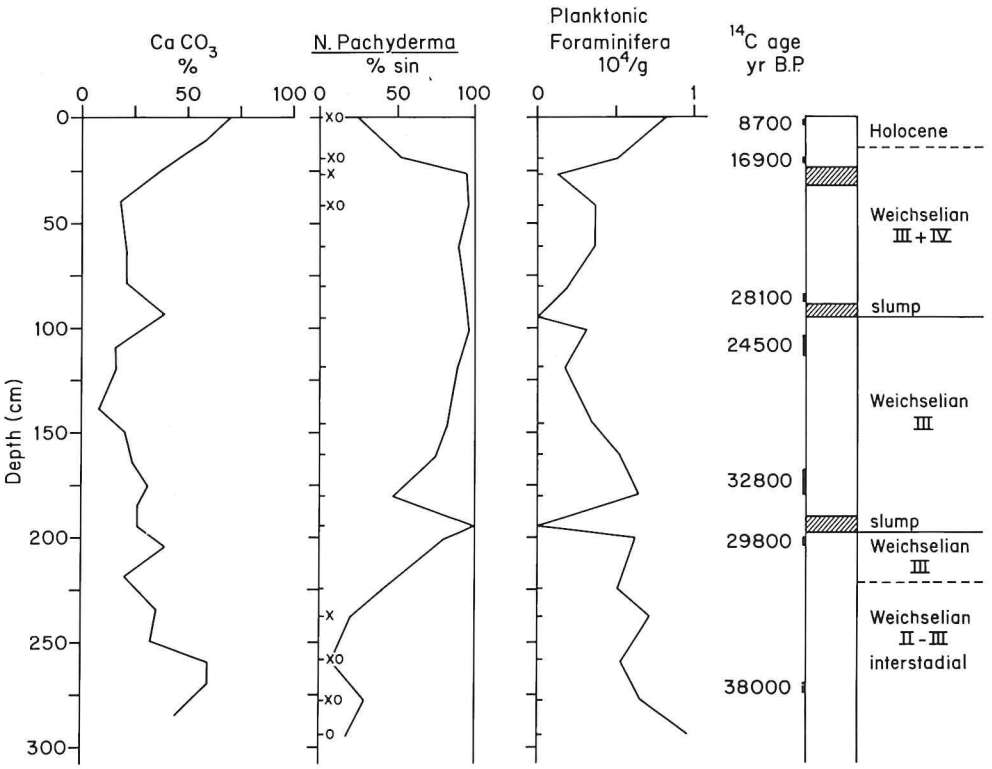


Fig.6. Sedimentological data of core 11G: Carbonate content, percentage of left turned specimens among *Neogloboquadrina pachyderma* and occurrence of *Globorotalia hirsuta* (x) and *G. truncatulinoides* (0), number of planktonic Foraminifera per gram of sediment, carbonate ^{14}C ages and the inferred stratigraphy.

Cores 8G (of which the top was lost) and 15G contained several turbiditic deposits or slumped beds, as evidenced by data in Figs 7 and 8. X-radiographs (Fig. 9) revealed the layered structure of these beds.

Core 5G (Fig. 8) was taken at a topographic high of 4000 m in the valley between two seamounts. The position of cores 15G and 15B is indicated in Fig 10 on a map of the Finn seamount area (Dickson, 1983). The slides of which evidence was found in core 15G may have been derived from the steep hillsides of the neighbouring seamounts. A 25% slope was preserved in boxcore 15B.

Core 8G (Fig. 7) was taken in the deep valley in the W part of the site, and the slides may have been derived from the hillsides nearby. The most evident slump or turbidite was found here at a depth of 173 cm in the core. At this depth, a recent sediment surface (^{14}C age 11-14 cm below the interface is 7500 yr) was covered by older sediment containing material with a ^{14}C age of 31 kyr and a bed of coarse grained sediment with anomalous elemental and mineralogical composition (see section 4.4). The composition

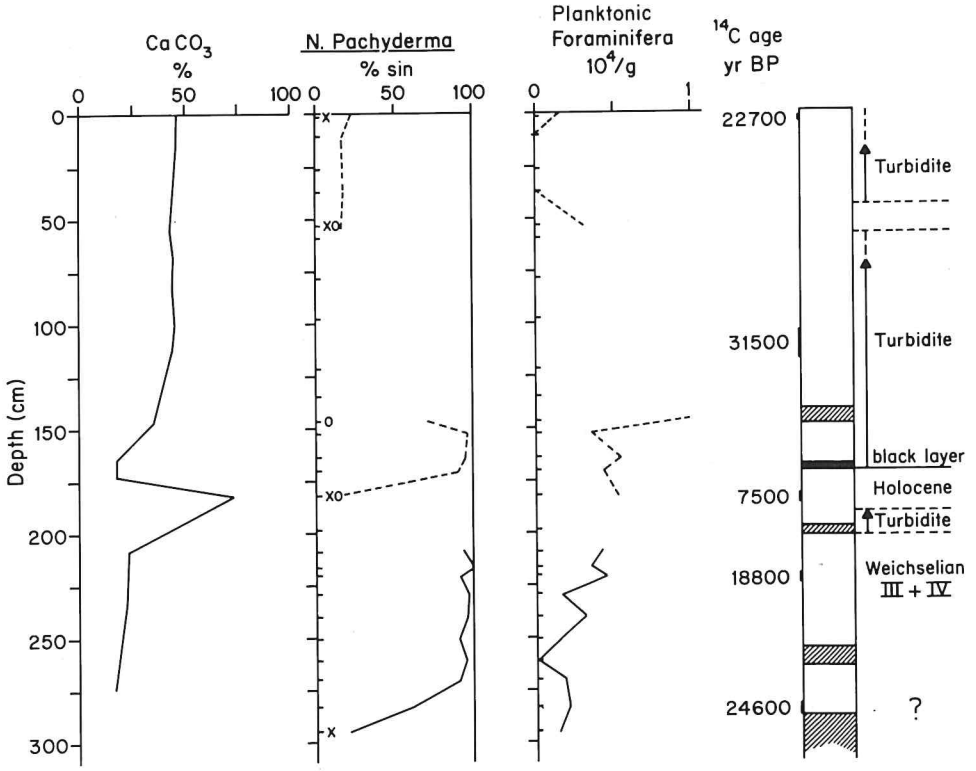


Fig.7. Sedimentological data of core 8G. For explanations see fig. 6.

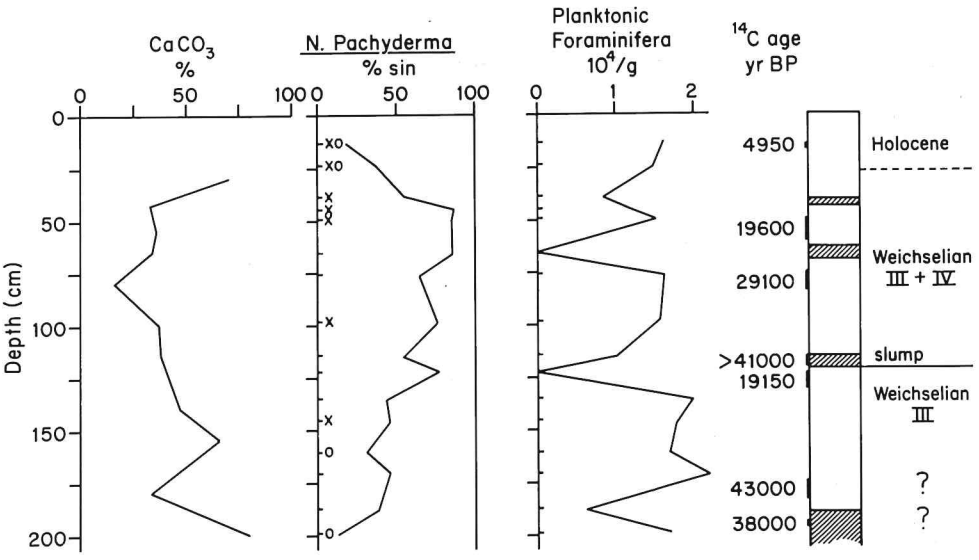


Fig.8. Sedimentological data of core 15G. For explanations see fig. 6.

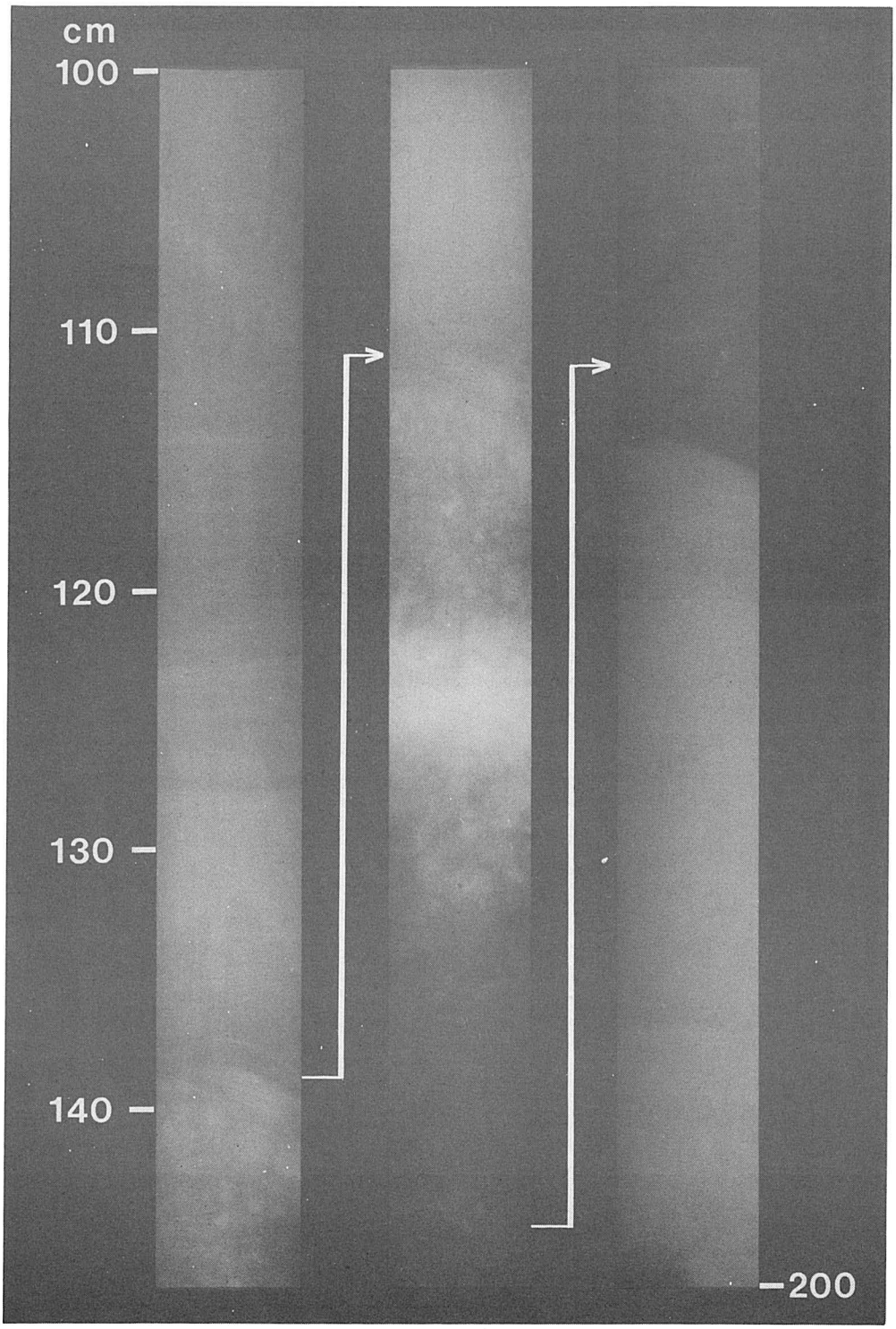

cm
100
110
120
130
140
200

Fig.9. X-radiograph of the 100 to 200 cm section of core 8G, showing layered structure.

of benthic Foraminifera found in this turbiditic deposit (X-radiograph: Fig. 9) was not different from the one found in core tops in the area, suggesting a local origin of the material.

WEAVER & SCHULTHEISS (1983b) showed that gravity cores may repenetrate the sediment and thus resample the sediment surface. This explanation for the occurrence of recent material below the slumped bed is unlikely because no sudden decrease in wire tension was observed after the extraction of the corer from the sea bottom. Moreover, the black colour of the interface indicates at reducing conditions, a usual phenomenon when fresh organic material is covered by a slump or turbidite. The coincidence that a repenetration would have occurred just below such an interface appears quite unlikely.

The high nitrate concentration in the pore water of the buried layer, relative to the layers above and below (Fig. 11) indicates that the turbidite occurred even more recently.

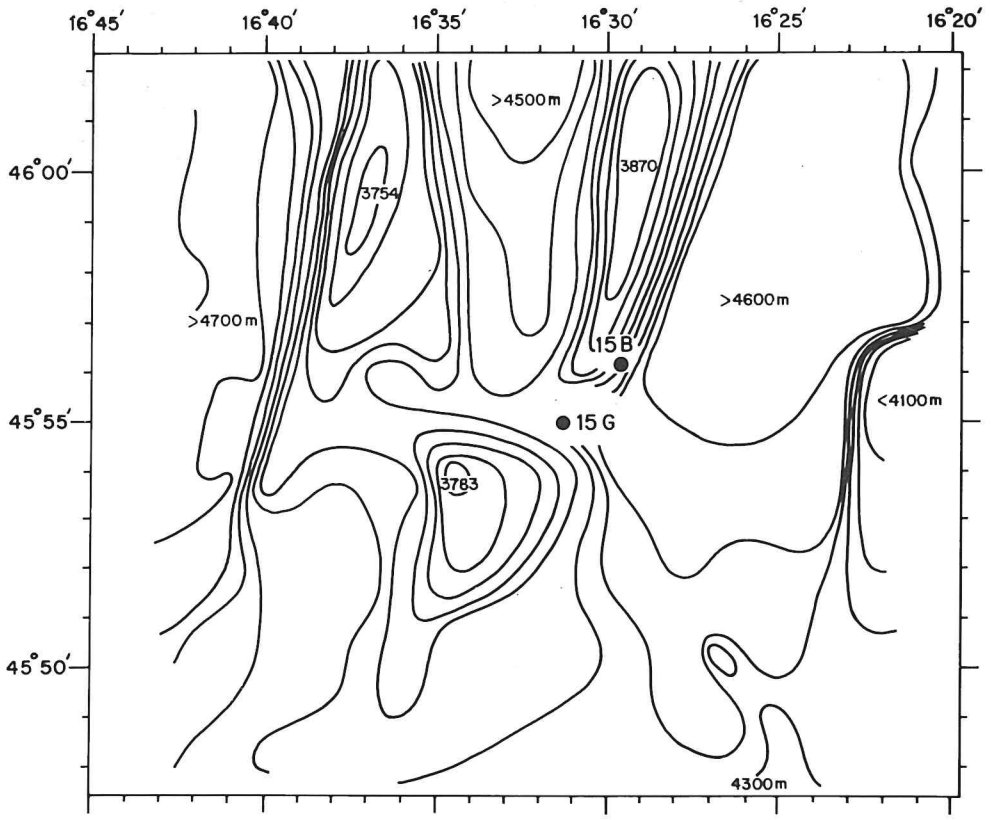


Fig. 10. Map of the area around Finn seamount (from DICKSON, 1983) with locations of cores 15B and 15G.

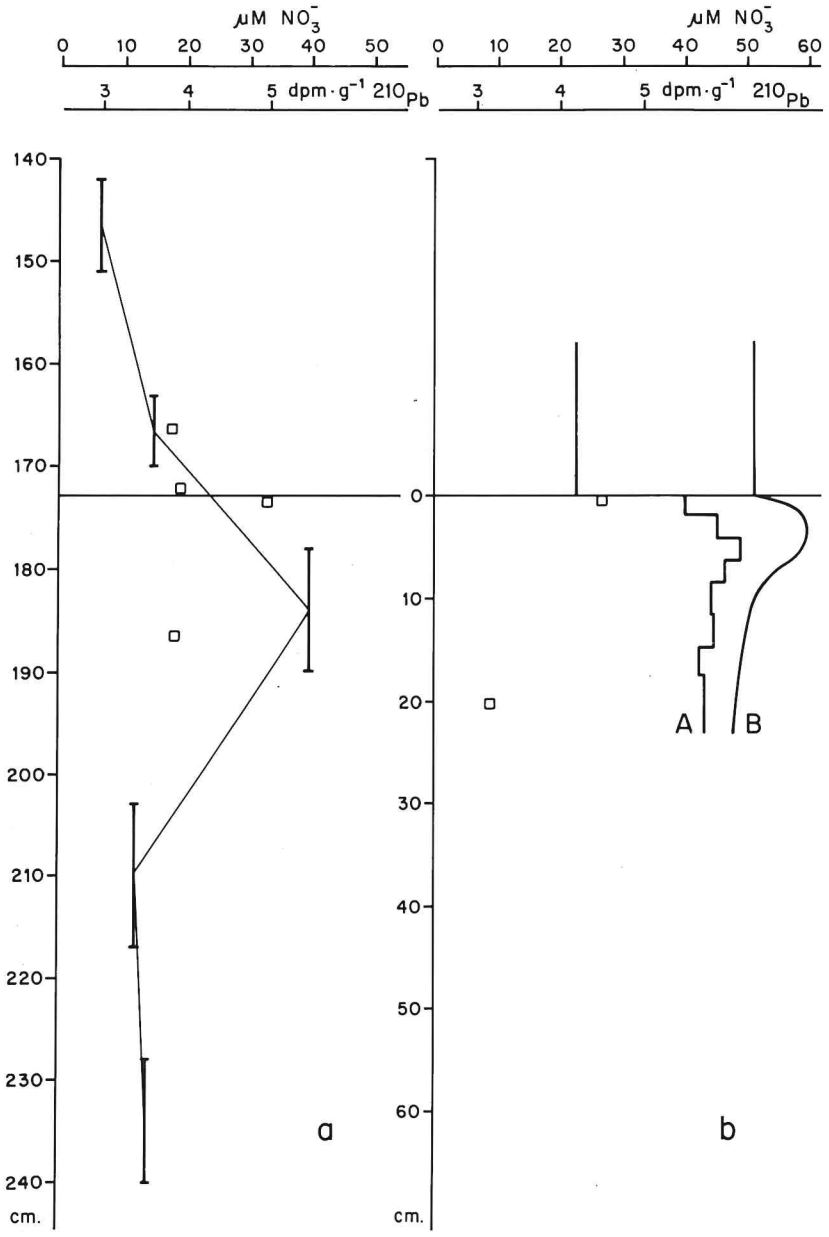


Fig. 11. a. Interstitial nitrate (vertical bars) and ^{210}Pb activity (open squares) around the buried interface in core 8G, b. interstitial nitrate (curve A) and potential nitrate (curve B, including nitrate produced by oxic mineralization) and ^{210}Pb activity (open squares) in nearby boxcore 8B.

Even though the actual NO_3^- gradient in and around the layer is poorly known, the mere existence of the nitrate maximum allows some interesting conclusions to be made. Nitrate reduction has apparently caused a decrease in NO_3^- above and below the buried top layer of about 25 cm. A minimum estimate of the upward and downward diffusive fluxes from this layer, obtained by assuming a linear gradient between sampling intervals, is 3.6 and 2.8 $10^{-15} \cdot mol \cdot cm^{-2} \cdot s^{-1}$, respectively (porosity = 0.75; $D_s(NO_3^-)$ = 3.5 $10^{-6} \cdot cm^2 \cdot s^{-1}$). The amount of nitrate initially present in the buried top 25 cm can be estimated as 1.0 $10^{-6} \cdot mol.cm^{-2}$ from the nitrate profile in the top sediment of a boxcore taken nearby (Fig. 11b, curve A), augmented by the nitrate resulting from oxidation of organic matter with buried oxygen (16/138 times the O_2 inventory in the same boxcore) (Fig. 11b, curve B). Diffusion along the gradients in Fig. 11a transports away this nitrate at a rate that would cause the concentration to fall below the observed value within a few years.

Additional evidence for the recent date of this slump comes from ^{210}Pb data , showing that some ^{210}Pb (halflife 22.3 yr) is left at the buried sediment surface. A calculation of excess ^{210}Pb is not possible for lack of data on the ^{226}Ra background of the samples.

The nitrate and ^{210}Pb data indicate that the slump must have occurred during the past few years and may have been triggered by a dumping operation.

4.4. ELEMENTAL AND MINERALOGICAL COMPOSITION OF THE SEDIMENT

Remains of Foraminifera and Coccoliths (mainly calcite) make up the bulk of the sediment. The X-ray diffraction patterns of the fine fractions ($< 2\ \mu m$) of the non-carbonate fraction of 32 samples taken from boxcores as well as from several meters depth in gravity cores, show a very constant composition of the clay minerals smectite, illite, chlorite and kaolinite. The bulk non-carbonate phase consisted of relatively constant amounts of the same minerals and feldspar and amorphous silica. The only exception was a coarse-grained bed in the turbidite of core 8G (143-155 cm, Fig. 7), which had low smectite content but high contents of quartz, feldspar, dolomite, vermiculite and amphibole. This material also had an anomalous trace element composition and cation exchange capacity (see below). Similar beds showed up on X-radiographs of all 3 gravity cores (Figs 6-8). They contain probably ice-rafted material, sorted by slumps.

Table 2
Major element composition of carbonate-free material, circulated by extrapolation to 0% $CaCO_3$, and expressed as their oxides.

SiO_2	56.6 %
Al_2O_3	17.0 %
Fe_2O_3	7.4 %
MgO	3.5 %
K_2O	3.9 %
Na_2O	0.8 %
TiO_2	0.8 %

The elemental composition of the sediment has been determined by EGTA titration (Ca) and Atomic Absorption Spectroscopy (Sr) of the HCl extract and by neutron activation (NA) and X-ray fluorescence (XRF) of bulk samples. $CaCO_3$ content of the sediment varies between 82% and 88% at the sediment surface down to 8% in an about 28 kyr old layer (140 cm, core 11G). HCl-extractable Sr covaries with Ca (Sr/Ca = 2.10^{-3}, atomic ratio). Most elements, however, are positively correlated with the non-

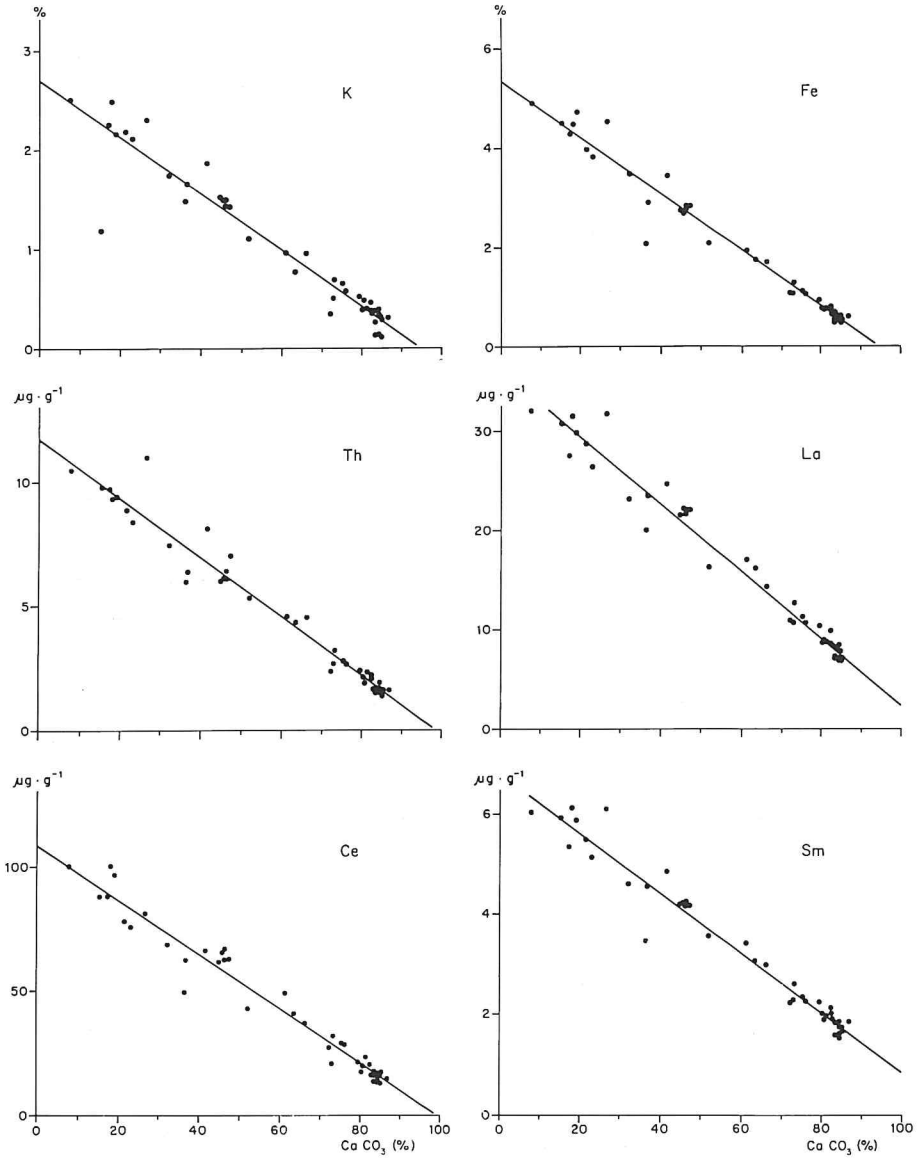


Fig.12. Contents of K, Fe, Th, La, Ce and Sm as a function of $CaCO_3$ content of 44 sediment samples.

carbonate fraction. From the correlation of Ca content with the results of XRF analyses for other major elements in 28 samples, the major element composition of the carbonate-free material can be calculated by extrapolation (Table 2). The major element oxides in this table add to 90%. Weight loss on ignition accounts for the remaining 10%.

Fig. 12 shows the relation with $CaCO_3$ of K, Fe, Th and of the rare earth elements La, Ce and Sm in 44 sediment samples, analysed with neutron activation analysis. These samples are taken from 9 cores distributed over the dumping area and vary in sediment depth from 0-1.5 cm (surface) to 215 cm. A list of correlations of various elements with $CaCO_3$ content is given in Table 3. Fe and K have been analysed both by XRF and by NA. NA results for K were somewhat lower than the XRF data, while Fe results were in good agreement.The sample from the coarse-grained layer in the turbidite from core 8G deviates from all linear correlations: the coarse admixture has low smectite and trace element contents and low cation exchange capacity. The linear relations shown in Table 3 suggest a conservative mixing of carbonate and non-carbonate fractions. The extrapolations of the relations to 100% $CaCO_3$ show that the carbonate fraction contains amounts of rare earth elements in reasonable agreement with analyses of limestone depostits by PAREKH *et al.* (1977). The negative values for the usually conservative elements K, Sc, Fe, Th might indicate a systematic error in the Ca analyses of 1-2%. This can however not explain the low value for Hf.

A plot of boxcore-top carbonate contents as a function of water depth (Fig. 13) shows that the lysocline is situated at a depth of about 4700 m at present. In the NE Atlantic, the position of the lysocline is determined by the pressure term in the carbonate equilibrium, unlike in the W Atlantic, where the lysocline coincides with the transition

Table 3

Linear correlation coefficients of various elements and $CaCO_3$ in 44 sediment samples and estimates (± standard errors) of the contents in the non-carbonate and in the carbonate phase.

element	r^2	extrapolated concentration at 0% $CaCO_3$	extrapolated concentration at 100% $CaCO_3$
K	0.921	2.70 ± 0.09 %	-0.15 ± 0.06 %
Sc	0.970	15.7 ± 0.3 PPM	-0.5 ± 0.2 PPM
Cr	0.968	96.1 ± 1.9 PPM	-6.2 ± 1.4 PPM
Fe	0.968	5.34 ± 0.10 %	-0.30 ± 0.08 %
Co	0.819	22.9 ± 1.0 PPM	2.5 ± 0.7 PPM
La	0.963	36.2 ± 0.7 PPM	2.3 ± 0.5 PPM
Ce	0.964	108.4 ± 2.2 PPM	-1.1 ± 1.6 PPM
Sm	0.964	6.8 ± 0.1 PPM	0.8 ± 0.1 PPM
Eu	0.840	1.90 ± 0.08 PPM	0.15 ± 0.06 PPM
Yb	0.873	2.34 ± 0.09 PPM	0.08 ± 0.07 PPM
Lu	0.867	0.41 ± 0.02 PPM	0.04 ± 0.01 PPM
Hf	0.930	5.3 ± 0.2 PPM	-0.6 ± 0.1 PPM
Th	0.964	11.8 ± 0.3 PPM	-0.2 ± 0.2 PPM

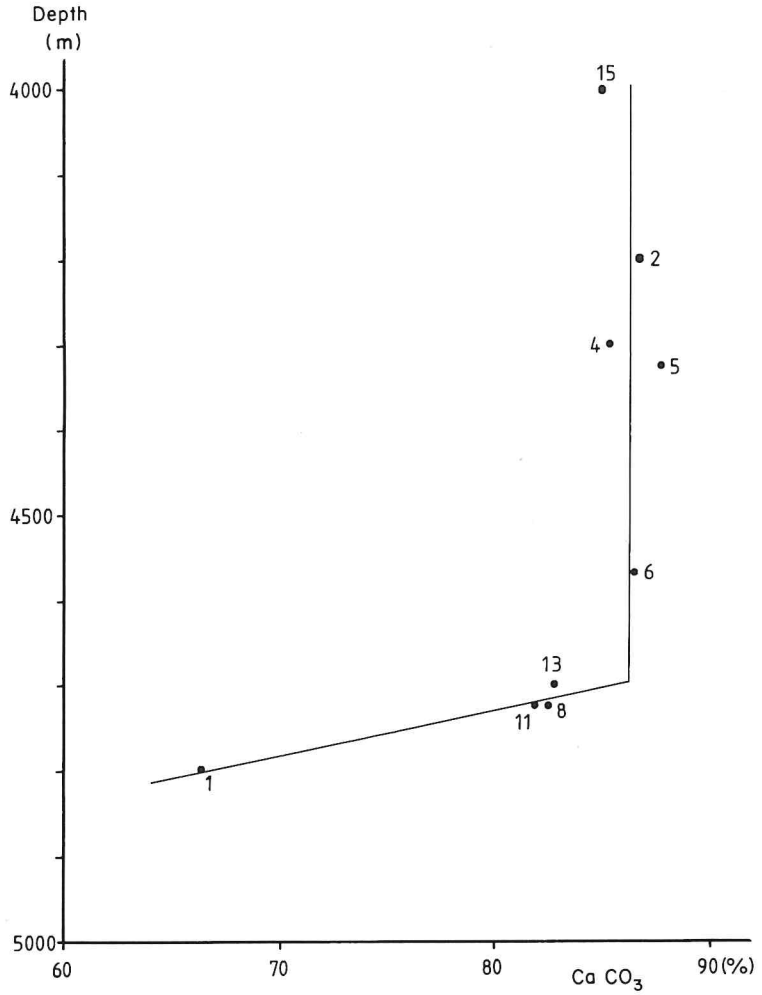


Fig. 13. Boxcore-top calcium carbonate content as a function of water depth. Station numbers are indicated.

between North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) (THUNELL, 1982).

From a bathymetric map of the dumping area (Fig. 2) and Fig. 13, a map could thus be constructed showing the distribution of $CaCO_3$ in surface sediments (Fig. 14). This same map can be used to show the distribution of other elements in surface sediments, using the correlations with $CaCO_3$ in Fig. 12 and in Table 3.

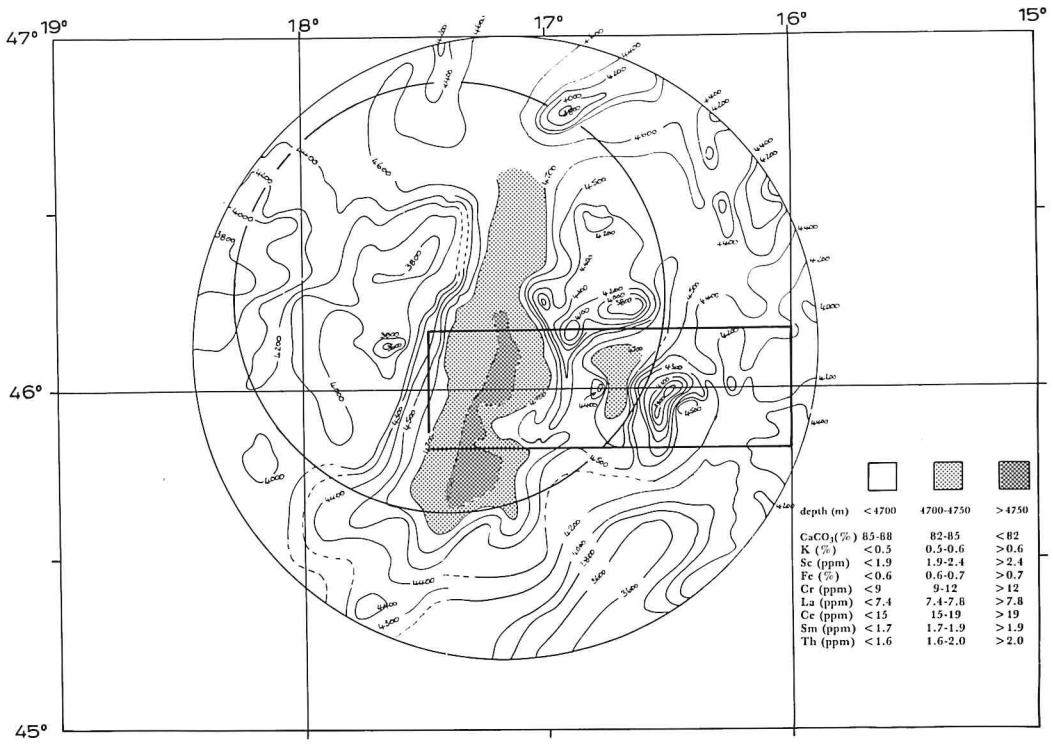


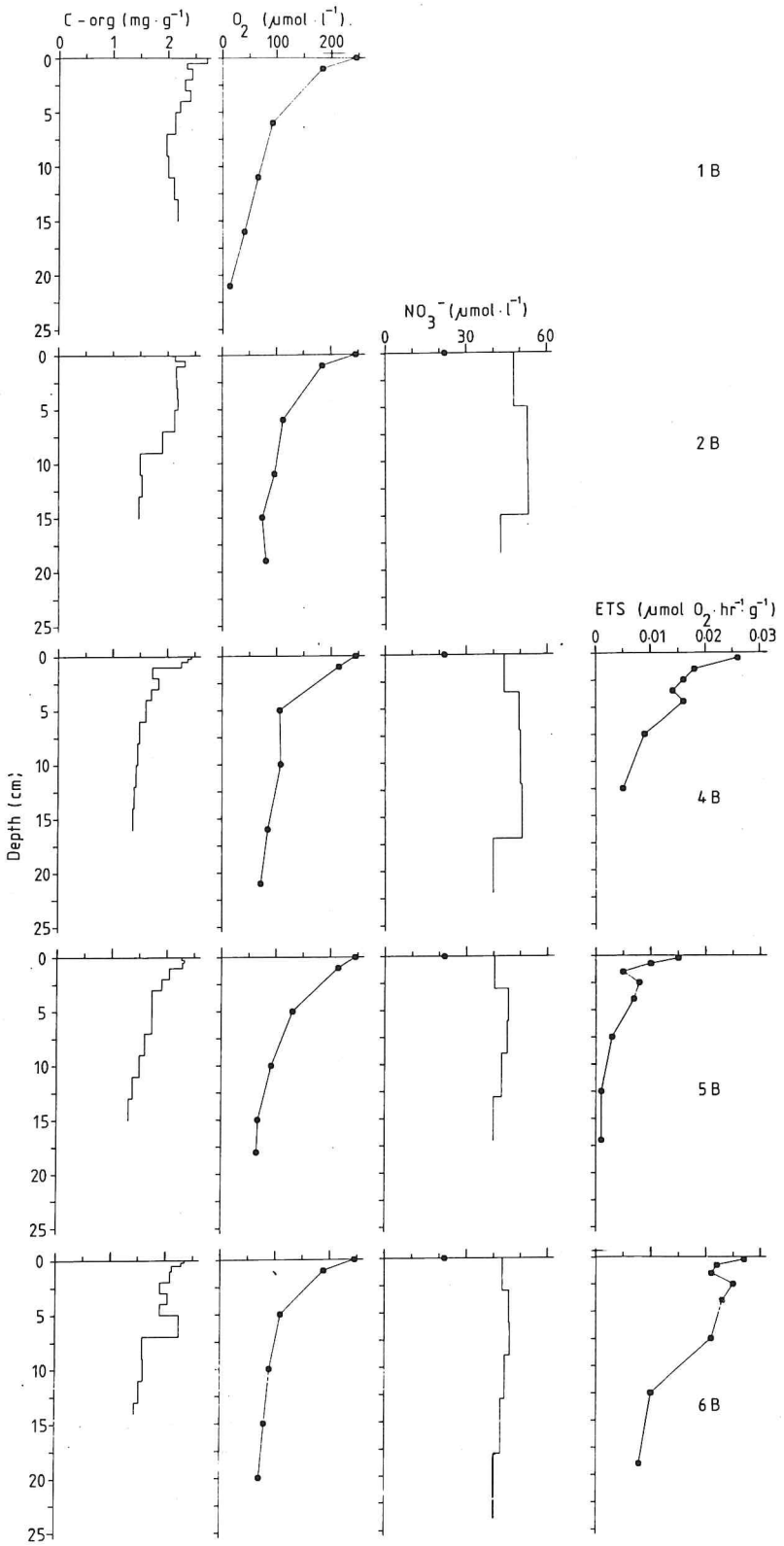
Fig. 14. Distribution in surface sediments of the dumping area of $CaCO_3$ and of some elements that are well correlated with carbonate content.

4.5. EARLY DIAGENETIC REACTIONS IN THE SEDIMENT

Sediment particles settling on the ocean floor can be assumed to be in equilibrium with bottom water. In this section we will discuss the diagenetic reactions in the upper few meters of the sediment that will influence these equilibria and thus can cause a redistribution and transport of trace elements and radionuclides.

4.5.1. MINERALIZATION OF ORGANIC MATTER

Organic matter settles continuously on the sediment surface. It is transported downward by bioturbation and as a result of burial by new deposition. As a result of mineralization, the content of organic carbon in the sediment declines from about 2.8 $mg \cdot g^{-1}$ at the surface to about 1.5 $mg \cdot g^{-1}$ at 20 cm depth (Fig. 15). The relative decrease is even more apparent if expressed on a carbonate free basis. The water content decreases from 56 weight % at the surface to 46% at 20 cm depth, corresponding to a decrease in porosity from 0.78 to 0.70 (assuming a specific mass of 2.65 for the solid phase). The decrease


C - org (mg · g⁻¹)
0
1
2
O2 (µmol · l⁻¹)
0
100
200
NO3⁻ (µmol · l⁻¹)
0
30
60
ETS (µmol O2 · hr⁻¹ · g⁻¹)
0
0.01
0.02
0.03
Depth (cm)
0
5
10
15
20
25
1 B
2 B
4 B
5 B
6 B

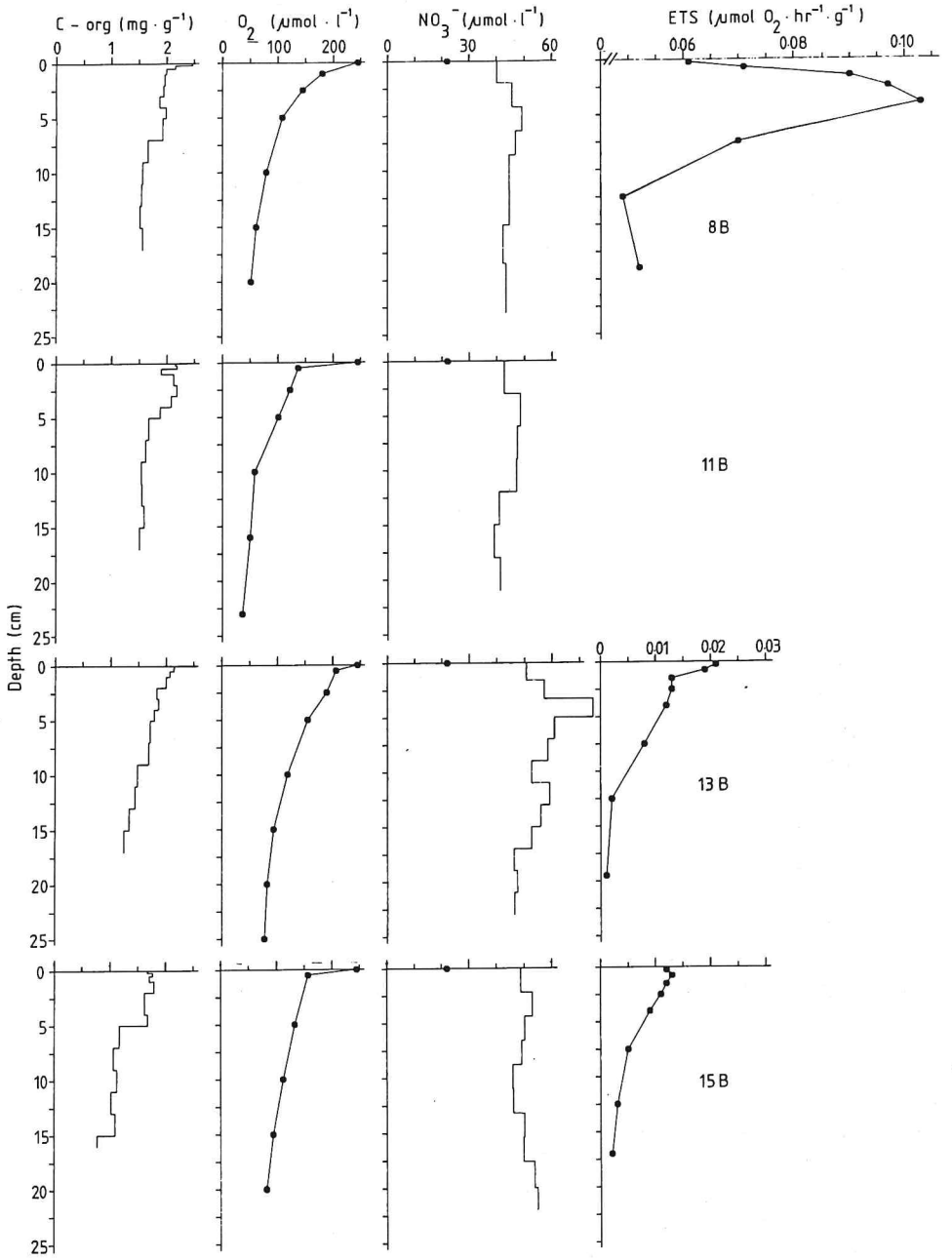


Fig.15. Depth distribution in boxcores of organic carbon in the sediment, of oxygen and of nitrate in the pore water and of ETS activity in the sediment.

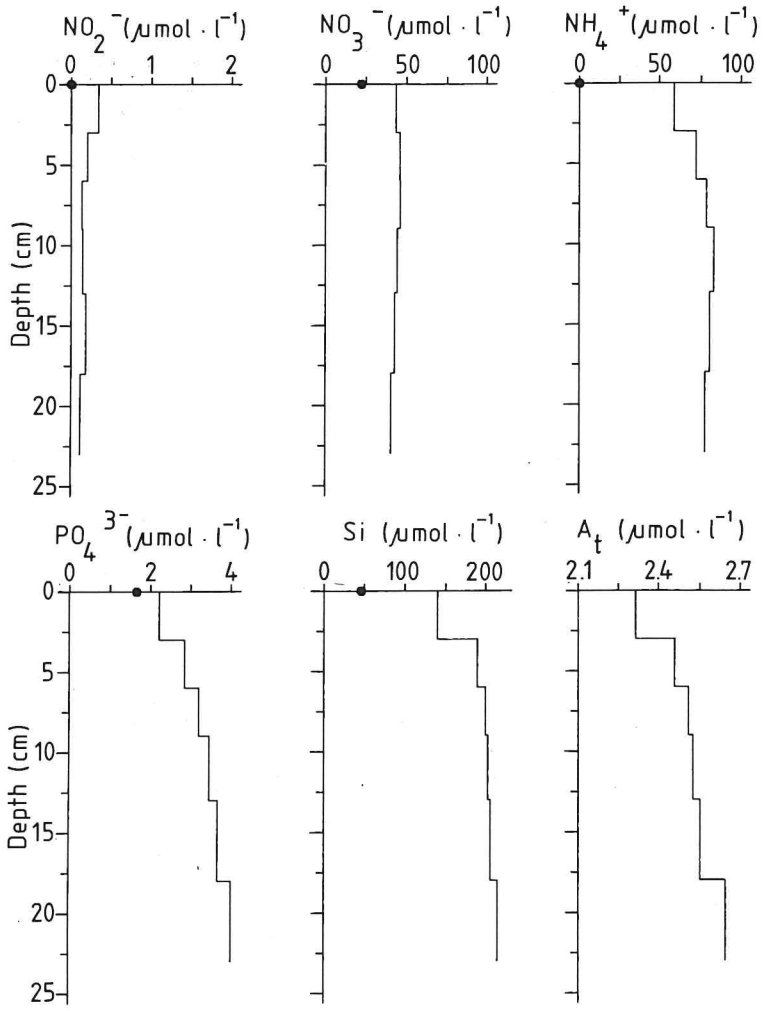


Fig. 16a. Depth distribution of nutrients and alkalinity in the pore water of boxcore 6B. Closed circles represent bottom water values.

in organic carbon content with depth is associated with an increase with depth in the concentrations of nutrient elements and alkalinity in the pore water (Fig. 16).

The depth distribution of potential Electron Transport System (ETS) activity (Fig. 15) shows that mineralization activity is highest in the upper few cm, in accordance with the carbon and oxygen data. The subsurface maximum in organic carbon content and ETS activity observed in many boxcores at a depth of 2 to 6 cm is discussed in section 6 (bioturbation).

The mobilization of elements that are constituent of or bound to organic material, is inherent to the process of mineralization. The release of nutrients was shown above.

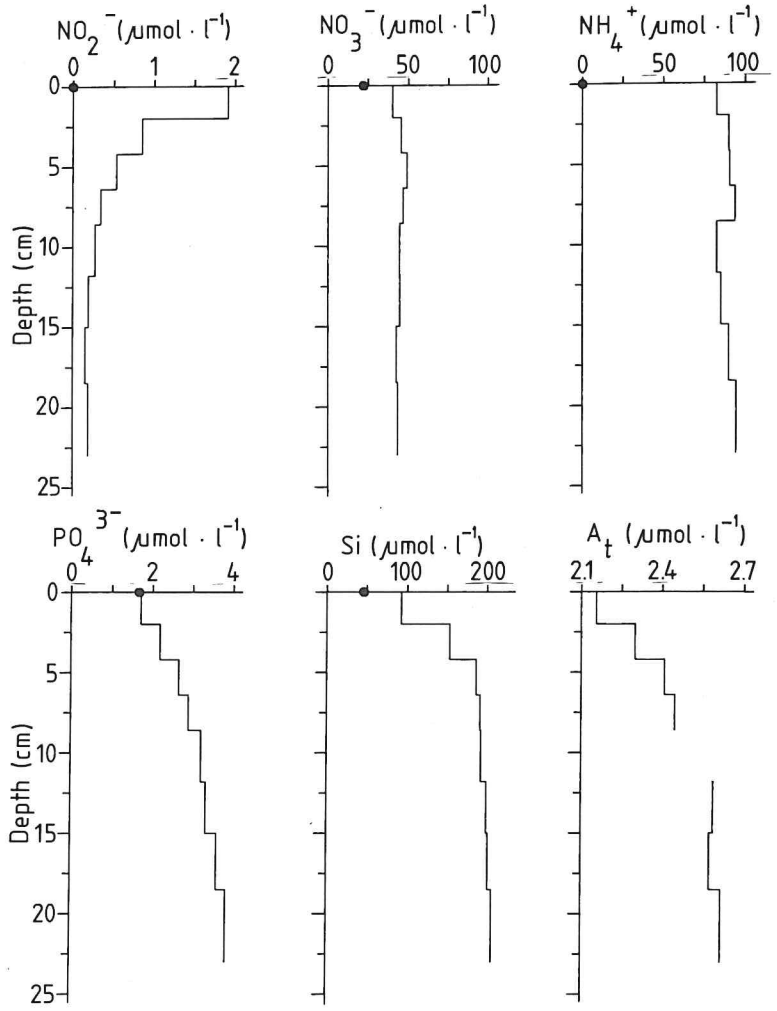


Fig. 16b. Depth distribution of nutrients and alkalinity in the pore water of boxcore 8B. Closed circles represent bottom water values.

Other elements released in this process are Ni, Cd (KLINKHAMMER *et al.*, 1982), Cu (KLINKHAMMER, 1980) and I (ULLMAN & ALLER, 1980), while a nutrient-related behaviour in sea water has been reported for many other elements (reviewed by QUINBY-HUNT & TUREKIAN, 1983). Since a large part of the mineralization takes place at the sediment surface, release rates of these elements can only partly be calculated from pore water gradients.

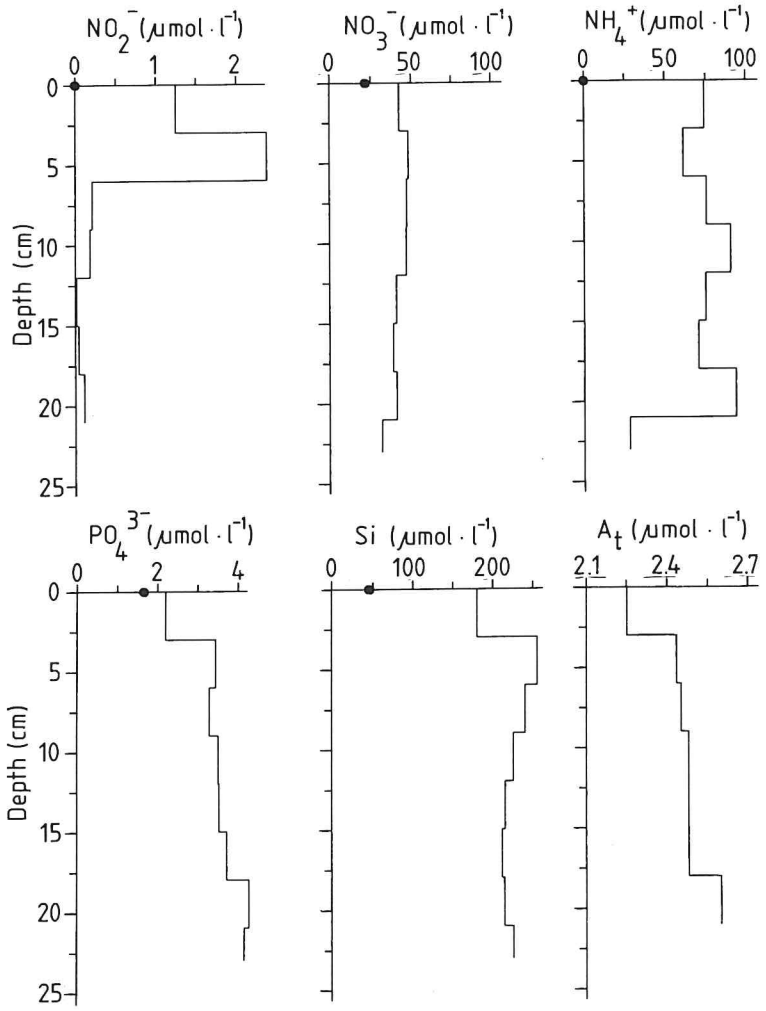


Fig. 16c. Depth distribution of nutrients and alkalinity in the pore water of boxcore 11B. Closed circles represent bottom water values. In this core a vertical burrow was found at 6 cm depth during sectioning of the core. Bioturbation may have caused the anomalous profiles.

4.5.2. CATION EXCHANGE

The cation exchange capacity is correlated with the non-carbonate fraction as could be expected:

$$CEC\ (mmol \cdot 100\ g^{-1}) = 29.3 \times (1\text{-}[CaCO_3]) + 1.0$$

(r^2 = 0.86; n = 32). When ammonia concentrations are built up in the pore water as a result of mineralization, ammonia will replace other cations from exchange sites leading to a remobilization of cations like K (HARTMANN *et al.*, 1976) and the same can be expected for Cs. In the aerobic sediment, ammonia is oxidized to nitrate, as evidenced by the increase of NO_3^- above bottom water values (Fig. 15), but still ammonia reaches 75-100 $\mu mol \cdot l^{-1}$ in this layer. In the anaerobic layer, cation exchange continues when ammonia levels increase further.

4.5.3. REDOX CONDITIONS IN THE SEDIMENT

The consumption of electron acceptors for the mineralization of organic matter leads to a reduction of redox potential (Eh) with sediment depth. Redox conditions have a profound influence on distribution coefficients and transport of trace elements within the sediment. Because of problems in the quantitative interpretation of Eh readings with platinum electrodes (BRECK, 1974; WHITFIELD, 1974; VERSHININ & ROZANOV, 1982), the redox state of the sediment should preferably be studied by analyses of the concentrations of redox species involved. In deep sea sediments poor in organic matter, like the sediments at the dumpsite, the zones of O_2, Mn, NO_3^- and Fe reduction are distributed over a relatively wide depth range, and the successive depletion of these electron acceptors can be studied in detail (FROELICH *et al.*, 1979; MURRAY & GRUNDMANIS, 1980).

Dissolved oxygen measurements in sediments from the dumpsite show that oxygen declines most rapidly in the upper 5 cm, followed by a more gradual decrease (Fig. 15), in agreement with the ETS activity measurements. The depth of oxygen depletion varied from 25 cm in core 1B (4800 m, outside the dumping area) to over 2 m in core 15G. The colour of the sediment in the layer just above this depth in core 1B suggests that pockets of oxygenated and oxygen-free sediment coexist here, which may cause a redistribution of trace elements between these phases (HARTMANN, 1979).

The succession of oxygen reduction by manganese reduction is clearly seen in core 11G at 1 m depth: Below 1 m, manganese is reduced and dissolves. The increase of the Mn^{++} concentration in the pore water of the reduced zone (Fig. 17) is limited by $MnCO_3$ precipitation (HOLDREN *et al.*, 1975; BALZER, 1982) or, in calcareous sediments, rather by the formation of a mixed Ca/Mn carbonate on the surface of Foraminifera tests (BOYLE, 1983). The upward diffusion of manganese and its subsequent oxidation causes an accumulation of Mn in the sediment at the bottom of the aerobic zone (Fig. 17), like described by FROELICH *et al.* (1979). This process prevents or retards the burial of Mn. Since many trace elements (like Cu, Ni, Co, Zn) are associated with the manganese oxide phase (CALVERT & PRICE, 1977), these will also be remobilized upon Mn reduction. The high contents of Cu, Ni, Mo and Zn at the lower surfaces of manganese nodules has been explained by diagenetic enrichment from the underlying sediment of metals associated with the manganese phase (CALVERT & PRICE, 1977; ELDERFIELD *et al.*, 1981). Upward diffusive transport associated with the Mn redox pump has been demonstrated for Ni (KLINKHAMMER, 1980). In core 11G, Cu is accumulated at the interface between O_2 and Mn reduction (Fig. 17). Data on Co and Ni are not yet available.

In environments where Mn reduction occurs closer to the sediment surface than in the present study as a result of a higher input of organic matter, Mn and associated elements escape the oxidation trap and diffuse into the bottom water (SUNDBY *et al.*, 1981). This is not likely to occur at the dumpsite where the aerobic layer is at least 25 cm thick (*cf.* ELDERFIELD, 1976). Elements remobilized by reduction in the anaerobic layer could however be released to the bottom water during slides or slumps, or by deep burrowing organisms (see section 5: Biology and WEAVER & SCHULTHEISS, 1983a). This pathway applies in principle to Co, but can not be of any significance for the radioisotope ^{60}Co (halflife 5.3 yr).

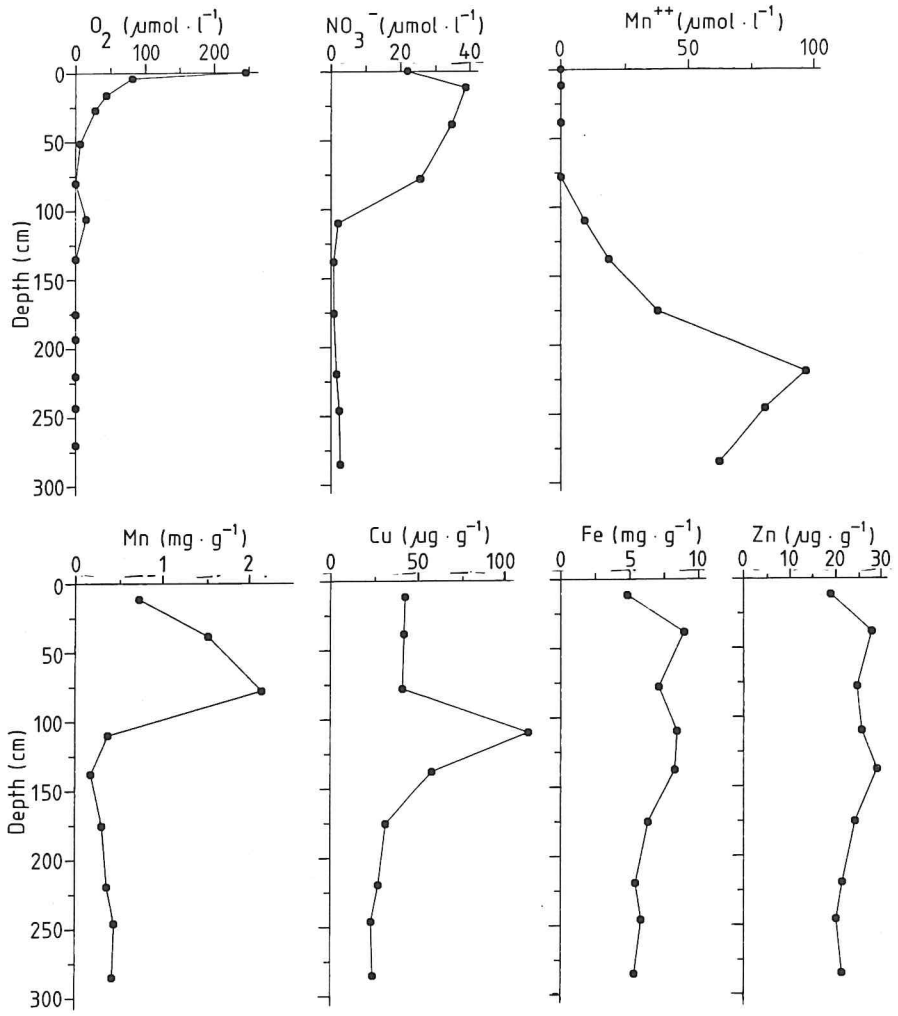


Fig.17. a. Oxygen, manganese and nitrate concentration in the pore water of core 11G. b. HCl-extractable manganese, copper, iron and zinc in the sediment of core 11G.

Only in one core (11G) the depth of nitrate depletion was reached (Fig. 17). From the above mentioned observations it can be concluded that sulfate reduction does not occur above a depth of 1 m in the sediment at the dumpsite. The pH in the sediment is about 7.8 and varies only slightly with depth due to the buffering capacity of the carbonate-rich sediment.

4.5.4. DISSOLUTION OF CARBONATE

The surface sediment contains 82% to 88% of $CaCO_3$ which is subject to dissolution when exposed to bottom water below the lysocline (4700 m, Fig. 13) and as a result of the production of acidity by the aerobic mineralization of organic matter. This results in the release of Ca, HCO_3^- and the associated elements Sr and Mg to pore water and bottom water. Sr is also released as a result of the recrystallization of carbonates to low-Sr calcite (MANHEIM *et al.*, 1971; BAKER *et al.*, 1981; ELDERFIELD *et al.*, 1982). Other elements that are present in trace amounts in the carbonate phase like U and the rare earth elements (PAREKH *et al.*, 1977, see also Table 3) will be released as well. It remains to be investigated if these trace elements released during carbonate dissolution are subsequently adsorbed on other phases like clay minerals, or released to bottom water and dispersed. The latter process would be in accordance with the suggestion of ELDERFIELD & GREAVES (1982) that rare earth elements are remobilized from the sediment surface.

5. BIOLOGY

5.1. INTRODUCTION

Our knowledge of the deep-sea bottom fauna of the NEA dumpsite until now was very small. FELDT *et al.* (1981) mentioned the occurrence of the sea anemone *Chitonanthus abyssorum*, and with traps fishes (*Coryphaenoides armatus*) and Amphipoda (*Eurythenes gryllus*) were caught near the bottom (PENTREATH, 1983 and WICKINS, 1983). Very recently GEIDAROV *et al.* (1983) gave far more information about the benthos. They found 70 different species of invertebrates and presented also a figure for the biomass. For the meiofauna no data at all were available, but in the neighbourhood of the dumpsite in the Iberian deep sea however research has been done by THIEL (1972), RACHOR (1975) and DINET & VIVIER (1977).

Therefore the biological program has been focussed on getting site-specific data on composition, density, biomass and vertical distribution in the sediment of the meio- and macrobenthos. They can give us an explanation for the (bio)turbation, that is known to exist there from measurements of $^{239+240}Pu$ and ^{210}Pb (see chapter 6). The vertical distribution will learn us the maximum penetration of bioturbation. Data on composition, density and biomass will give a better understanding of the deep-sea foodweb, which is a necessity to get an idea of the importance of these animals as accumulators of radionuclides and as food source for mobile predators connecting the benthic region with higher levels in the water column.

5.2. METHODS

From the boxcore samples several subcores with perspex tubes of 24.6 cm^2 were taken for research of the meiofauna. These subcores were cut horizontally in slices of 1 cm, below 5 cm depth into slices of 2.5 cm and below 10 cm into 5 cm slices and then preserved in buffered formalin 4%. In the lab the samples were coloured with rosebengal with the addition of phenol (THIEL, 1966). Because of the phenol rosebengal will give an optimum colouring in a wider range of pH, but has also to our experience a remarkable effect on the sticky clay. It makes the sediment 'softer', with the consequence that the colour will penetrate better and moreover, it makes the sieving or elutration much easier and quicker. The samples of 25 to 125 cm^3 were fractioned by elutration (UHLIG, THIEL & GRAY, 1973) in a 5 liter conical glass jar by a tapwater current of 1 $l \cdot min^{-1}$ until the water in the jar was clean. A second fraction was retrieved by a current of 2 $l \cdot min^{-1}$. All fractions were sieved over 50 μm and the residu of the sample also over 200 μm (Fig. 19). Contamination with *e.g.* freshwater Nematoda in the used tapwater was avoided by a 10 μm sieve, that was cleaned regularly. The 4 different fractions were searched out under a stereo microscope (20x) and always checked by a second person. Checking increased the number of animals found with 25%. Most animals were concentrated in the very small "1 $l \cdot min^{-1}$" fraction. The animals were picked out and mounted in lactophenol, but later on in glycerin because of the better conservation on the long term. The measuring and counting was done with a microscope (100-400x). The Nematoda biomass has been calculated by the method of ANDRASSY (1956). For the Nematoda with a short and thick body, *e.g.* the family Desmoscolecidae, we used the following formula: $G = 0.436 * a^2b$. In which G = wet weight, a = the largest diameter and b = the length. For the conversion of wet weights to dry weights we multiplied the first with 0.25 (see *e.g.* WITTE & ZIJLSTRA, 1984). The volume of Copepoda and nauplii was calculated in a similar way by breaking up the animal in cones, cilinders etc. For the calculation of the dry weight we used a factor derived from 100 copepods of the North Sea . No attempt has been made to estimate the biomass of the other less important meiofauna taxa. Results of 1 subcore per station are reported here.

Of the same boxcore sample used for subcoring, we skimmed off the upper 3 centimeter of the rest (1864-2046 cm^2) of the sample, while the perspex subcores were still in the sediment. This could not be done very accurately. This upper 3 cm layer and the remaining part were sieved on board seperately over 1 mm to collect the macrofauna, which was stored in formalin. To prevent contamination with plankton we sieved the used sea water over 50μm. The fauna was identified to the level of higher groups. Since too few animals were available to get reliable dry weights by normal weighing, we measured the volume of each animal in a similar way as with the meiofauna. In using a value of 1 for the specific gravity (which is of course an underestimate) and with the conversion table of ROWE (1983) for wet weights to dry weights for the different deep-sea animals the shell-free dry weight was calculated. For Tunicata and the indeterminanda we had to estimate a factor (0.25 and 0.10 respectively) and for Bivalvia we used the factor derived from ROWE's carbon data.

The larger macrofauna was sampled only qualitatively with an Agassiz trawl. In lowering and hieving the net, the catch was inevitably contaminated with pelagic

organisms, since the net was not equipped with a closing mechanism. Part of the meager catches were frozen for chemical and radionuclide analyses and a part was preserved for identification. The small catches are probably not only caused by the small standing stock, but also by the use of a very light synthetic wire (Kevlar), which may have resulted in a poor bottom contact.

5.3. RESULTS AND DISCUSSION

5.3.1. MEIOFAUNA

The meiofauna (>50 μm and <1 mm) consisted mainly of Nematoda, Foraminifera, nauplii and Copepoda and several less important groups (Table 4, Figs 18 and 19).

Table 4
Number of specimens of the different meiofauna groups in a subcore (24.6 cm^2) of the boxcore samples.

Station	1	2	4	5	6	8	11	13	15	% of total
Nematoda	792	248	607	950	740	919	989	1466	2436	88.01%
Foraminifera	56	15	3	93	34	47	18	18	84	3.54%
nauplii	6	6	6	29	16	12	16	50	69	2.02%
Copepoda	8	18	23	12	22	20	15	29	51	1.91%
Polychaeta		1		3			2	3	14	0.22%
Ostracoda	1	2	2	5	1	1	2	1	6	0.20%
Kinorhyncha						2			3	0.05%
Tardigrada			2		1				1	0.04%
Oligochaeta		1		1					1	0.03%
Bivalvia			1						2	0.03%
Tanaidacea							1	1	1	0.03%
Sipunculida	1									0.01%
Porifera							1			0.01%
Loricifera								1		0.01%
Eggs+spheres	8	2	2	3	15	20	5	40	15	1.05%
Indeterminanda	5	6	3	45	27	23	13	80	93	2.84%
Total	877	299	649	1141	856	1044	1062	1689	2776	100.00%

All these groups are known to occur on those water depths, except for the Loricifera, a new phylum described very recently by KRISTENSEN (1983) and until now only known from rather shallow water. The indeterminanda contained mainly wormlike bodies, for a part maybe Foraminifera.

Density.—As expected from most other deep-sea meiofaunal studies the Nematoda have the highest density (88% of the total meiofauna) with a mean of 412 600 per m^2. The absolute density varied between 100 700 and 989 000 per m^2 (Tables 4 and 5).

These figures are rather high compared with other studies in the Atlantic from the same depth (Table 6), but not exceptional. A density of almost 1 million per m^2 in station 15 must however be considered as a new record for those depths. It cannot be immediately concluded that the dumping area is richer than the other studied areas, while

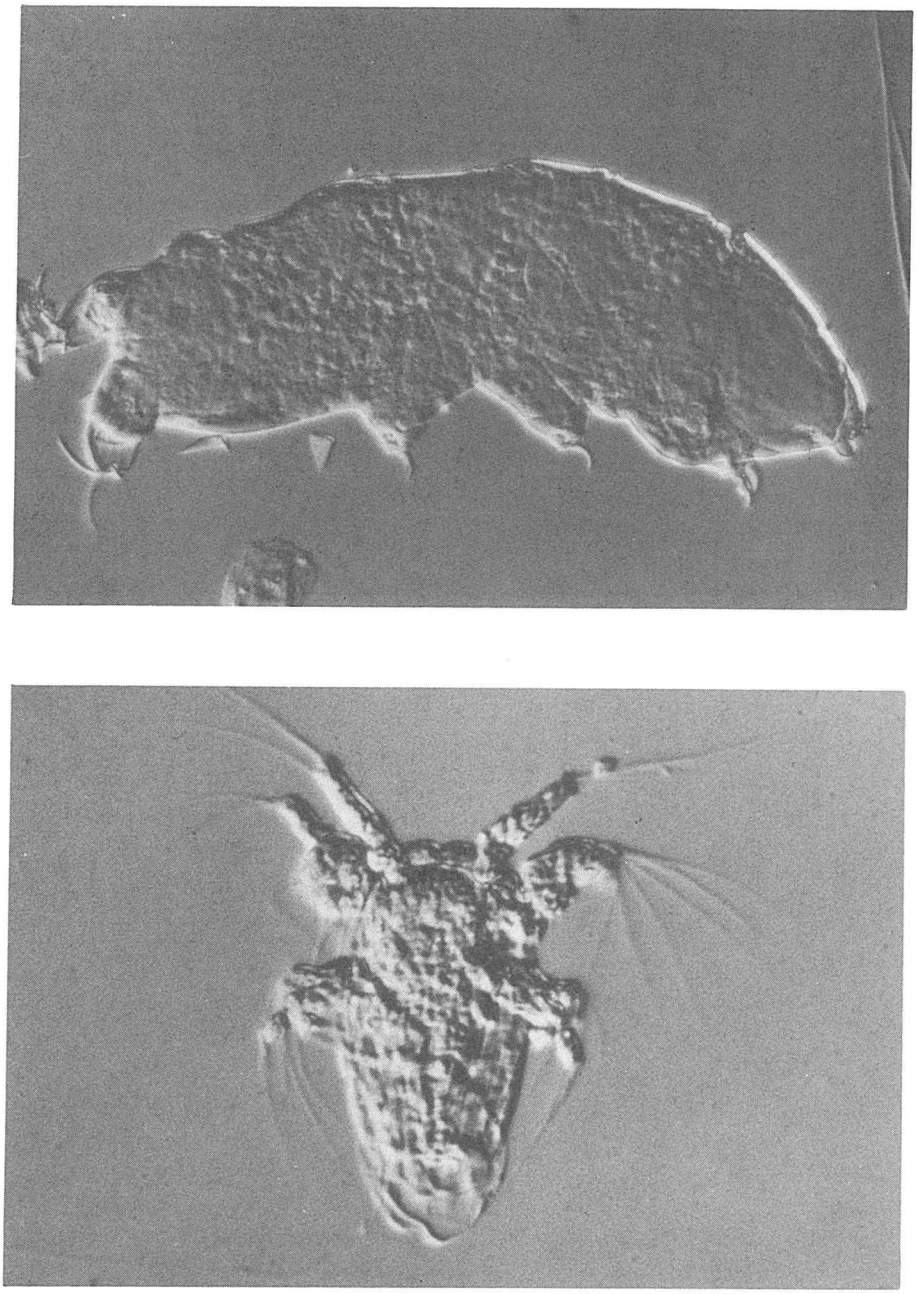


Fig. 18. Meiofauna from the boxcores. Above: Specimen of the phylum Tardigrada, length 240 μm (core 4B). Below: Nauplius, length 86 μm (core 6B).

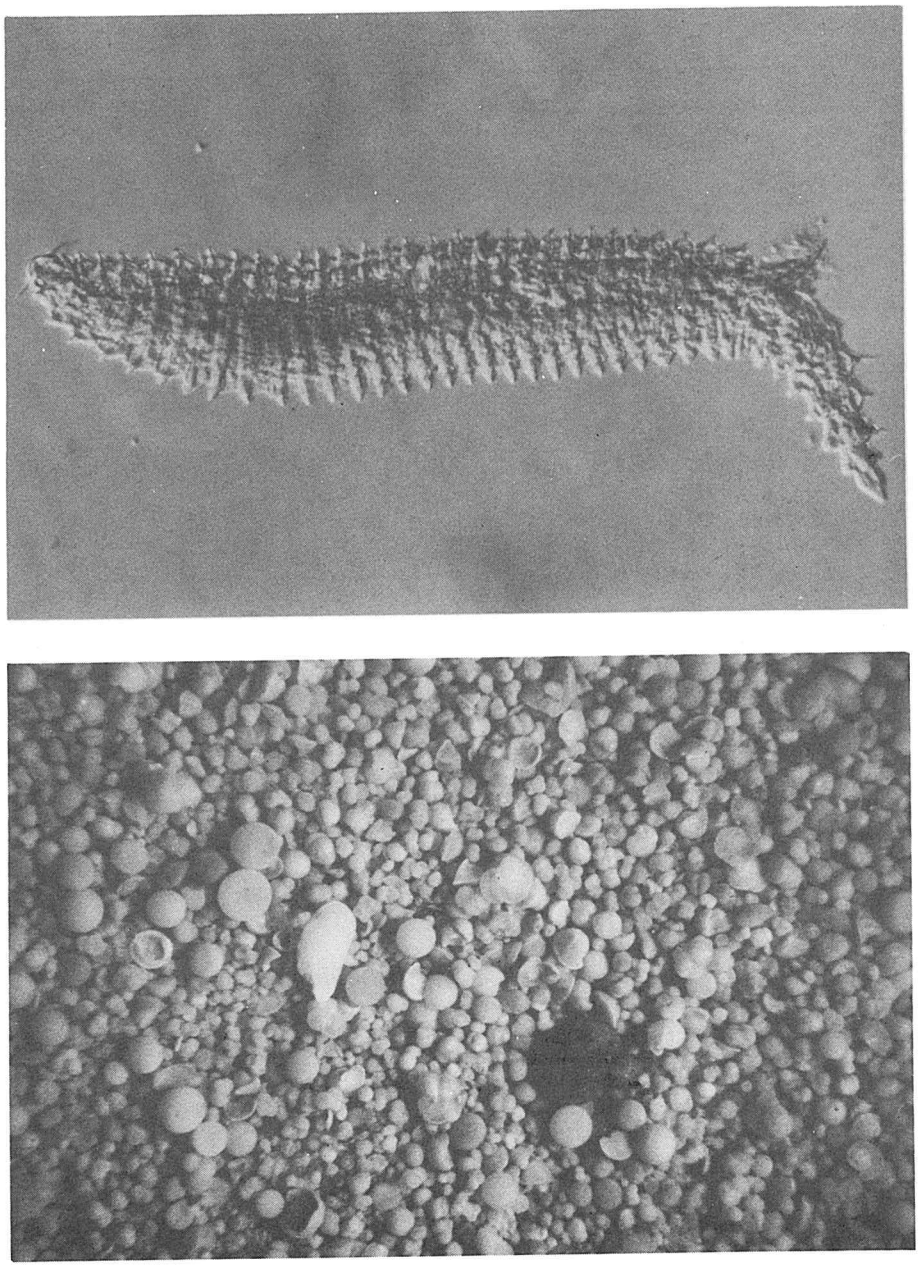


Fig. 19. Above: Meiofauna from the boxcores. Nematod belonging to the family Desmoscolecidae, length 330 μm (core 5B). Below: Coarse fraction (>200 μm) of sediment from the boxcore 8B, containing for the larger part test of pelagic Foraminifera. The sphere shaped tests are from *Orbulina universa* d'Orbigny, 1839. Length of photo 14 mm.

Table 5
Density of meiofauna groups in thousands per m^2, calculated from 1 subcore (24.6 cm^2) of each station.

Station	1	2	4	5	6	8	11	13	15	mean	%
Nematoda	321.6	100.7	246.4	385.7	300.4	373.1	401.5	595.2	989.0	412.6	88.0%
Copepoda +nauplii	5.7	9.7	11.8	16.6	15.4	13.0	12.6	32.1	48.7	18.4	3.9%
Other groups	28.8	11.0	5.3	60.9	31.7	37.8	17.1	58.8	89.3	37.8	8.1%
Total	356.1	121.4	263.5	463.2	347.5	423.9	431.2	685.7	1127.1	468.8	

Table 6
Density and biomass of Nematoda, Copepoda and nauplii from different quantitative studies on the benthos of the Atlantic Ocean below 4000 m.

	depth	area	Nematoda			Copepoda and nauplii	
			Density[1]	mean	Biomass[2]	Density[1]	Biomass[2]
Thiel, 1972	5272-5340 m	Iberian deepsea	156 -278	219	150 mg	4.7	1.9 mg
Rachor, 1975	4878-5510 m	Iberian deepsea	15.5- 76	46	5.9mg	11.6	1.5 mg
Dinet & Vivier, 1976	4096-4725 m	Gulf of Biscay	86 -383[3]	243		20.5	
This study	4000-4800 m	Iberian deepsea	101 -989	413	16.4mg	18.4	10.0 mg
Dinet, 1973	4100-5170 m	South Atlantic	294 -504	364		14.7	

[1] density in thousand per m^2.
[2] Biomass in dry weights.
[3] Leaving out two probably biased samples with densities of 5 to 12 thousand per m^2.

a part of the differences can be explained by differences in methods. Elutration will concentrate the meiofauna better and works more gently than the normal sieving method as used by THIEL (1972) and RACHOR (1975). We agree with THIEL (1983) that decantation before fixation of the sediment samples can be the explanation of the low figures of RACHOR (1975), because fixation makes the animals more stiff and less fragile, with the consequence that less animals will break up and/or be pressed through the sieve. Moreover other studies only studied the upper centimeters of the sediment.

Two other important groups are the Copepoda and the nauplii with densities varying from 5700 to 48 700 with a mean of 18 400 per m^2 (Table 5). They constitute 4% of the total number of meiofauna animals (Table 4). Figures of comparable studies in the Atlantic (Table 6) are of the same order.

Foraminifera are scoring 3.5% (Table 4), but for this group it is difficult to get reliable data. In spite of the colouring with rosebengal it is often difficult to decide whether a foraminifer was living at the time of collection. Tests with one to all chambers coloured were found. If only one or two chambers were coloured, these were not always the last chambers as would have been expected. On the other hand pelagic Foraminifera known to be living only in the upper 100 m of the sea, are sometimes coloured well. This can partly be due to naked Foraminifera inhabiting the empty tests (A.J. GOODAY, IOS, Wormley, U.K., personal communication).

Biomass.—Nematoda biomass varied from 8.2 to 28.2 mg dry weight per m^2,with a mean of 16.4 mg per m^2 (Table 7). Few data from the area are available to compare these figures with (Table 6). The low figures of RACHOR (1975) are explained by his low values for the densities, but still they overlap our data. THIEL (1972) gives much higher figures, notwithstanding his lower values for densities. RACHOR already noted and later on THIEL (1983) agreed that these amounts were probably too high, because of the use of a mean individual weight for Nematoda, that was derived from a study of a much shallower area (290-2500 m). Our estimates of the individual weights for Nematoda (Table 8) are much smaller and they differ from values for intertidal Nematoda (see *e.g.* WITTE & ZIJLSTRA, 1984) by a factor of 7.

Table 7
Biomass of Nematoda in the upper 3 cm, the rest and the total of a subcore (24.6 cm^2) of the box-core in μg dry weight.

Station	1	2	4	5	6	8	11	13	15	mean	%
0 - 3cm	21.0	12.3	31.6	39.3	26.5	39.6	23.8	38.1	47.4	31.1	77.0%
3 - ±20cm	8.9	7.9	10.9	6.0	3.4	6.8	4.5	13.8	22.1	9.4	23.0%
Total	29.9	20.2	42.5	45.3	29.9	46.4	28.3	51.9	69.5	40.4	
Total in mg/m^2	12.1	8.2	17.3	18.4	12.1	18.8	11.5	21.1	28.2	16.4	

Table 8
Mean individual biomass of Nematoda in μg dry weight.

	depth	mean dry weight
This study	4000-4800 m	0.04µgr (0.03-0.07)
Thiel,1972	290-2800 m	0.27-1.9µgr
Witte & Zijlstra,1984	littoral	0.28µgr (0.23-0.42)

From Figs 20 and 21 it can be seen that the mode of the individual Nematoda biomass is 0.020-0.025 μg and the mode of the Nematoda length is 300-350 μm.

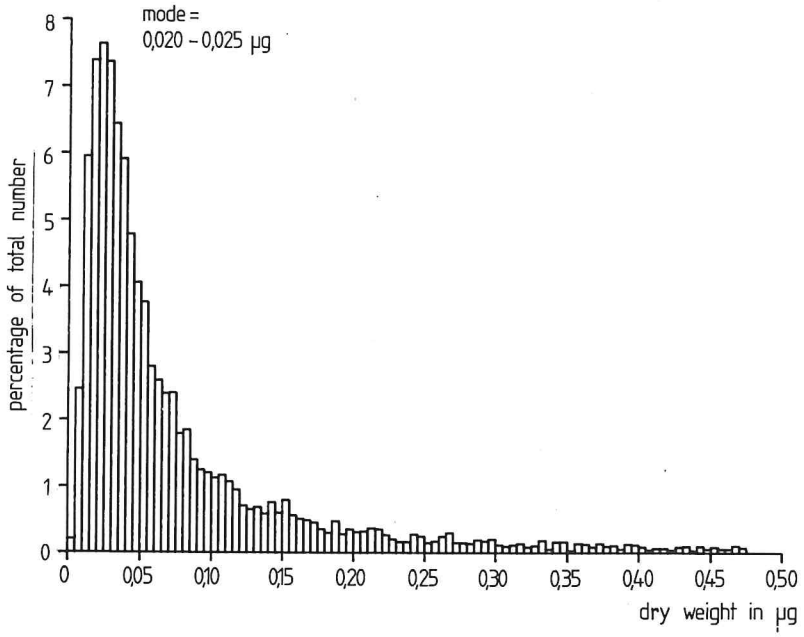


Fig. 20. Frequency distribution of the individual biomass (dry weight) of 9147 Nematoda from all stations.

The biomass of Copepoda and nauplii varied from 1.1 to 32.9 mg dry weight per m^2, with a mean of 10.0 $mg \cdot m^{-2}$ (Table 9). Compared to the Nematoda, the biomass is much more variable, which is caused by the lower densities and the high diversity in body sizes. On the average the biomass is lower than that of the Nematoda, but more important than the densities would have suggested. Only RACHOR (1975) calculated the biomass of Copepoda in a similar way. For stations deeper than 4000 m he found wet weights from 0 to 16.4 $mg \cdot m^{-2}$, with a mean value of 5.9 $mg \cdot m^{-2}$. This means a mean biomass of only about 1.5 $mg \cdot m^{-2}$ dry weight (if calculated with the conversion factor 0.25). THIEL (1972) also gave a rough estimate of wet weights for Copepoda by assuming that the mean individual weight was 2 μg (Table 6).

Table 9
Biomass of Copepoda and nauplii in the upper 3 cm, the rest and the total of the subcore (24.6 cm^2) of the boxcores in μg dry weight.

Station	1	2	4	5	6	8	11	13	15	mean	%
0 – 3cm	1.0	3.0	3.4	4.1	11.0	44.2	8	35.7	46.1	17.4	70.4%
3 – ±20cm	1.6	4.1	5.0	0.5	3.7	0.9	1.8	12.5	34.9	7.3	29.6%
Total	2.6	7.1	8.4	4.6	14.7	45.1	10.6	48.2	81.0	24.7	
Total in mg/m²	1.1	2.9	3.4	1.9	6.0	18.3	4.3	19.6	32.9	10.0	

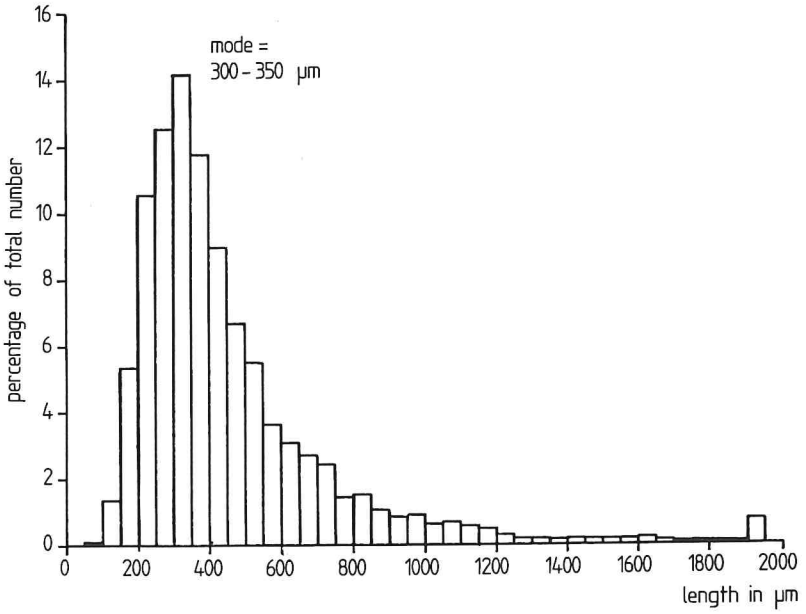


Fig. 21. Frequency distribution of the length of 9147 Nematoda from all stations.

The total biomass of the meiofauna given in Table 10 does not include other meiofauna groups than Nematoda, Copepoda and nauplii. The contribution of these other groups is estimated to be very small, and no attempt has been made to calculate it.

Vertical distribution.—At all stations except station 15 the highest density as well as the highest biomass for Nematoda is found in the upper centimeter (Figs 22 and 23). As a mean 77% of the Nematoda biomass occurs in the upper 3 cm (Table 7). The other taxa are in general also concentrated in the upper layer of the sediment. The density of Nematoda is declining very rapidly with depth in the sediment. Below 10 cm the density is very low, but they were found until 20 cm depth. The vertical distribution of

Table 10
Biomass of meiofauna (Nematoda, Copepoda and nauplii) in the upper 3 cm, the rest and the total of a subcore (24.6 cm^2) of the boxcores in µg dry weight.

Station	1	2	4	5	6	8	11	13	15	mean	%
0 - 3cm	22.0	15.3	35.0	43.4	37.5	83.8	32.6	73.8	93.5	48.5	74.5%
3 - ±20cm	10.5	12.0	15.9	6.5	7.1	7.7	6.3	26.3	57.0	16.6	25.5%
Total	32.5	27.3	50.9	49.9	44.6	91.5	38.9	100.1	150.5	65.1	
Total in mg/m^2	13.2	11.1	20.7	20.3	18.1	37.1	15.8	40.7	61.1	26.5	

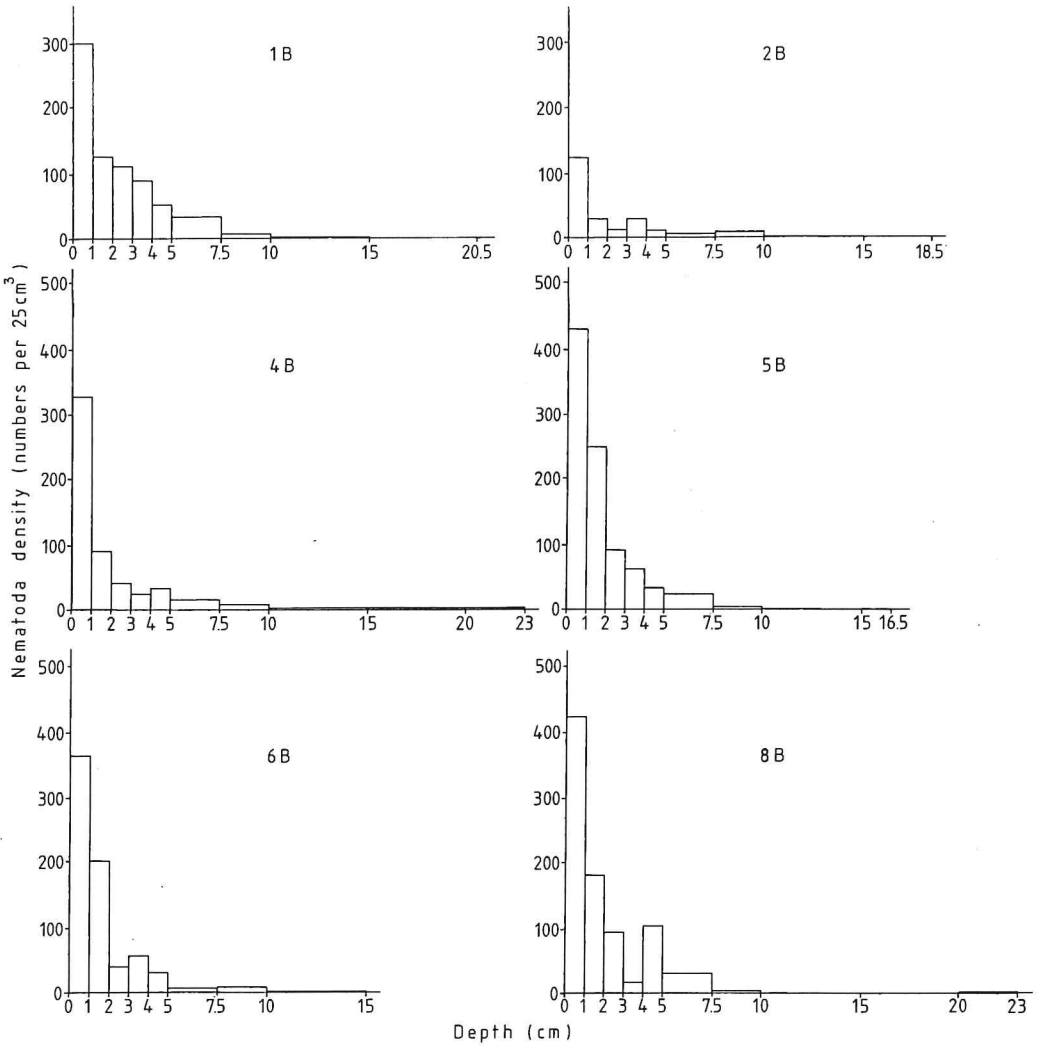
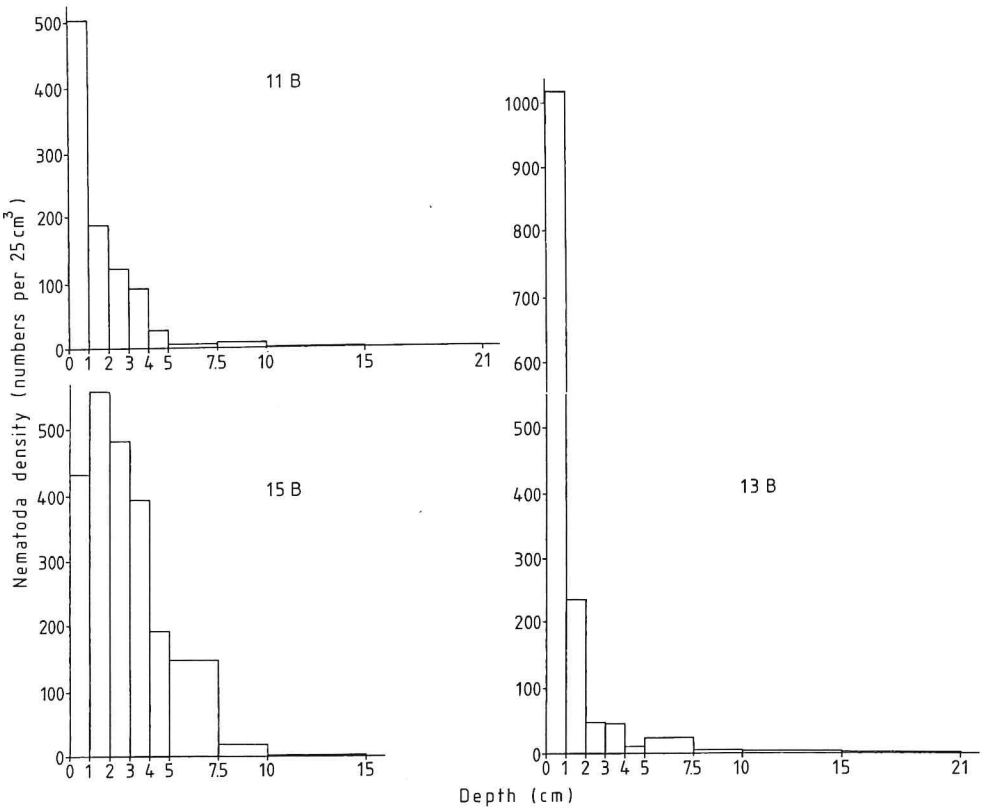


Fig. 22. Vertical distribution of the density of Nematoda (number per 25 cm^3) in each of the boxcores.

biomass is similar, but we can detect at some stations a weak subsurface maximum at 4-5 or 5-7.5 cm (see stations 2, 4, 8 and 13 in Fig. 23). This corresponds approximately with the border between the soft upper layer and the thick clay underlayer.

Because of the low densities of Copepoda and nauplii we cannot say much about their vertical distribution, but as a mean 70% of their biomass is present in the upper 3 cm (Table 9). They penetrated as deep as the Nematoda in the sediment.


11 B
15 B
13 B
Nematoda density (numbers per 25 cm³)
Depth (cm)
0 1 2 3 4 5 7.5 10 15 21

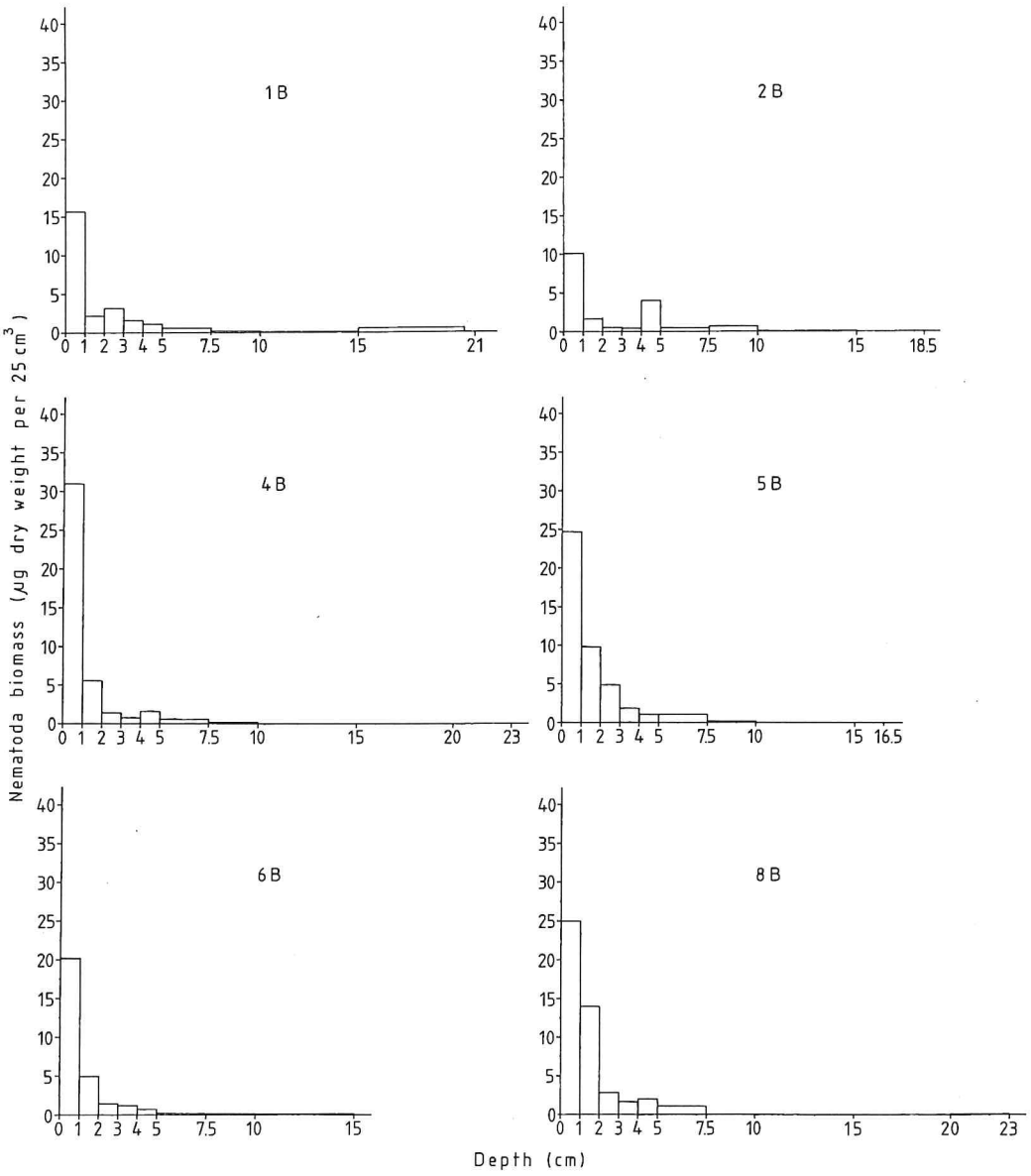
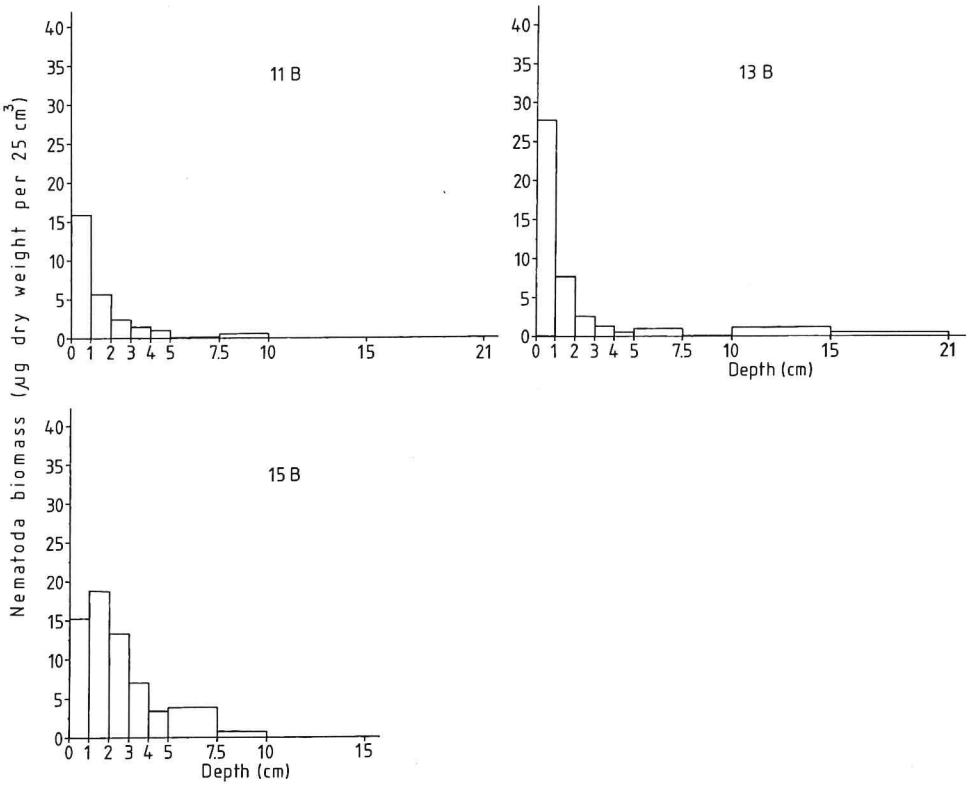


Fig. 23. Vertical distribution of biomass of Nematoda (µg dry weight per 25 cm^3) in each of the boxcores.



5.3.2. MACROFAUNA

The density of the different macrofauna groups is given in Table 11. Polychaeta have the highest average density (67 per m^2), followed by the Sipunculida (Fig. 25) and Bivalvia (Fig. 24) (13 per m^2). The indeterminanda, mostly wormlike animals without clear taxonomic characteristics, had a density of 29 per m^2. Tunicata, Isopoda and Tanaidacea (Fig. 25) and the larger Nematoda reach all a mean density of more than 5 per m^2. Bivalvia were the only macrofauna group that was represented in all 9 boxcores. Polychaeta were found in 8, Sipunculida in 7, Tanaidacea in 6 and Tunicata and Porifera in only 5 boxcores.

Expressed as a fraction of the total macrofauna biomass, Sipunculida dominate in the boxcores with 53% (Table 12). These Sipunculida can reach a length of about 15 cm and will burrow at least their own length deep. Other important groups are Polychaeta (17%), Tunicata (10%), Bivalvia (8%) and Porifera, Tanaidacea, Ophiuroidea and Holothuroidea (1-2%). At station 8 we found 2 large Ophiuroidea in the boxcore sample with a dry weight of almost 80 mg. We considered them as a lucky strike and did not include them in Tables 12 and 13.

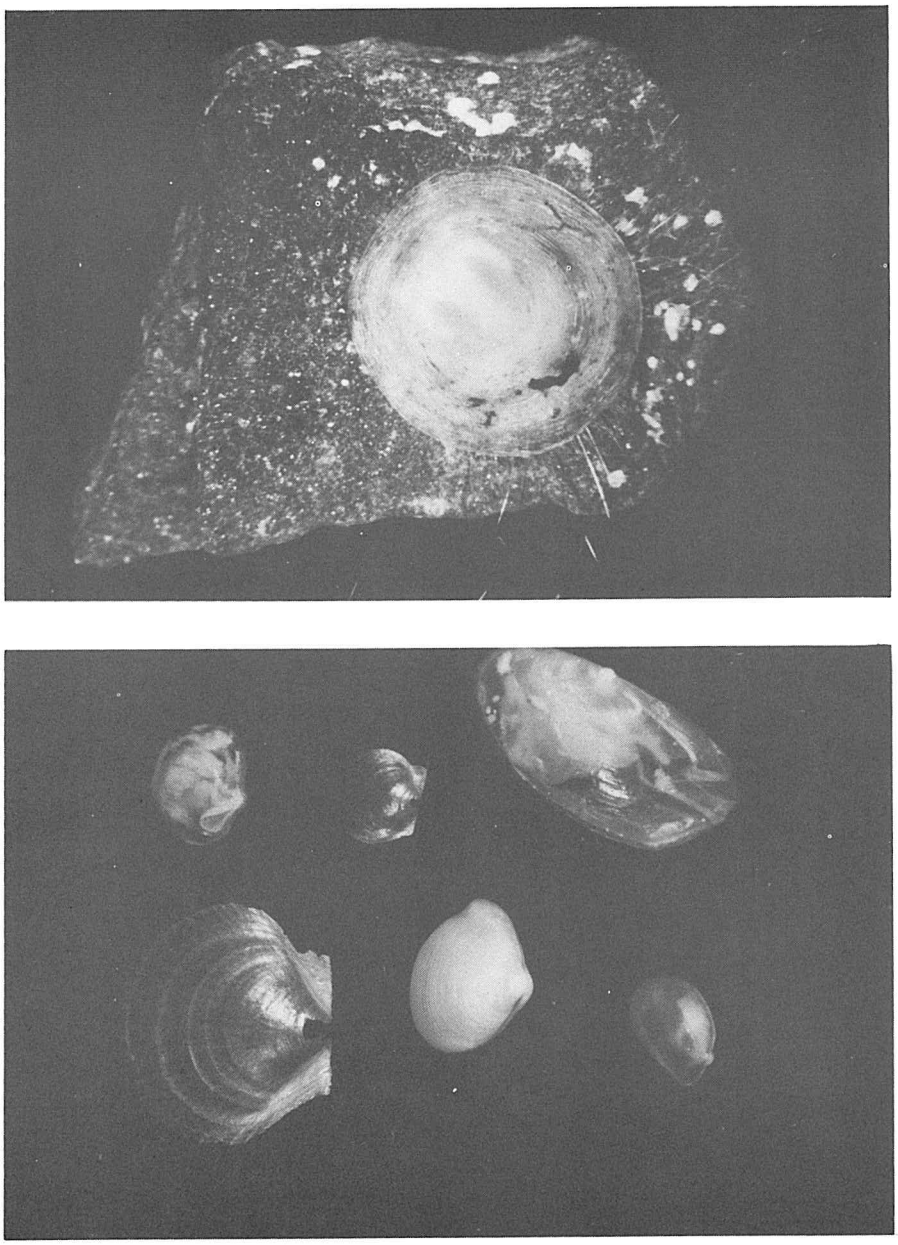


Fig. 24. Macrofauna of the boxcores. Above: *Pelagodiscus atlanticus* King, 1868 (Brachiopoda) (length 5.1 mm, core 8B) on a little stone. Below: Several Bivalvia. Upper row from left to right: *Yoldiella abyssorum* Knudsen, 1970 (length 2.3 mm, core 2B), *Cyclopecten* spec. (length 1.8 mm, core 2B), *Silicula fragilis* Jeffreys, 1879 (length 5.5 mm, core 2B). Lower row: *Propeamussium* spec. (length 4.6 mm, core 2B), *Ledella crassa* Knudsen, 1970 (length 3 mm, core 2B), *Dacrydium vitreum* Möller, 1842 (length 2.1 mm, core 1B).

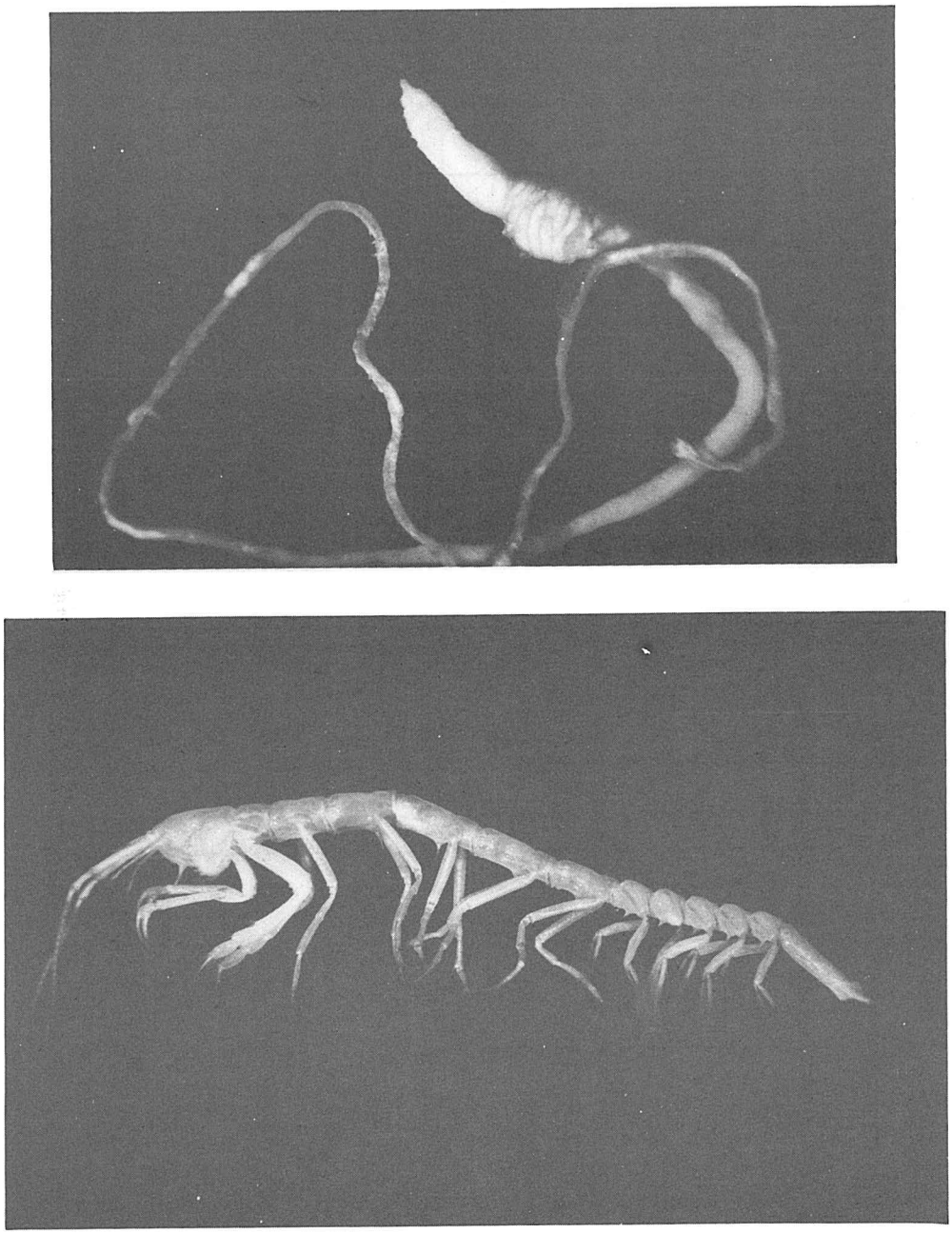


Fig. 25. Macrofauna from the boxcores. Above: *Golfingia* spec. (Sipunculida), length 52.6 mm (core 2B). Below: *Leiopus gracilis* (Norman & Stebbing, 1886) (Tanaidacea), length 13.3 mm (core 2B).

Table 11

Number of specimens of macrofauna in the upper 3 cm and the rest of the boxcores. Between stations the sieved boxcore area varied from 1864 to 2046 cm^2 (* = epifauna).

Station	1	2		4		5		6		8		11		13		15		total	mean density in n / m^2
Depth in core a=0 - 3cm b=3 - ± 20cm	a+b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b		
Foraminifera								3						1			3	7	4.0
Komokiacea		2																2	1.1
Porifera				1		2		1						1		1	1	7	4.0
Cnidaria		1																1	0.6
Stephanoscyphus *		2																2	1.1
Nematoda	1	1		2			2			1	1					1	1	10	5.7
Polychaeta		9	1	19	2	7	2	8	1	11	4	2	1	16	5	10	18	116	66.7
Oligochaeta					1													1	0.6
Sipunculida	2		3	2	5		3		1		3		3					22	12.6
Bivalvia	3	5		1		2		2		1			1	1	1	3	2	22	12.6
Crustacea		1												2	1			4	2.3
Copepoda														1				1	0.6
Amphipoda						2		1					1					4	2.3
Cumacea						1											1	2	1.1
Tanaidacea			1	1	1	1	1	2			1			1				9	5.2
Isopoda					1			3		2		1		3	1			11	6.3
Ectoprocta *		1															2	3	1.7
Brachiopoda *										1								1	0.6
Crinoidea *						1		1										2	1.1
Ophiuroidea	1										2					2		5	2.9
Holothuroidea	1										1							2	1.1
Tunicata *		1		2				2		2						3	3	13	7.5
Indeterminanda				11		13	2	2		3			2	9		5	4	51	29.3
Total	8	23	5	39	10	29	10	25	2	21	12	3	7	36	8	25	35	298	
Total /m^2	39	143		253		202		143		167		54		234		311			171.3

Table 12

Macrofauna biomass of the different important higher taxa in percentages of the total macrofauna biomass of each boxcore sample.

Station	1	2	4	5	6	8	11	13	15	mean
Sipunculida	66.4	82.1	49.6	65.4	65.5	66.6	84.6			53.356
Polychaeta		5.9	42.1	10.4	9.5	9.0	3.2	41.7	30.7	16.944
Tunicata		0.1	0.7		16.2	18.2			55.0	10.022
Bivalvia	3.8	8.5	3.6	2.1	2.2	0.5	2.8	45.6	3.5	8.067
Holothuroidea	17.2					1.9				2.122
Porifera			2.0	8.2	0.3			1.2	4.0	1.744
Ophiuroidea	12.4								0.2	1.400
Tanaidacea		2.9	0.3	4.3	2.5	0.7		0.1		1.200
Isopoda			0.4		1.7	0.2	0.4	3.2		0.656
Amphipoda				3.0	0.5			0.6		4.456
Ectoprocta									2.7	0.300
Brachiopoda						2.3				0.256
Cumacea				0.6					0.5	0.122
Indeterminanda		0.2	0.7	5.8	1.6	0.5	9.0	6.9	3.1	3.089

If we had included them, the total biomass for station 8 would be 570 mg per m^2. This is more than 3 times the second highest station in biomass (station 15), and would have a great effect on mean macrofauna biomass. At station 13, poor in macrofauna, Bivalvia and Polychaeta dominated and at station 15 Tunicata and Polychaeta were the major components of the biomass. It was striking that at these last 2 stations no Sipunculida were found.

The total macrofauna biomass varied between 8 and 182.4 $mg \cdot m^{-2}$ with a mean of 101.7 $mg \cdot m^{-2}$ (Table 13).

Table 13
Biomass of the macrofauna in the upper 3 cm, the rest and the total of a boxcore in mg dry weight$\cdot m^{-2}$.

Station	1	2	4	5	6	8	11	13	15	mean	%
0 – 3cm	-	12.1	22.4	23.4	28.6	40.6	2.7	38.9	96.9	33.2	29.3%
3 – ±20cm	-	76.9	124.2	79.8	58.4	141.8*	76.3	17.7	66.4	80.2	70.7%
Total	8.0	89.0	146.6	103.2	87.0	182.4*	79.0	56.6	163.3	101.7	

*not included are two relatively large Ophiuroidea with a shellfree dry weight of 78.86 mg which would have add 387.1 mg/m².

Research on the vertical distribution of the macrofauna resulted in the striking fact that on the average 71% of the biomass was found deeper than 3 cm in the sediment (Table 13). The deeper biomass consisted almost exclusively of Sipunculida. Also the 2 large Ophiuroidea, belonging to the burrowing family Amphiuridae were found below 3 cm. Only some parts of their arms were found in the upper 3 cm. This upper layer had on the contrary the highest macrofauna density, except for station 11 and 15. Station 11 is very poor in individuals and in station 15 the deviding into 2 parts of the sediment is probably biased, which is shown by the findings of Ectoprocta and Tunicata in the deeper layer. Those animals could have lived to our knowledge only on the surface of the sediment.

The macrofauna density of 171 m^{-2} found in this study is not exceptional in comparison with other quantitative deep sea macrofauna studies in the Atlantic (Table 14), but we have to take into consideration that the other researchers had a different definition of macrofauna, because they used a finer sieve (*e.g.* SMITH (1978) worked with a 297 μm sieve). Literature values of the biomass of the macrofauna are very variable (Table 14). Our value for the mean wet weight falls well within the range given by ZENKEVITCH *et al.* (1971) in his map of the benthic biomass for the world oceans.

Table 14
Density and biomass of macrofauna benthos at great depth in the Atlantic Ocean.

	depth	density N/m²	wet weight in mg/m²
Kusnetzov, 1960	3300-5400		0-50
Spärck, 1951	3782		3100
Sanders,Hessler & Hampson, 1965	4436-5001 4525	85 55	
Zenkevitch et al., 1971	3000-5000		100-1000
Smith, 1978	4670-5200	354	155
This study	4000-4800	171	700
Menzies,George & Rowe,1973	4000 5000		1500 160
Geidarov et al., 1983	4050-4700		2010

5.3.3. COMPARISON OF MEIO- AND MACROFAUNA

If we compare the macrofauna with the meiofauna than we see that both have the highest densities in the upper centimeters, but for the meiofauna this is much more clear and it holds for every station. In biomass (Table 15) the macrofauna is always more important than the meiofauna, except for station 1. As a mean it is 4 (0.6 to 8) times more important. This figure agrees with the results of other researchers (compiled by THIEL, 1983), that meiofauna becomes more important with increasing water depth if compared with the macrofauna. However, the effect of water depth on the macrofauna to meiofauna ratio is not as striking as expected. The ratio 1:1 suggested by THIEL (1972) for a somewhat deeper (>5000 m) area appears too low. Still because of a suspected higher metabolism rate (GERLACH, 1971) the meiofauna can be more important in productivity than the macrofauna.

Table 15
Biomass of the meiofauna (Nematoda, Copepoda and nauplii) and the macrofauna of the boxcores in mg dry weight·m^{-2}.

Station	1	2	4	5	6	8	11	13	15	mean	%
Meiofauna	13.2	11.1	20.7	20.3	18.1	37.1	15.8	40.7	61.1	26.4	20.6%
Macrofauna	8.0	89.0	146.6	103.2	87.0	182.4	79.0	56.6	163.3	101.7	79.4%
Total	21.2	100.1	167.3	123.5	105.1	219.5	94.8	97.3	224.4	128.1	

5.4. TRAWL CATCHES

Few benthonic animals were caught with the Agassiz-trawl. The catches existed for the larger part of pelagic organisms. A list of pelagic fishes (with depth distribution from the literature) is given in Table 16. No near bottom dwelling fishes were caught. The following representatives of the benthos were collected: Cnidaria (Actiniaria), Turbellaria (egg capsule), Polychaeta, Bivalvia (Pectinidae), Cephalopoda (*Grimpoteuthis umbellata*, *Cirrothauma murrayi*, Fig. 26), Crustacea (Amphipoda, Isopoda, Cirripedia), Brachiopoda (*Pelagodiscus atlanticus*), Ophiuroidea (*Ophiomusium planum*, Fig. 26), Holothuroidea, Tunicata. Interesting finds were the large mobile bottom dwelling predators (length 25 and 40 cm), belonging to the order of the Octopoda (Cephalopoda). The crustacean larva *Eryoneicus spinoculatus* (Fig. 26), of which we caught 2 specimens of 30 and 35 mm length, is an example of the large vertical migrating capacities of some

Table 16
List of all (pelagic) fish caught with the Agassiz trawl, with number of specimens per station.

Name	Station							likely depth of occurence
	3	5	8	11	12	13	15	
Myctophum punctatum	1			1				night 0– 125 m day 225– 750 m
Lampanyctus crocodilus	1			1				night 0– 650 m day 275–1000 m
Benthosema glaciale	1		2				3	night 0– 225 m day 275– 800 m
Symbolophorus veranyi	1							0– 800 m
Opisthoproctus soleatus				1				> 400 m
Gonostoma bathyphilum			2			1		usually > 2000 m
Cyclothone braueri			1	1				night < 300 m day 300–1500 m
Cyclothone microdon	16		54	8		5	12	500–1500 m
Cyclothone spec.				3				——
Argyropelecus hemigymnus	2			1		1	1	0– 300 m
Agryropelecus olfersi			2	1				1800 m
Stomias boa cf ferox				1	1			0– 300 m
Mentodus cf crassus							1	> 1000 m
Scopeloberyx robustus			1					0– 600 m

marine animals. According to BERNARD (1953) this larva lives at a water depth of 400 m, when it is about 2 mm long. During growth it descends down to 4000 m, where it has reached a length of 35 mm. The adult, probably *Stereomastis andamanensis*, lives benthonic, between 500 and 1800 m.

5.5. PRIMARY PRODUCTION

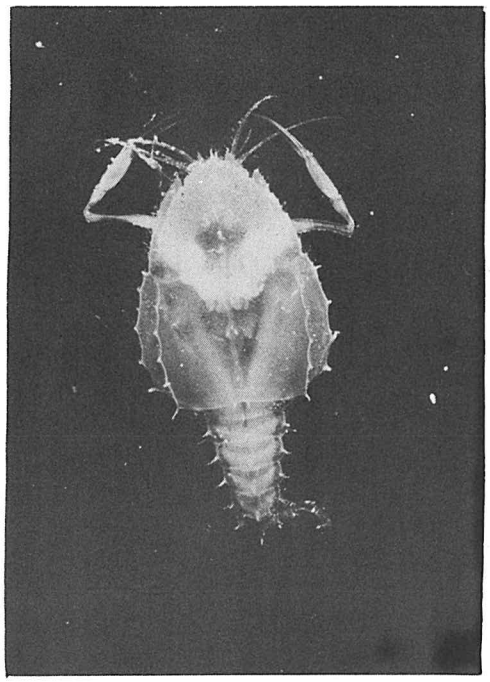
Primary production was measured on three occasions and varied between 150 and 360 mg $C \cdot m^{-2} \cdot d^{-1}$, not significantly different from average values for oceanic waters (130-270 mg $C \cdot m^{-2} \cdot d^{-1}$).

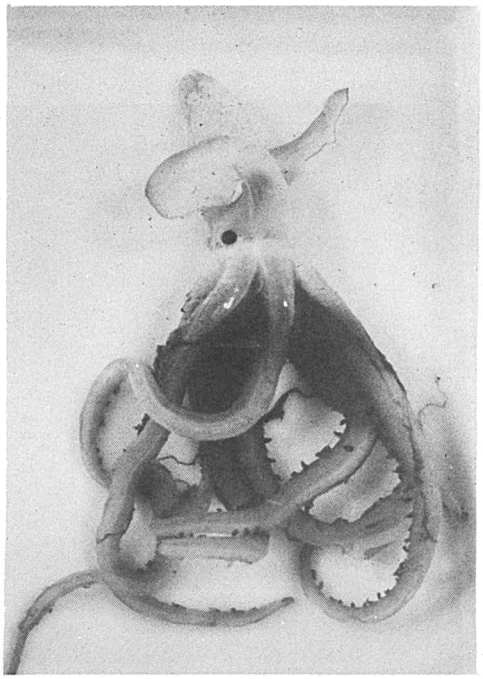
5. BIOTURBATION

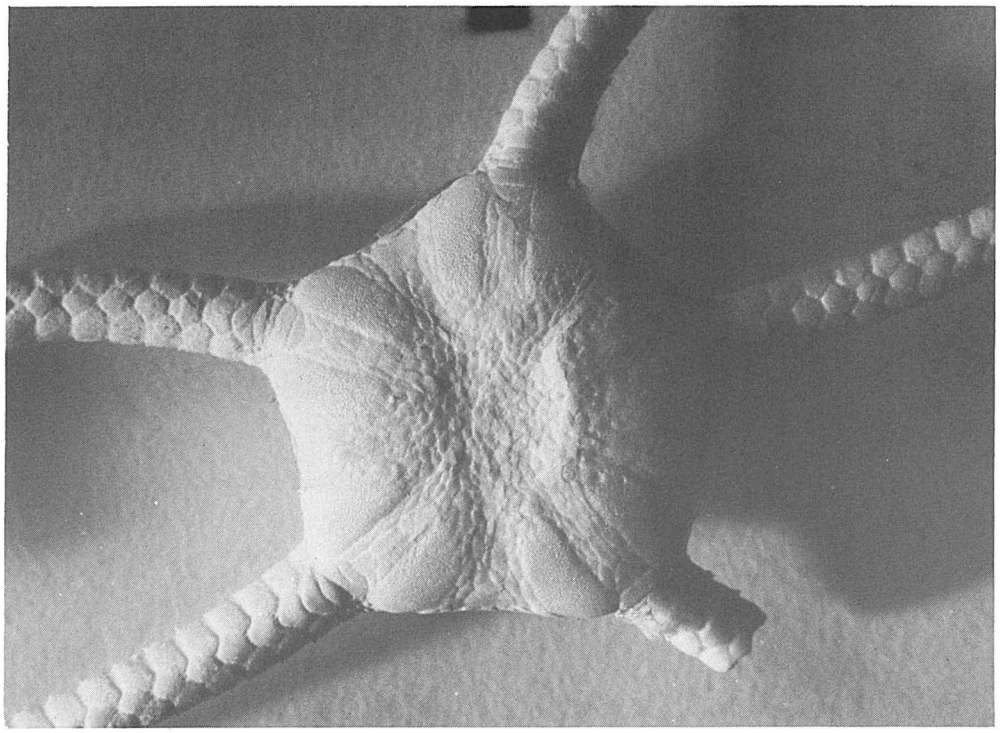
X-radiographs of 2 cm thick slices taken from the boxcores (Fig. 27) gave evidence of extensive burrowing activity of bottom fauna. Bioturbation in deep-sea sediments can be quantified by measuring the ^{210}Pb activity profile in the sediment surface layer (NOZAKI *et al.*, 1977), and similar information can be obtained from the depth distribution of $^{239+240}Pu$ in the sediments. Analyses of the distribution of ^{210}Pb (by Smith, Bedford, Canada) and of $^{239+240}Pu$ (by Noshkin, Livermore, U.S.A.) in the same subcore from each of 8 boxcores showed coinciding subsurface maxima at about 3 to 6 cm depth. This distribution cannot be explained by a model of homogeneous mixing in the upper sediment layer, but instead points to a net transport of surface sediment downwards to the depth where the maximum was observed. At this same depth interval a small but distinct maximum was also found frequently in ETS activity and in the organic carbon content of the sediment (section 4.4.1., Fig. 15).

From the vertical distribution of the meiofauna (Fig. 23) and the smaller macrofauna it is clear that any significant contribution of these groups to bioturbation must be limited to the upper few cm. The larger macrofauna like Sipunculida and Polychaeta, burrow down to at least 15 cm depth. Although their density is low (13 per m^2 for Sipunculida), they must be considered the major cause of the bioturbation below the upper few cm. Sipunculida, representing 53% of macrofauna biomass, are surface deposit feeders, as indicated by the large quantity of ingested sediment. They could therefore also be responsible for the subsurface maxima described above, through the direct transport of surface sediment down to deeper layers via their gut.

Fig. 26. Macrofauna caught with the trawl. Above left: *Eryoneicus spinoculatus* Bouvier, 1905 (Crustacea, Decapoda), length 30 mm (trawl 8T). Above right: *Cirrothauma murrayi* Chun, 1914 (Cephalopoda, Octopoda), length 425 mm (trawl 12T). Below: *Ophiomusium planum* Lyman, 1878 (Ophiuroidea), diameter of disk 20 mm (trawl 13T).







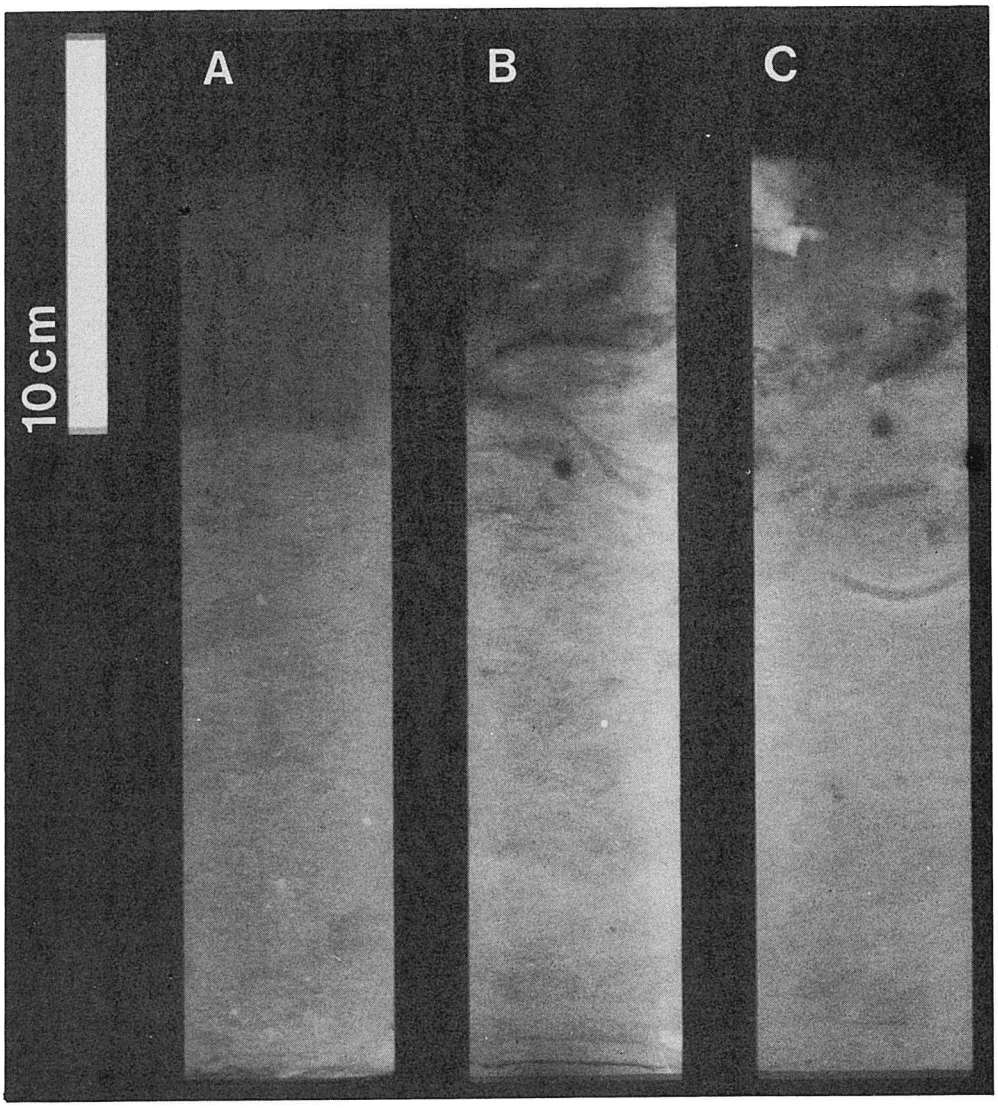


Fig. 27. X-radiographs of 2 cm thick subcores from boxcores 4B (A), 8B (B) and 11B (C).

7. SUMMARY

A geochemical and biological study of the sea floor at the NEA dumpsite for low-level radioactive waste is reported. The sea bottom has rather steep hillsides. Slumps are usual phenomena and could be triggered by the dumping operations.

The sediment is described in terms of its mineralogical and elemental composition. The variation in $CaCO_3$ content accounts for most of the variation in the elemental composition and cation exchange capacity. The present depth of the lysocline is shown to be about 4700 m. A description is given of the early diagenetic processes: (1) Mineralization of organic material, (2) Cation exchange, (3) Change in redox conditions and (4) Carbonate dissolution and recrystallization; and discussed in terms of their effects on the redistribution and transport of trace elements and radionuclides within the sediment and between sediment and overlying water.

Composition, density, biomass and vertical distribution has been studied of benthic meio- as well as macrofauna. The meiofauna has a mean density of 470 000 per m^2 and a mean biomass of 26.5 mg dry weight per m^2. Nematoda are the most important group in density and in biomass. 75% of meiofauna biomass is concentrated in the upper 3 cm.

The macrofauna has a mean density of 171 per m^2 and a mean biomass of 100 mg dry weight per m^2 of which only 29% is found in the upper 3 cm. Sipunculida, forming the main constituent of macrofauna biomass, probably play a major role in bioturbation.

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