united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR/1108 - 19

COURSE ON "MEDITERRANEAN SEA(S) CIRCULATION & ECOSYSTEM FUNCTIONING" 2 - 20 November 1998

Trieste, Italy

"Benthic Mineral Cycling in Marine Ecosystems:" Adriatic Sea versus North Sea

L. LOHSE
Netherlands Institute for Sea Research
Texel, The Netherlands

Benthic Mineral Cycling in Marine Ecosystems:

Adriatic Sea versus North Sea

Lutz Lohse

Netherlands Institute for Sea Research (NIOZ)

Department of Marine Chemistry and Geology

Texel

The Netherlands

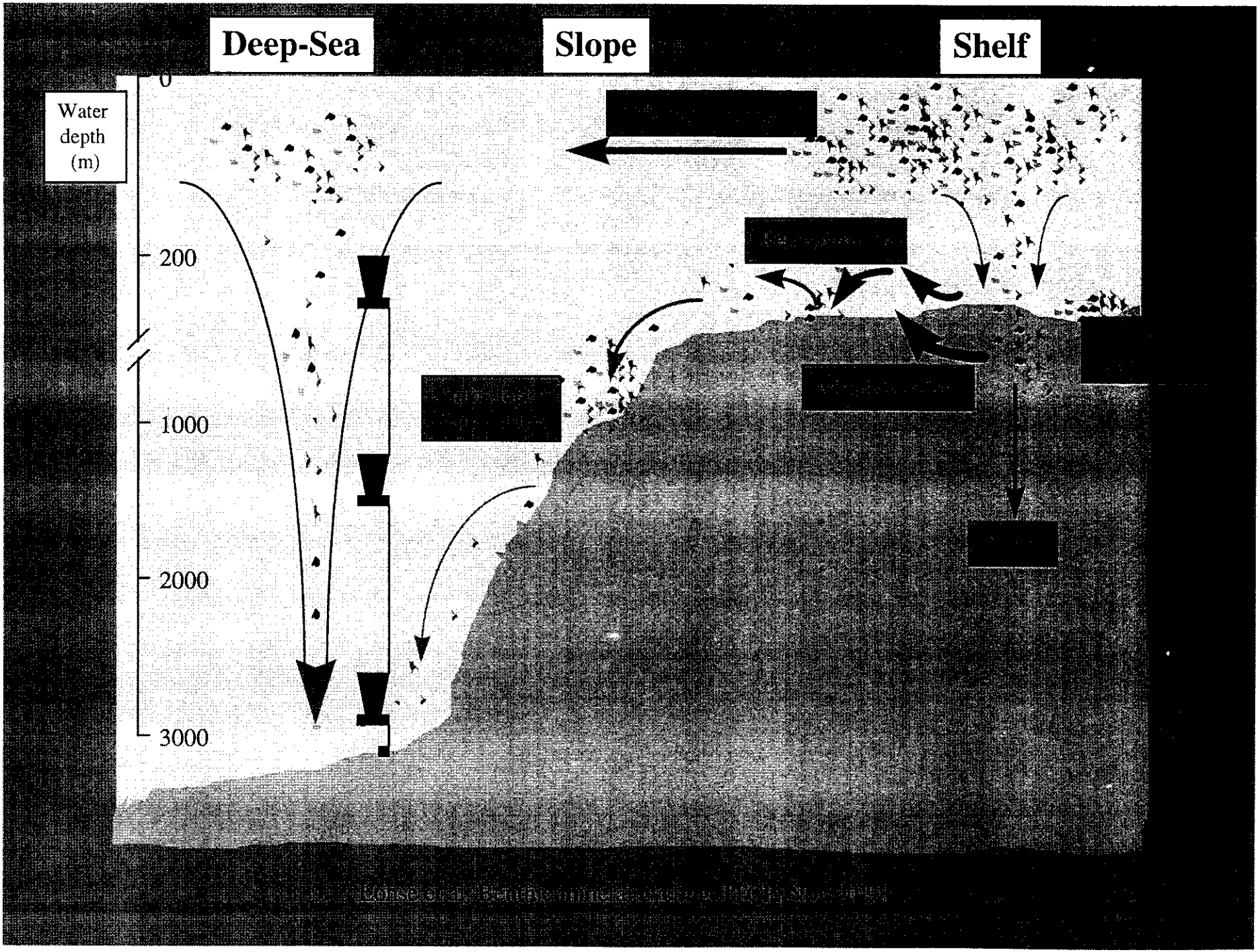
Outline

- *General introduction to benthic-pelagic coupling*
  - *sedimentation of organic matter in marine ecosystems*
  - *general benthic processes*
  - *early diagenesis*
  - *methodological considerations*

- *Case Studies*

  1. Adriatic Sea
  2. North Sea

  3. N. W. European Continental Margin


Deep-Sea
Slope
Shelf
Water depth (m)
0
200
1000
2000
3000

Importance of shelf sediments in global biochemical cycles

- Although the continental shelf covers only 15% of the world ocean it accounts for nearly 50% of the global primary production
- 85% of the global sediment minerlisation takes place on the shelf
- Benthic mineralisation accounts averagely for 45% (?) of the total minerlisation in shelf ecosystems

Typical values of transport and reaction parameters in marine sediments*

	Deep-Sea	**Slope**	**Shelf/Coastal**
water depth (m)	3000-6000	200-3000	<200
sedimentation rate ($cm\ yr^{-1}$)	0.001	0.001-0.01	0-1
bioturbation ($cm^2\ yr^{-1}$)	0.1	1.5	10
degradability (yr^{-1})	0.001	0.02	0.1-10
characteristic lenght scale (cm)	10-100	1-10	0.1-1
characteristic time scale (yr)	10000	100-1000	0.01-100

(*modified after Van Capellen and Gaillard)

Methods to estimate (benthic) carbon mineralisation

1. Direct Methods

(Incubation of sediment or sediment-water enclosures)

Electron acceptor consumption or reduced product formation over time

- O_2, N_2, Fe_2^+, CH_4^+, .ΣCO_2^-.....)

Remineralisation of organic substances

- acetate, fatty acids, glucose .....)

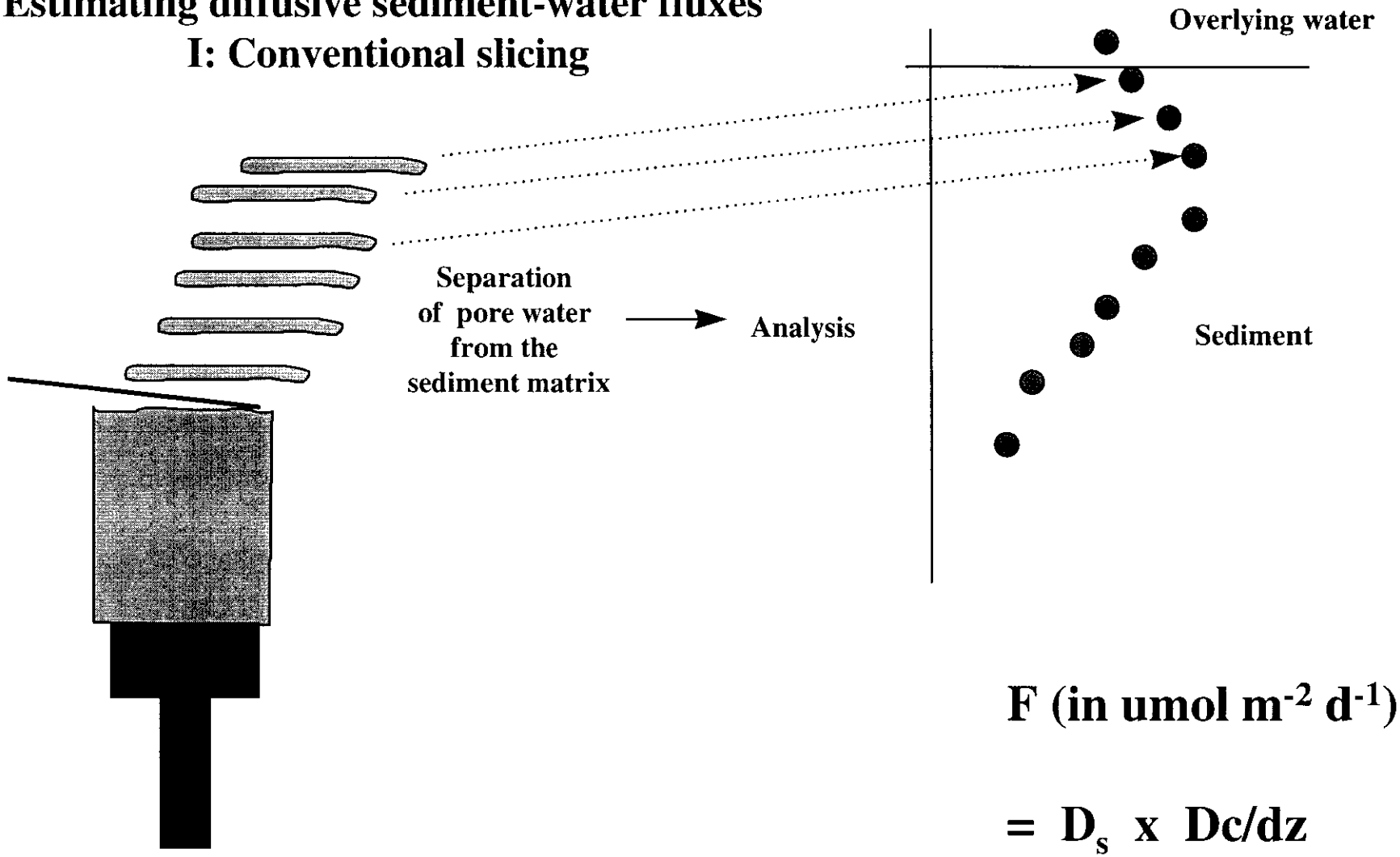
2. Indirect Methods

(Pore water profiling)

- solid phase organic carbon
- hydrolysable amino acids

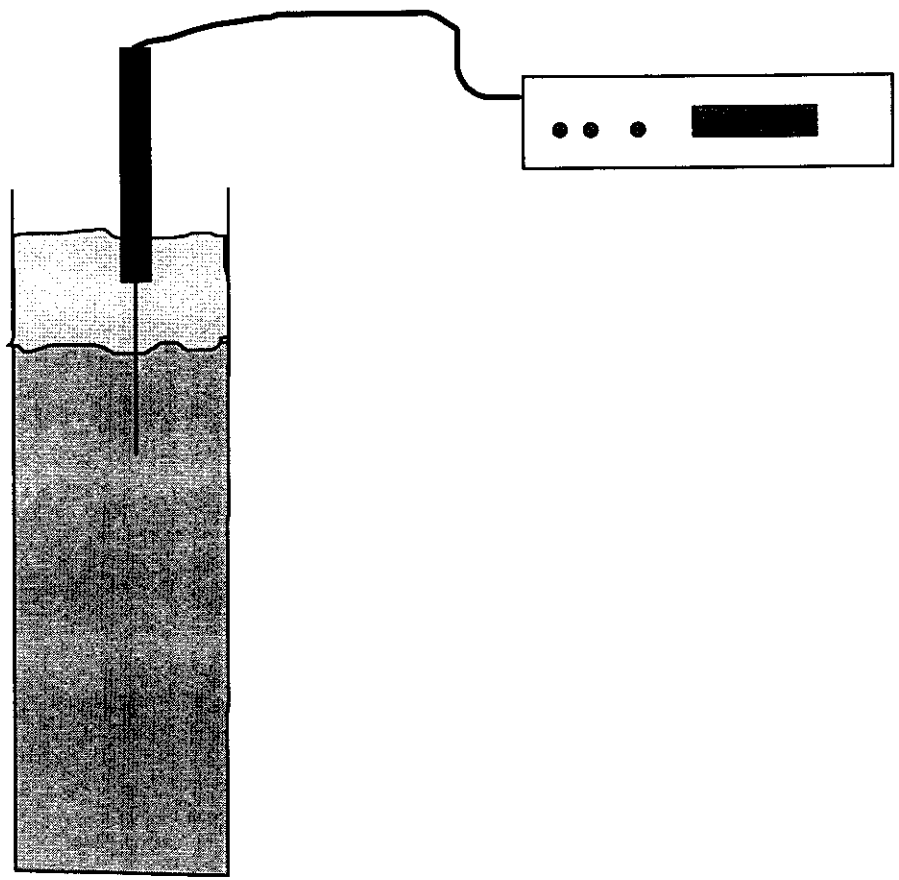
- electron acceptors (e. g. O_2, NO_3^-)
- reduced products (Mn_2^+, Fe_2^+, ΣCO_2^-, NH_4^+.....)

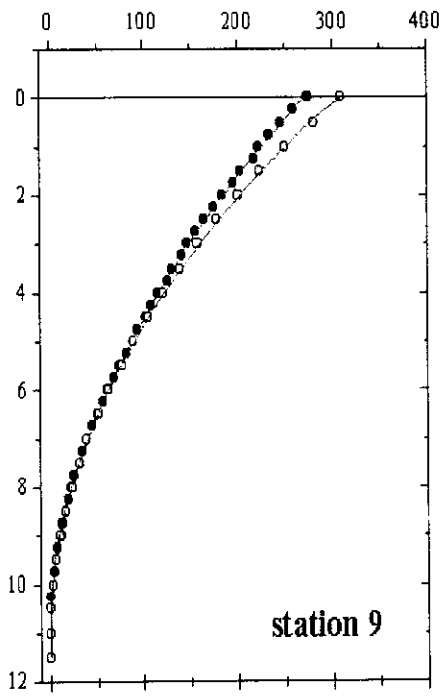
Estimating diffusive sediment-water fluxes
I: Conventional slicing



$$F \text{ (in umol m}^{-2}\text{ d}^{-1}) = D_s \times Dc/dz$$

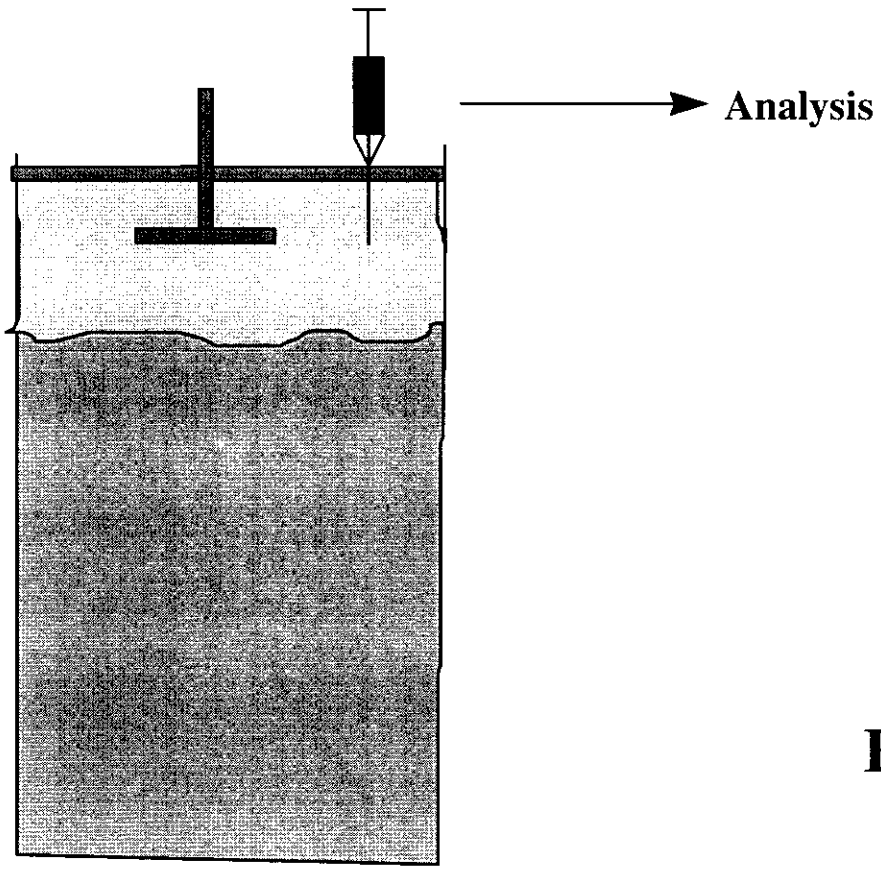
Estimating diffusive sediment-water fluxes
II: Ion-specific micro-electrodes

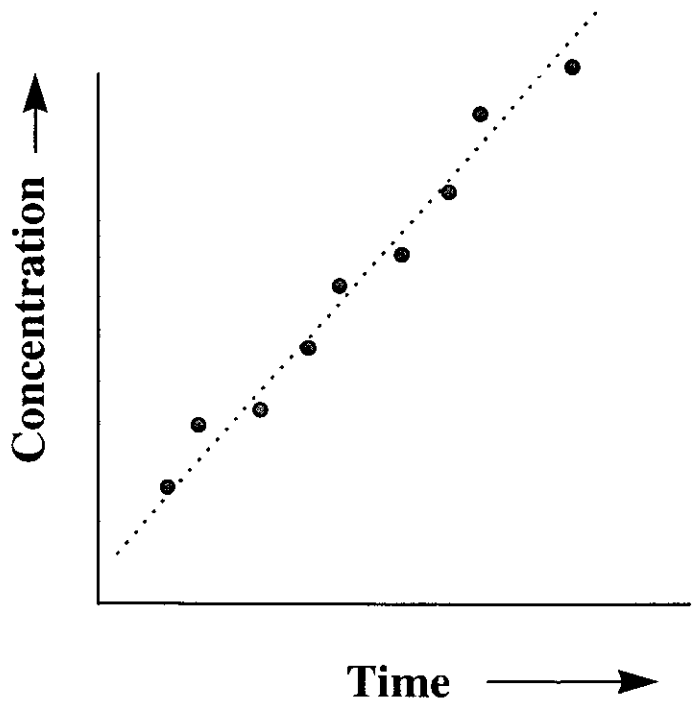




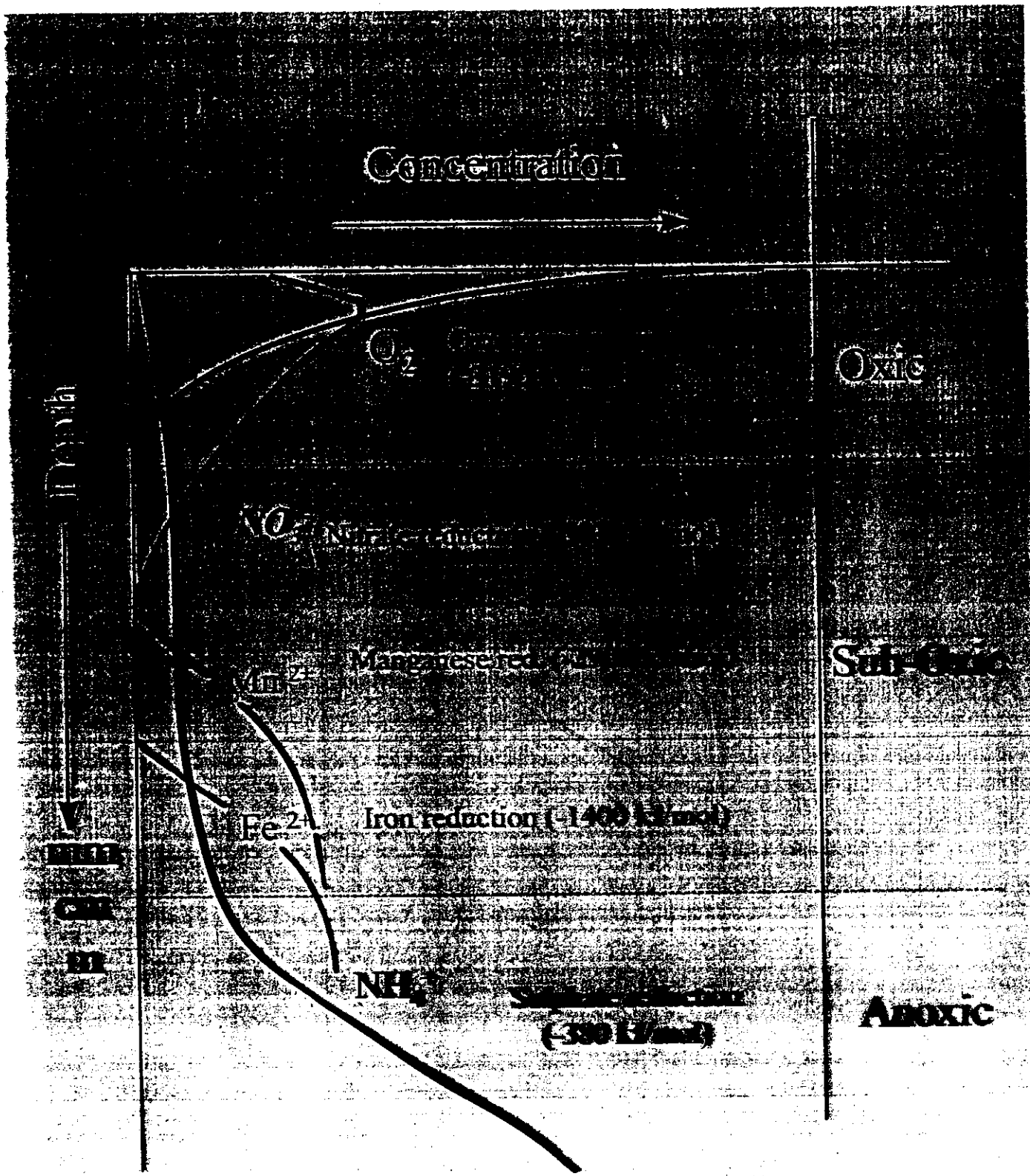
Lohse et al, Benthic Mineral Cycling, IT(

Estimating sediment-water fluxes
III. Whole core incubations





$$F = dc/dt \times A/V$$


Concentration
Oxic
Anoxic

Organic carbon oxidation reactions and the subsequent oxidation of reduced species.

O_2 respiration:

$$CH_2O + \mathbf{O_2} \rightarrow H_2O + CO_2$$

Denitrification:

$$CH_2O + 4/5\ H^+ + 4/5\ \mathbf{NO_3^-} \rightarrow CO_2 + 2/5\ N_2 + 7/5\ H_2O$$

Mn reduction:

$$CH_2O + 4H^+ + 2MnO_2 \rightarrow 2\mathbf{Mn^{2+}} + 3H_2O + CO_2$$
$$\underline{2H_2O + 2\ Mn^{2+} + O_2 \rightarrow 2MnO_2 + 4H^+}$$
$$CH_2O + O_2 \rightarrow H_2O + CO_2$$

Fe reduction:

$$CH_2O + 8H^+ + 4FeOOH \rightarrow 4\mathbf{Fe^{2+}} + CO_2 + 7H_2O$$
$$\underline{6\ H_2O + O_2 + 4Fe^{2+} \rightarrow 4\ FeOOH + 8H^+}$$
$$CH_2O + O_2 \rightarrow H_2O + CO_2$$

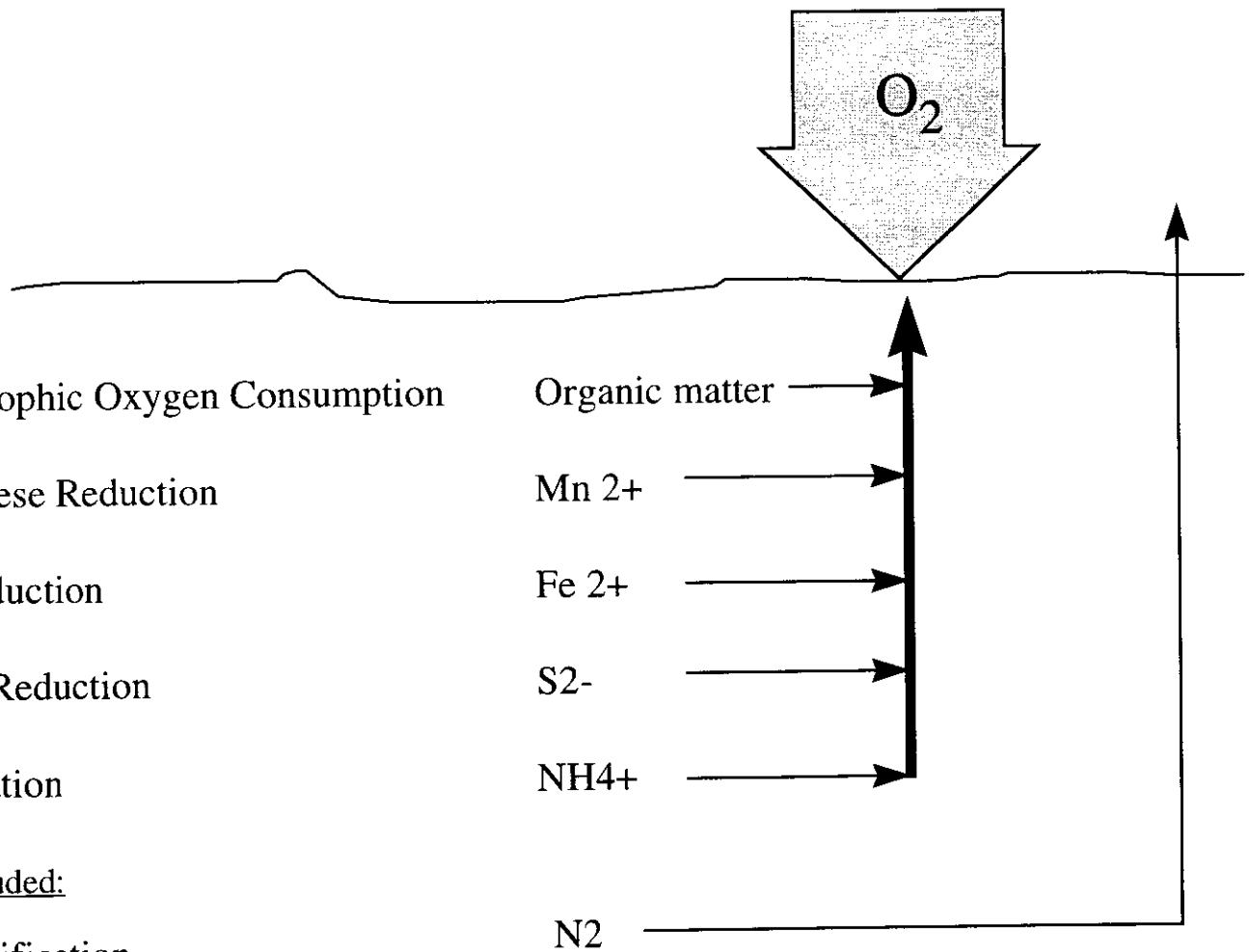
Sulfate reduction:

$$CH_2O + H^+ + 1/2\ \mathbf{SO_4^{2-}} \rightarrow CO_2 + ½\ H_2S + H_2O$$
$$\underline{O2 + ½\ H_2S \rightarrow ½\ SO_4^{2-} + H^+}$$
$$CH_2O + O_2 \rightarrow H_2O + CO_2$$

NH_4^+ oxidation:

$$\mathbf{NH_4^+} + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

Carbon oxidation rates
derived from benthic oxygen uptake rates



CARBON OXIDATION RATE

=

OXYGEN UPTAKE RATE

+ DENITRIFICATION

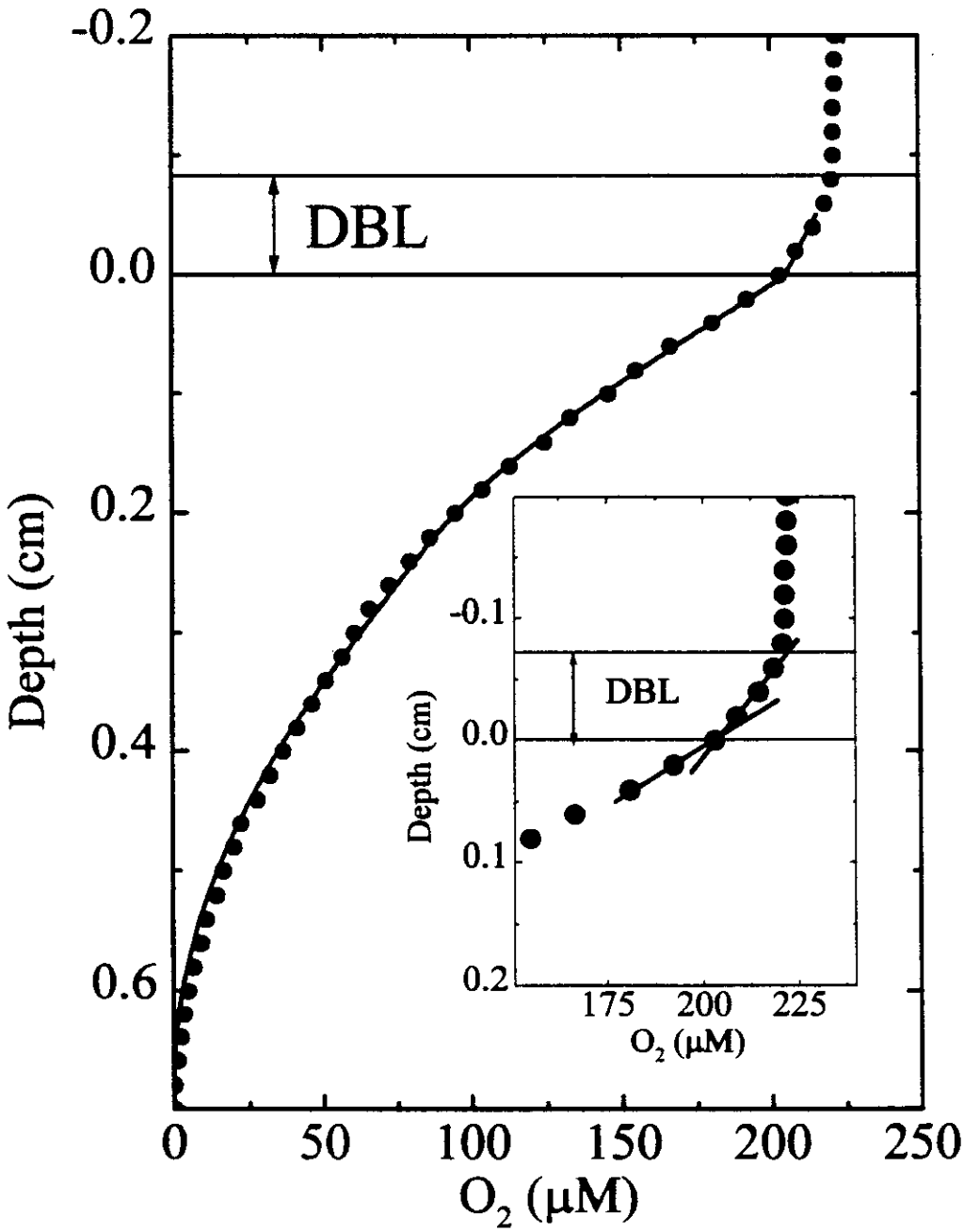
- OXYGEN CONSUMED BY NITRIFICATION

Constraints:

1) All reduced metabolites produced during suboxic and anoxic diagenesis are re-oxidised

2) CO_2 is the ultimate reaction product of all mineralisation processes

3) Burial of reduced compounds is negligible


-0.2
0.0
0.2
0.4
0.6
DBL
Depth (cm)
0
50
100
150
200
250
O2 (µM)
-0.1
0.0
0.1
0.2
DBL
Depth (cm)
175
200
225
O2 (µM)

Steady state distribution of dissolved solutes (oxygen)

$$0 = D_s \frac{d^2C}{dz^2} - R$$

Diffusion coefficient

Diffusive gradient

Reaction

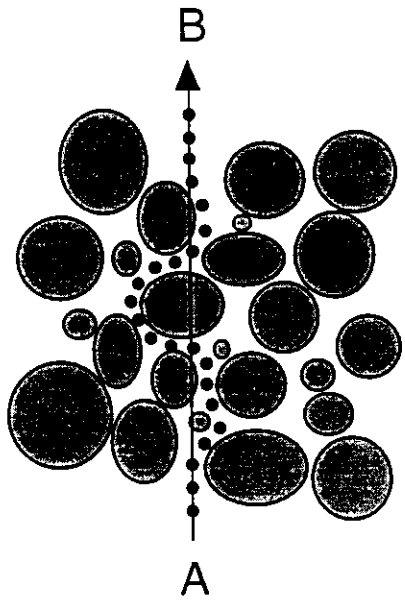


Figure 3.13. A solute trying to diffuse from point A to point B cannot pass through solid sediment particles (filled shapes). The solute must travel around these particles and so traverses the *tortuous* dotted path, rather than the direct solid-line path.

from Boudreau, 1998

Determination of the sediment diffusion coefficient D_s

$$D_s = \frac{D_0}{\phi F}$$

where Do is the diffusion coefficient for a free solution

ϕ is the porosity

F is the resistivity formation factor

$$F = \frac{R_{sediment}}{R_{water}}$$

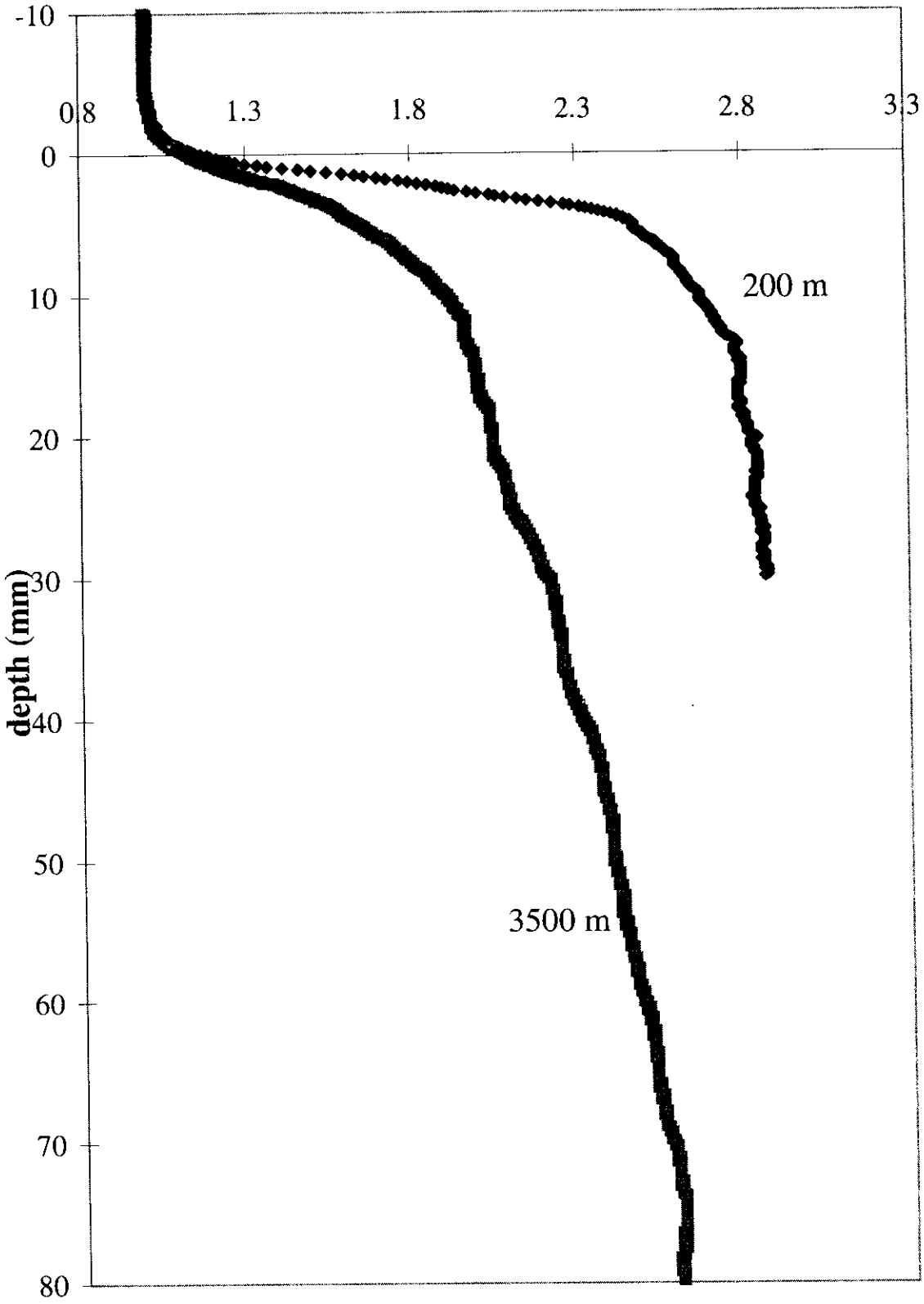
then the porosity profile can be calculated by

$$\phi = F^{\frac{1}{n}}$$

where n ranges between 1.5 and 3.5 for sandy and muddy sediments, respectively.

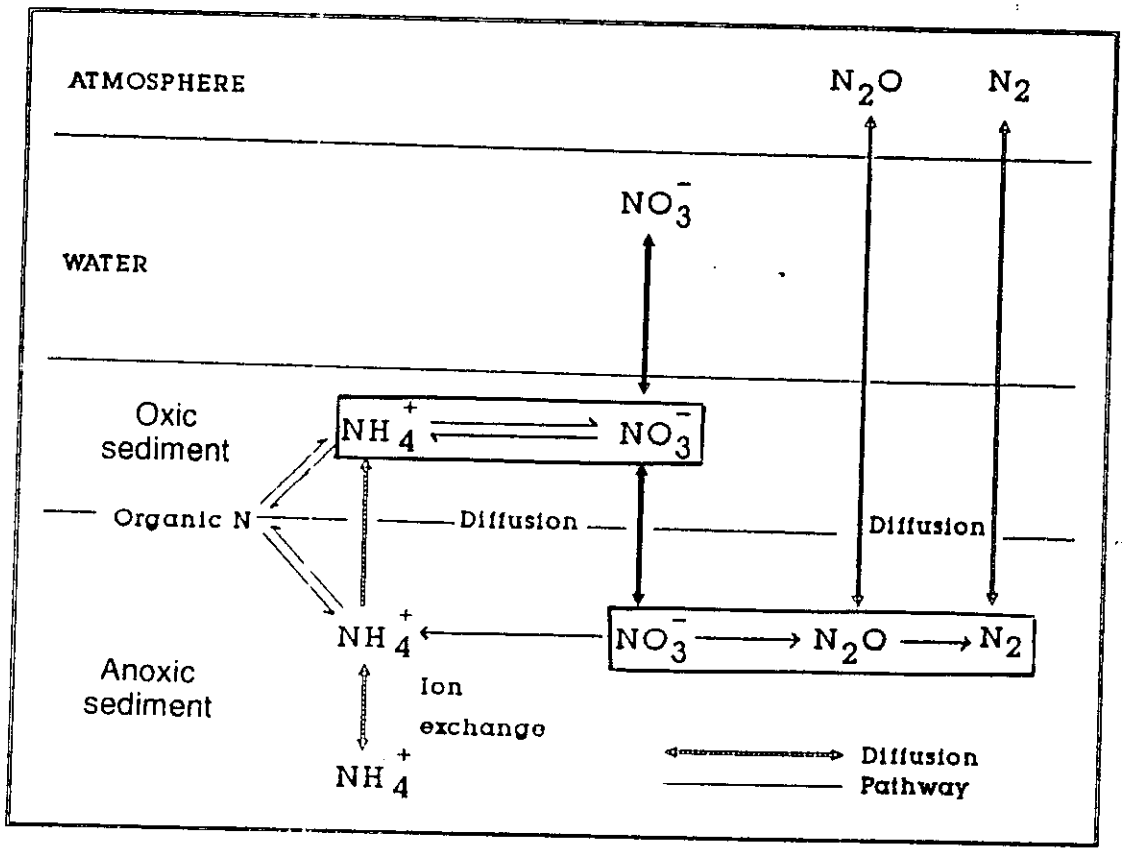
Resistivity Formation Factor

F [-]



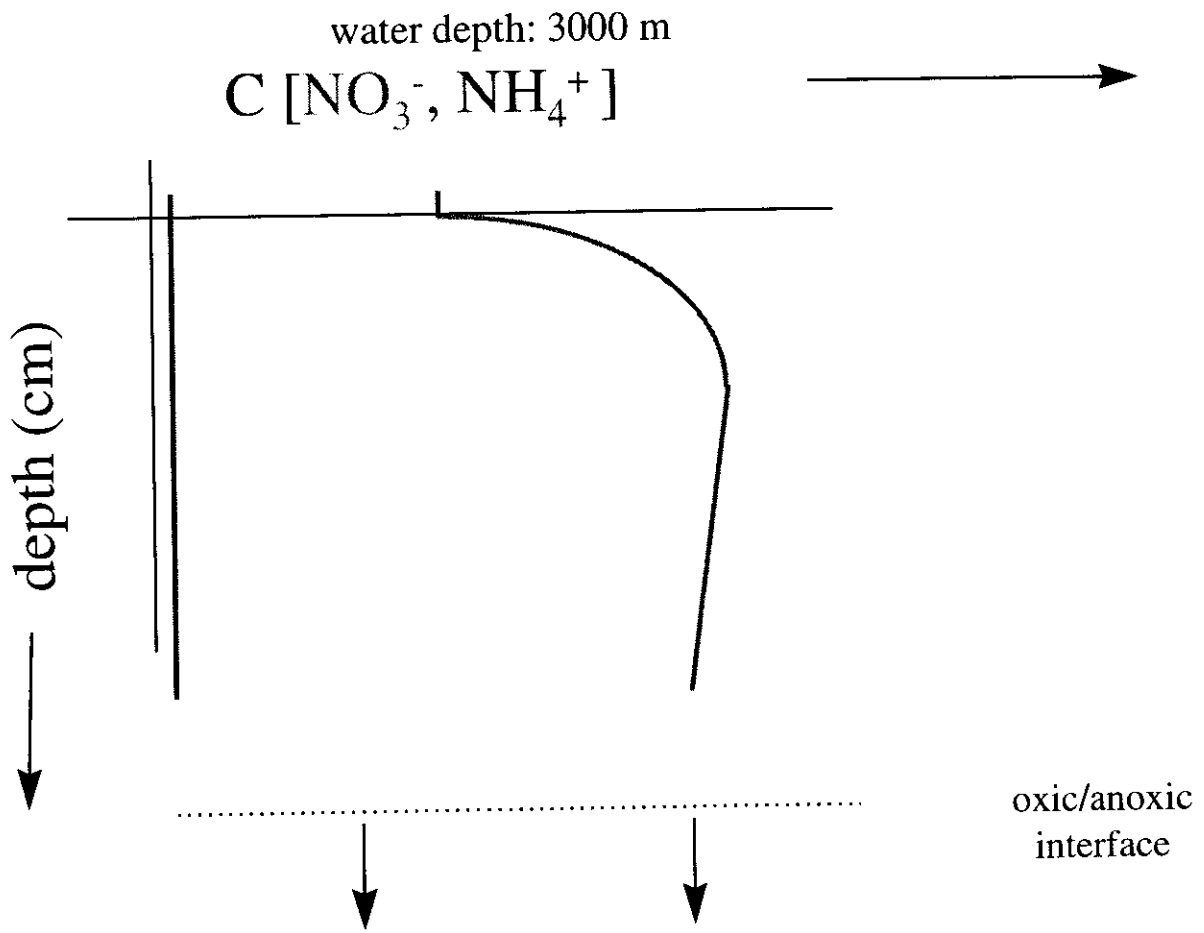
18

N-mineralisation in marine sediments: A conceptual view



Generalised nitrogen mineralisation

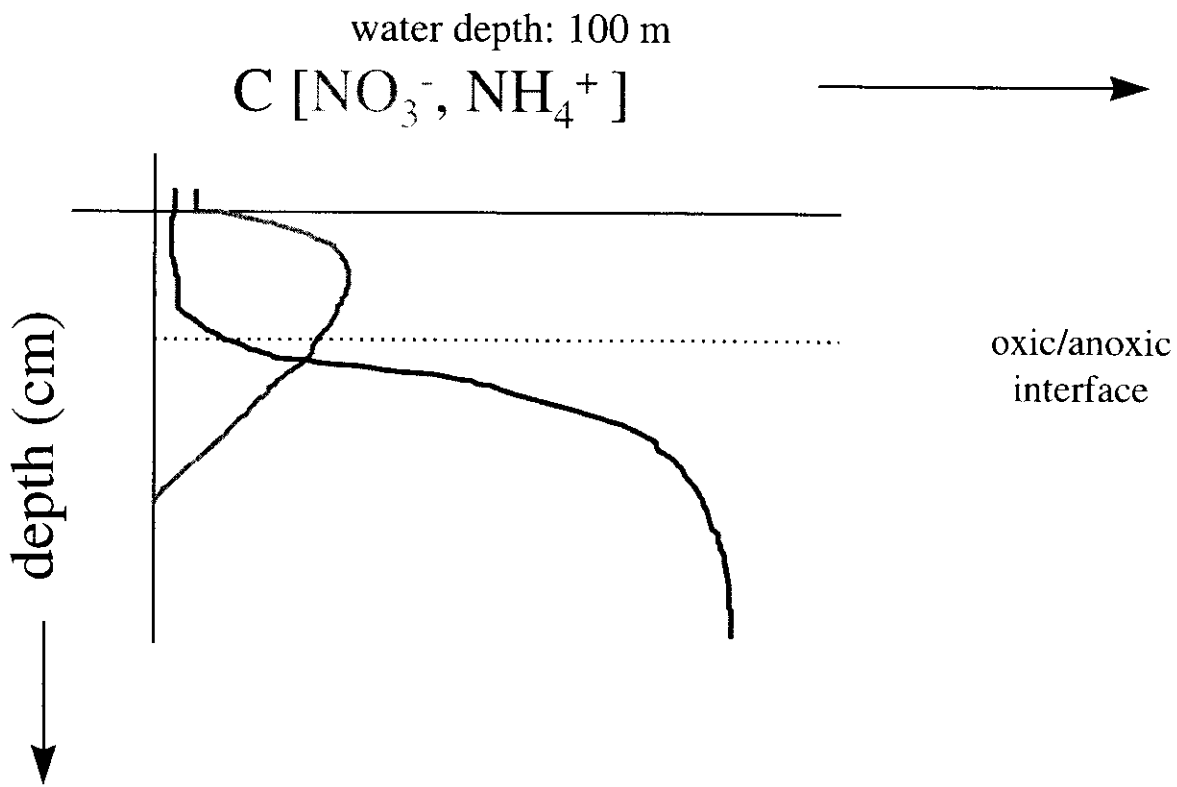
Case 1: Pelagic sediments



Lohse et al, Benthic mineral cycling, ITCP, Nov 1998

Generalised nitrogen mineralisation

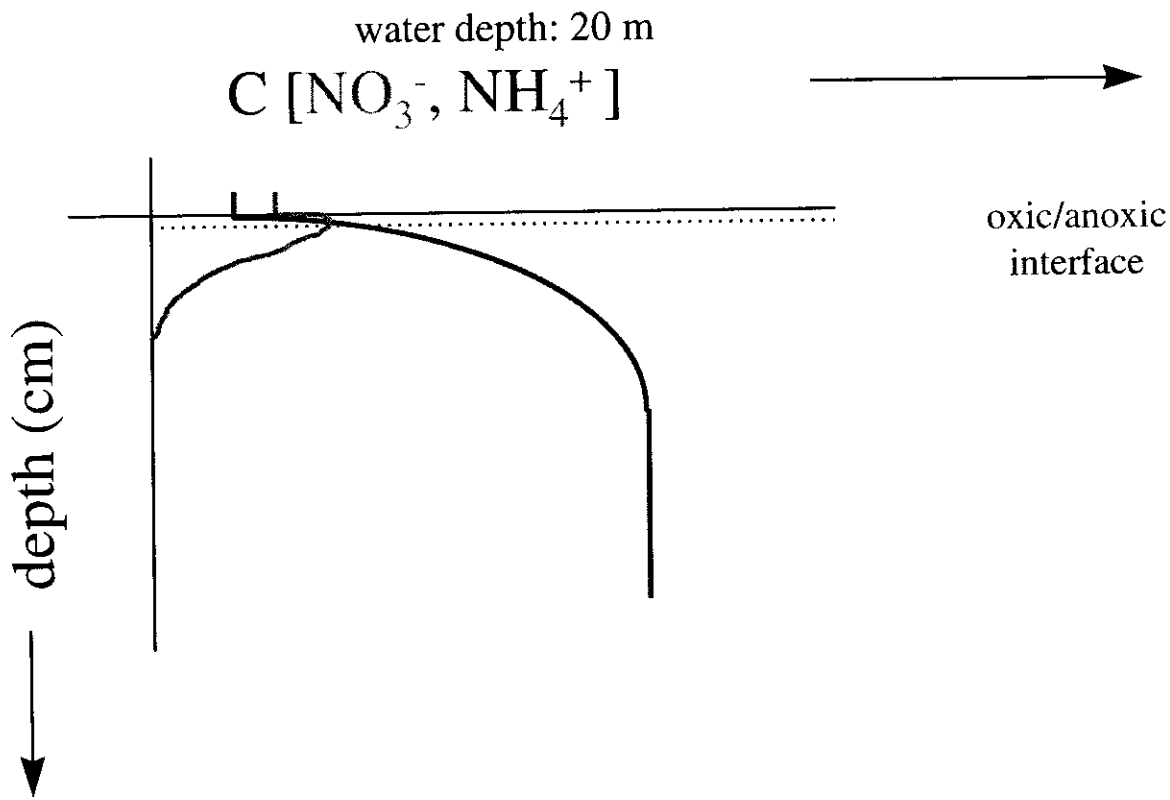
Case 2: Shelf sediments



Lohse et al, Benthic mineral cycling, ITCP, Nov 1998

Generalised nitrogen mineralisation

Case 3: Coastal sediments



Lohse et al, Benthic mineral cycling, ITCP, Nov 1998

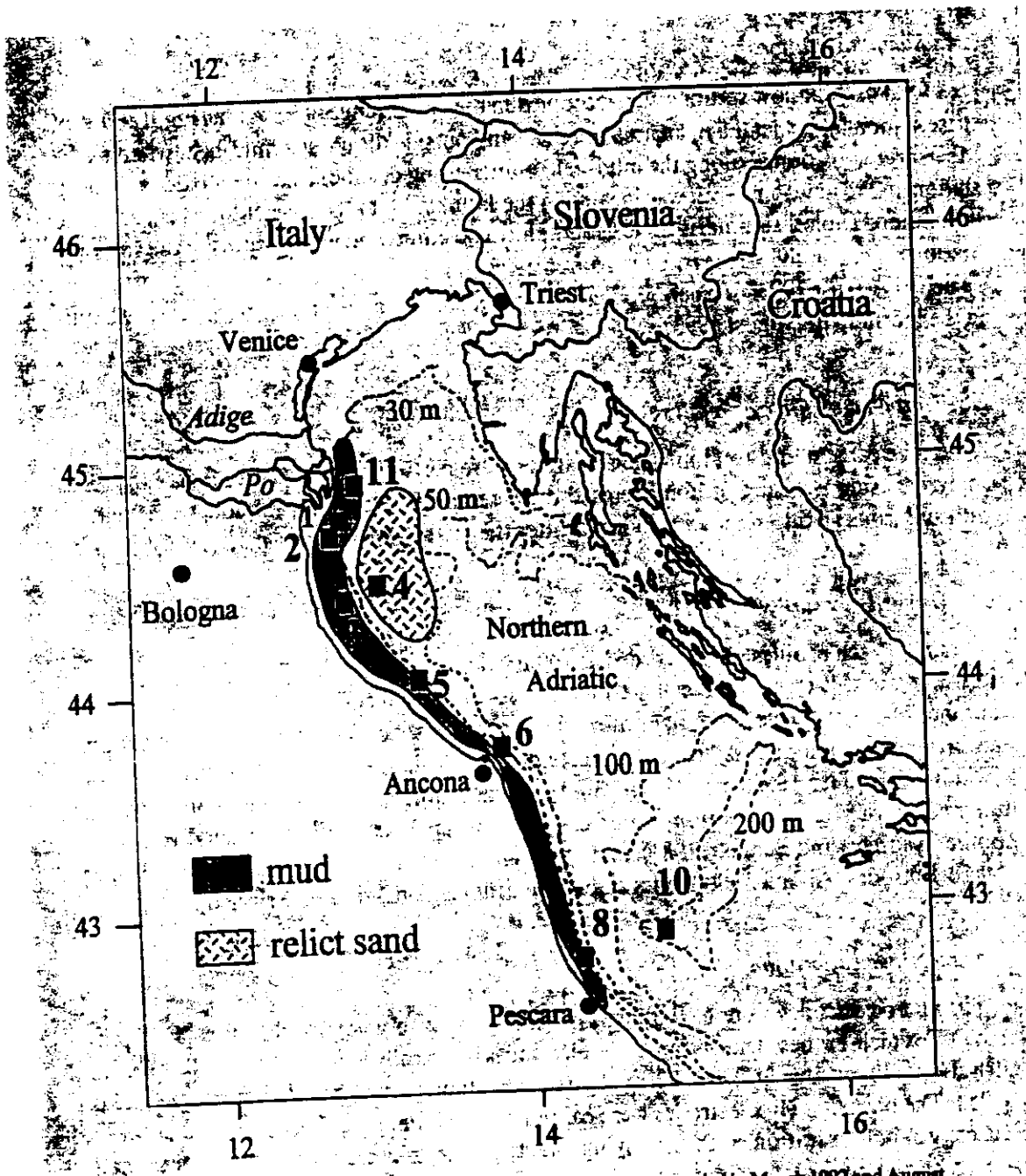
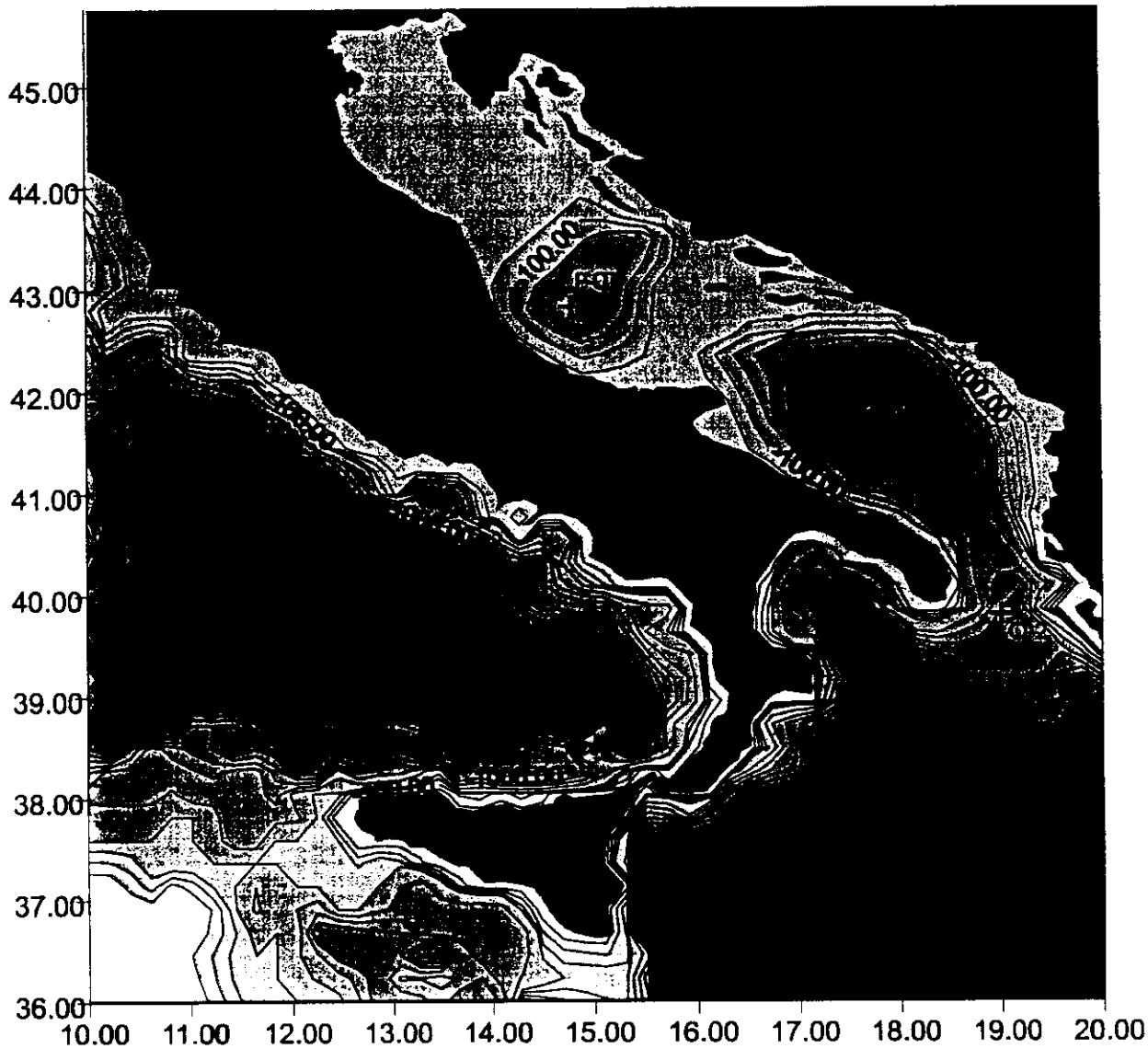


Fig. 1. Map of the Northern Adriatic Sea showing the stations occupied in March 1992 and August 1993.


45.00
44.00
43.00
42.00
41.00
40.00
39.00
38.00
37.00
36.00
10.00
11.00
12.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00

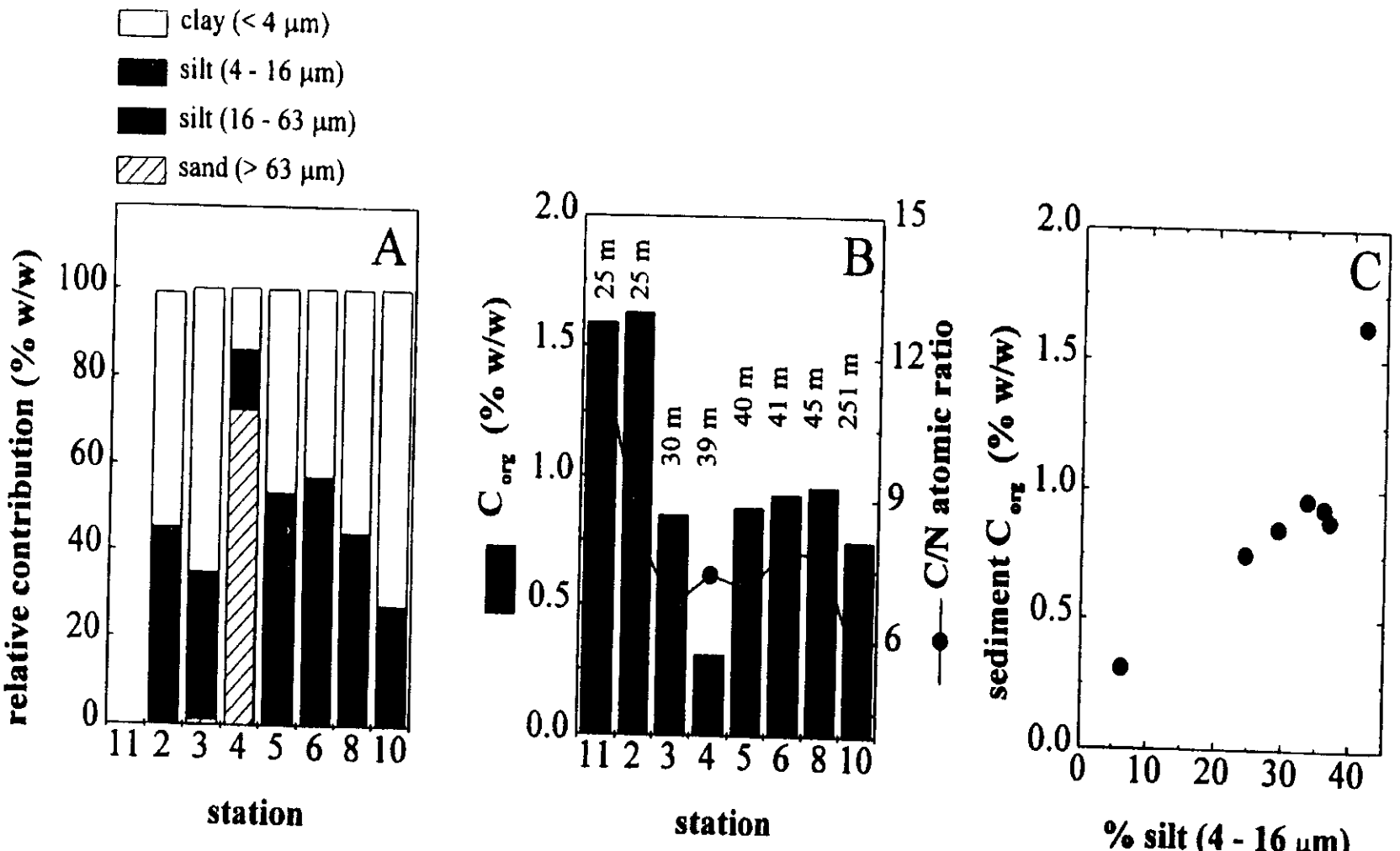


Fig. 2. Sediment characteristics of the occupied stations. (A) Sediment composition. Station 4 was located outside the coastal mudbelt in the relict sand area. Station 10 was located in the south at the Meso Adriatic Depression. Data were kindly provided by Dr P. Giordani, Institute for Marine Geology, Bologna. (B) Organic carbon content and the atomic C:N ratio for the surface 0–5 mm of the sediment. (C) Organic carbon content plotted against the silt (4–16 μm fraction) content of the sediments in August 1993.

Station	S (‰)		T (°C)		O_2 (µmol dm^{-3})		I_{sed} (µE m^{-2} s^{-1})	
	3-'92	8-'93	3-'92	8-'93	3-'92	8-'93	3-'92	8-'93
11		38.2		15.7		215 (88%)		15.2
2		38.1		14.1		192 (75%)		20.8
3	38.1	38.1	9.8	16.3	238 (85%)	207 (86%)	1.4	35.1
4		38.2		14.0		196 (77%)		8.1
5	38.2	38.2	10.0	14.0	277 (100%)	272 (108%)	-	19.4
6	38.3	38.3	10.5	13.1	275 (100%)	277 (108%)	1.1	11.4
8	38.3	38.1	11.2	15.7	255 (95%)	245 (102%)	0.5	-
10		38.3		10.9		224 (81%)		

Table 2. *Bottom water salinity (S), temperature (T), oxygen concentration and PAR quantic irradiance at the seafloor, in March 1992 and August 1993. PAR values were kindly provided by prof. M.Innamorati and dr. L.Massi, Laboratorio di Ecologia, Florence, Italy.*

Epping and Kelder, 1992
Cont. Shelf Res 17 (4) 1737-1769

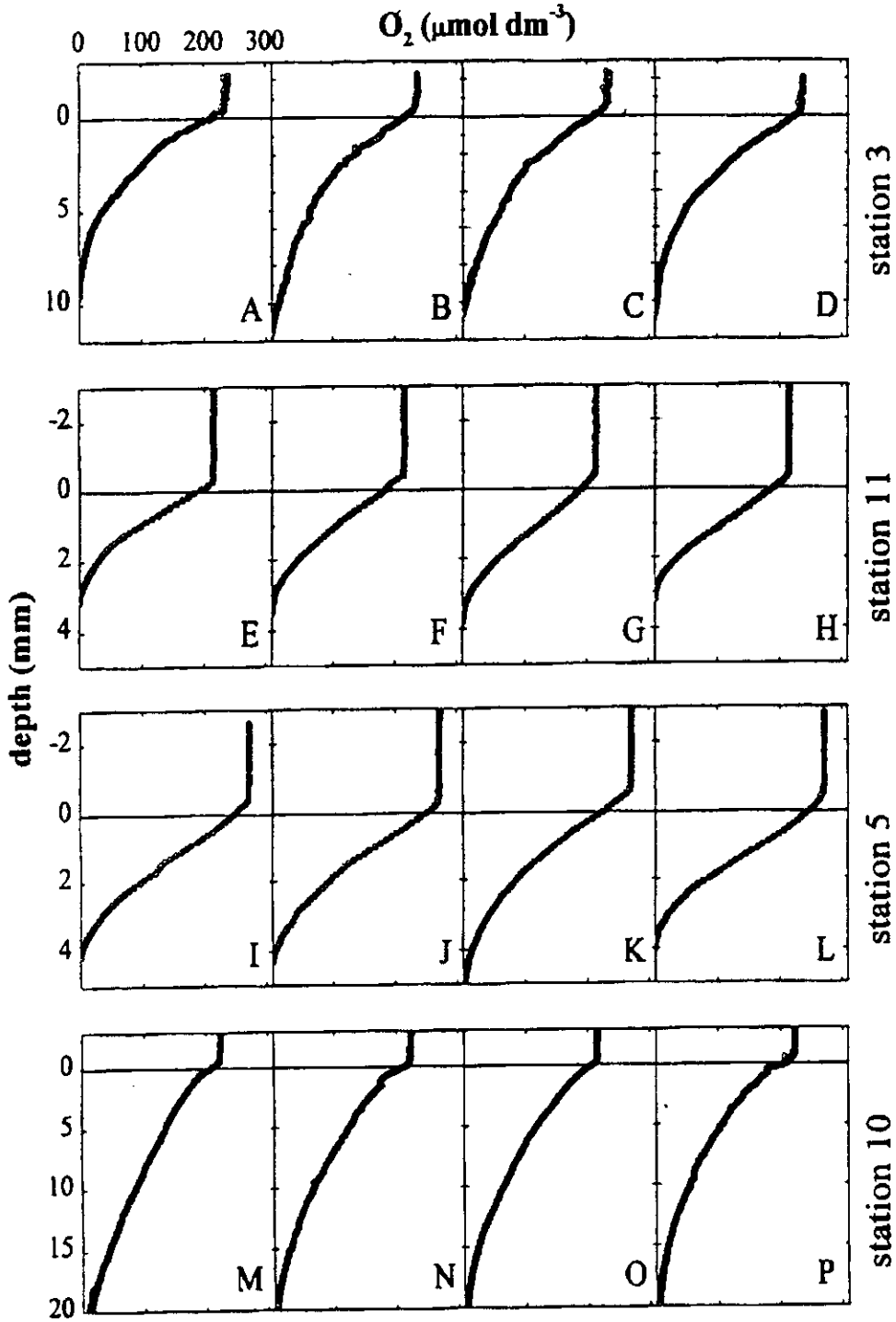


Fig. 6. *In situ* oxygen profiles and the best fit according to model 4. (A–D) station 3 in March 1992, (E–H) station 11 in August 1993, (I–L) station 5 in August 1993, and (M–P) station 10 in August 1993. Profiles from station 11 and 5 could only be described by assuming benthic photosynthesis.

Reactivity and Photosynthesis in Adriatic Sediments
(after Epping & Helder 1997)

$$0 = D_s \frac{d^2C}{dz^2} - R$$

MODEL I:

$$\sum R(O_2)\,(z) = -R$$

Model II

$$\sum R(O_2)\,(z) = -R_0 \exp^{az}$$

Model III

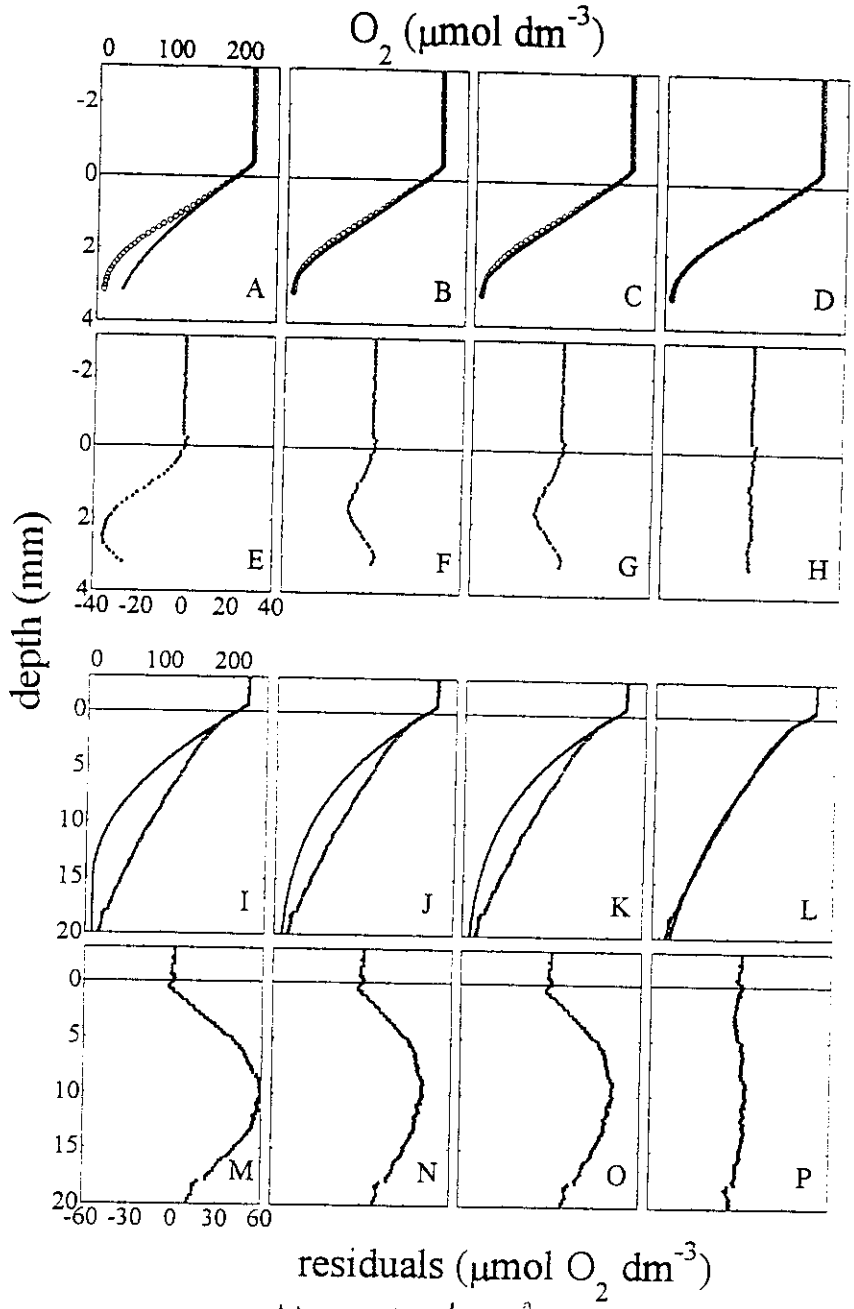
Layer I $\quad \sum R(O_2)\,(z) = -R_0$

Layer II $\quad \sum R(O_2)\,(z) = -R_0 e^{-a(z-z1)}$

Model IV

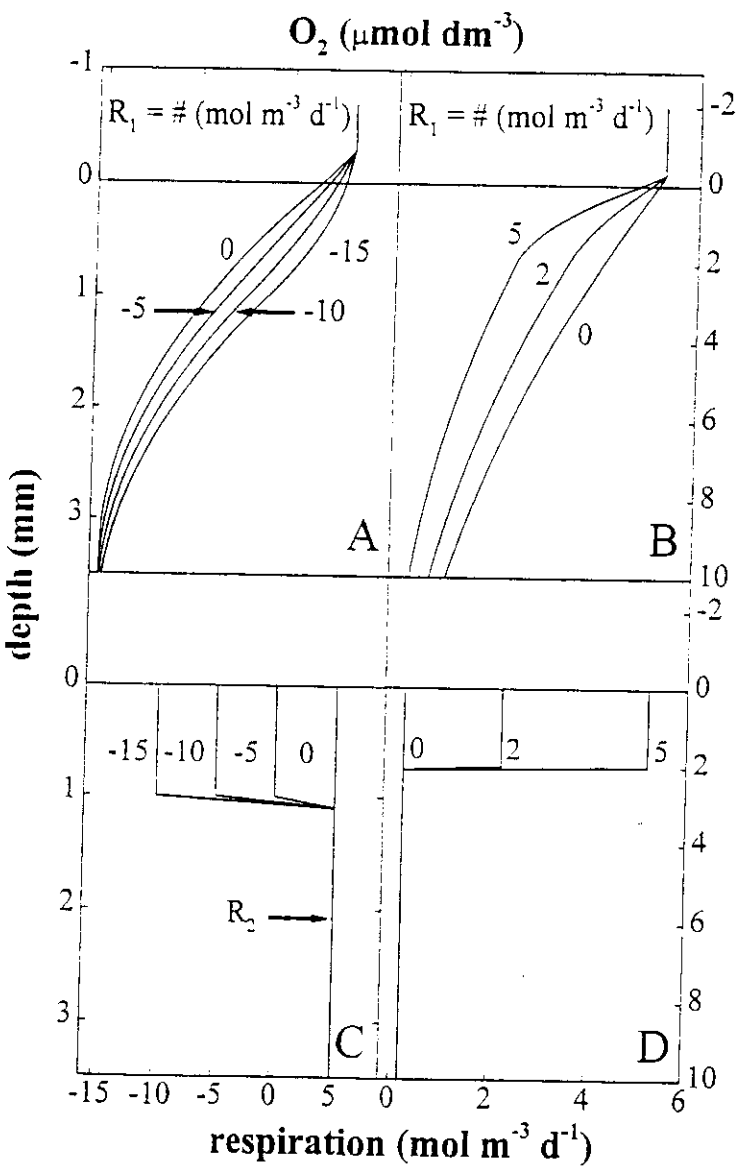
Layer I $\quad \sum R(O_2)\,(z) = -(R_1 + R_2)$

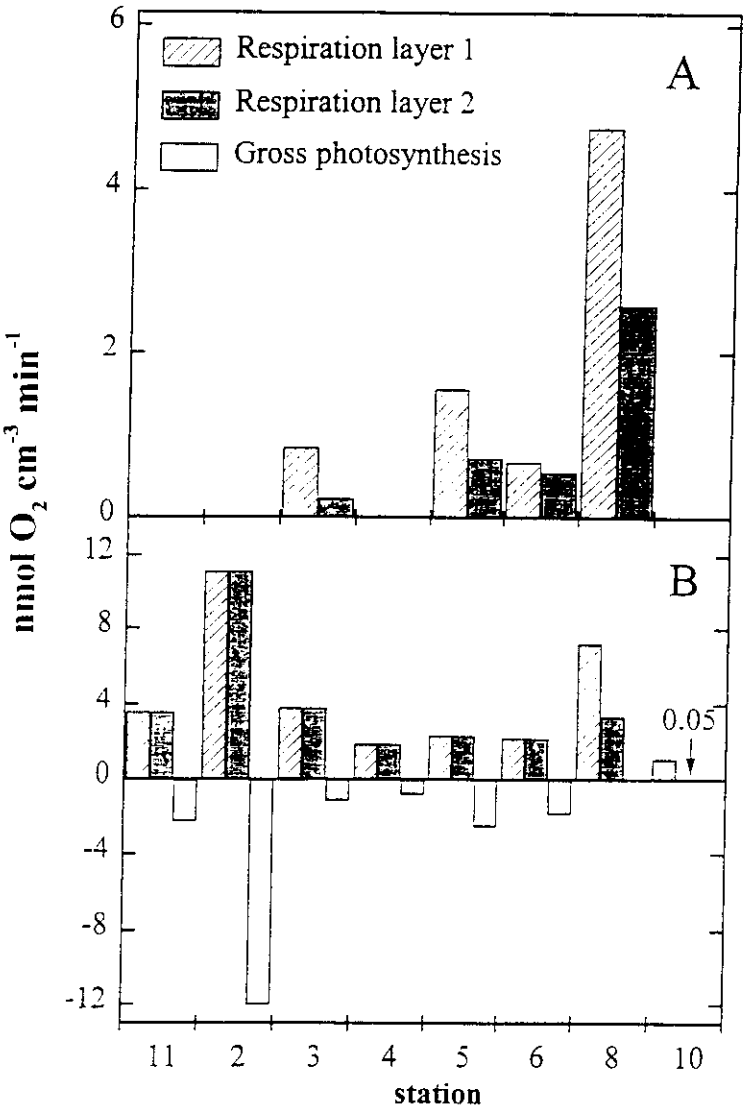
Layer II $\quad \sum R(O_2)\,(z) = -R_2$



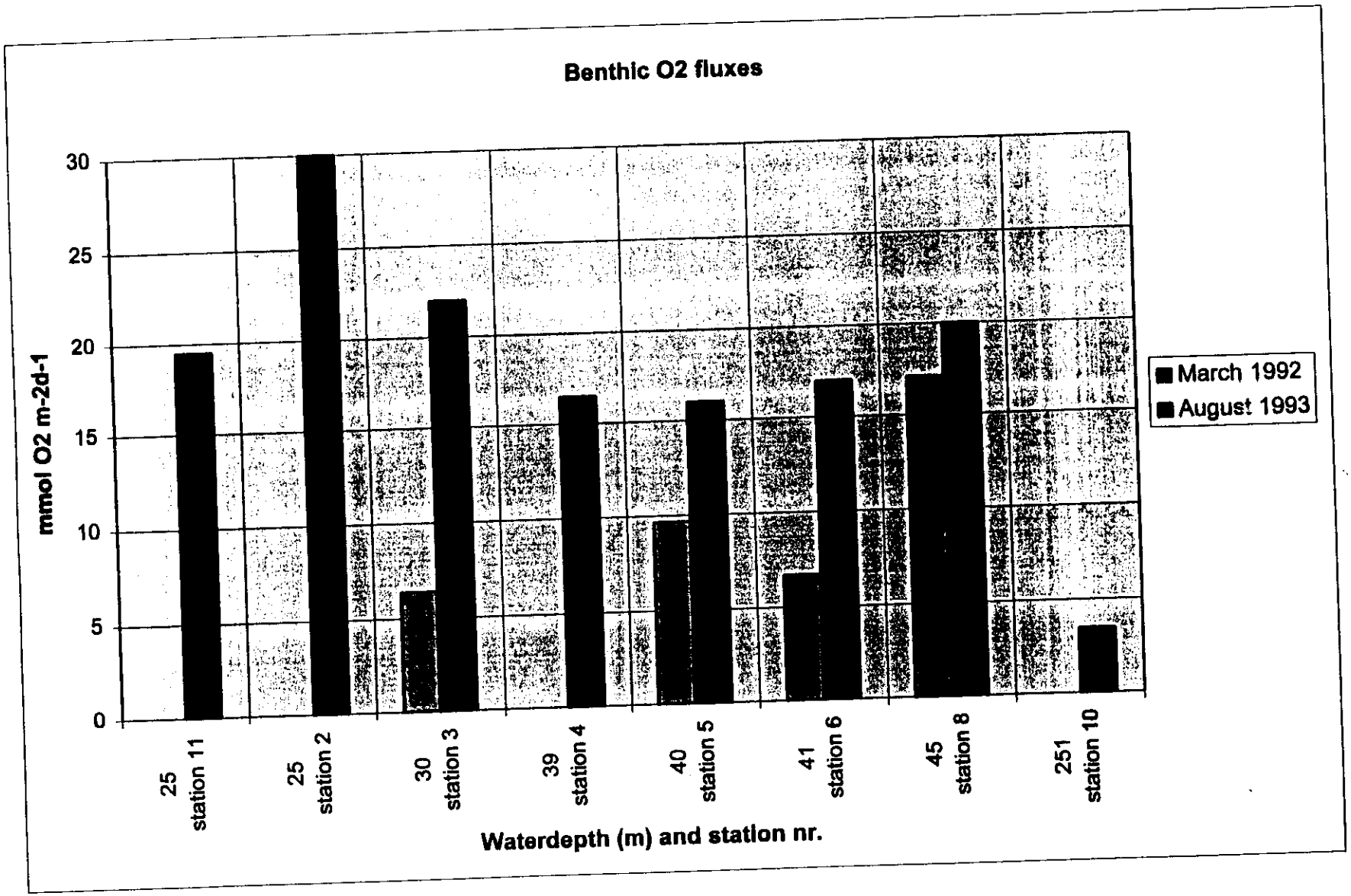
Epping and Helder. Cont Shelf Res. 17:1737-1764 (1998)

Figure 5. *(A-L) Comparison of the four models (solid lines) with a representative in situ profile (symbols) for the shallow stations (A-D) and for the deep station (I-L). (E-P) Residuals, defined as the difference between the experimental and modeled value. (E-H) The residuals for the oxygen profile from the shallow station and (M-P) for the profile from the deep station. The left lane of panels refer to model i, the central left lane to model ii, the central right lane to model iii and the rightmost lane to model iv.*


O2 (μmol dm-3)
R1 = # (mol m-3 d-1)
R1 = # (mol m-3 d-1)
0
-15
-5
-10
5
2
0
A
B
C
D
R2
depth (mm)
respiration (mol m-3 d-1)

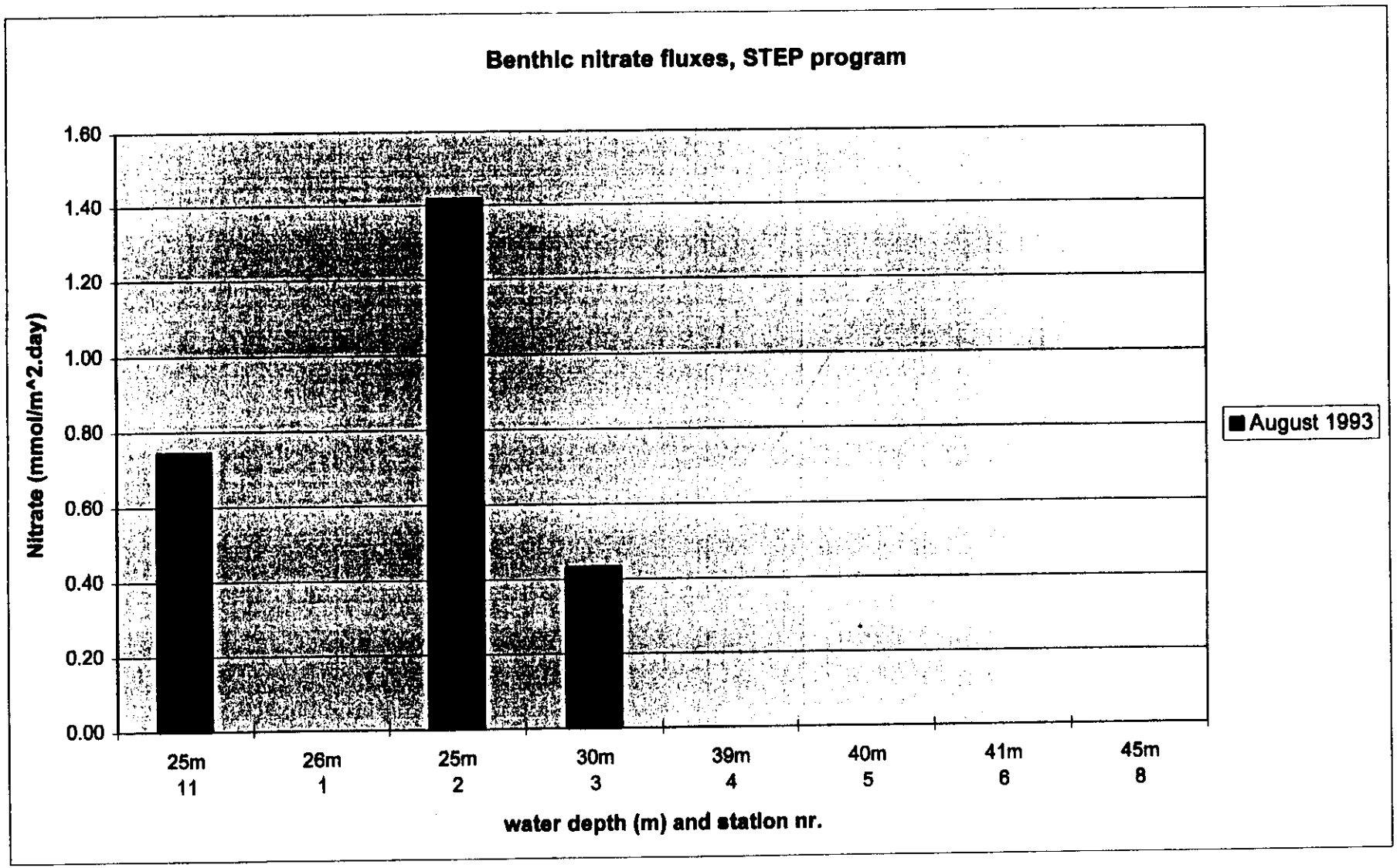


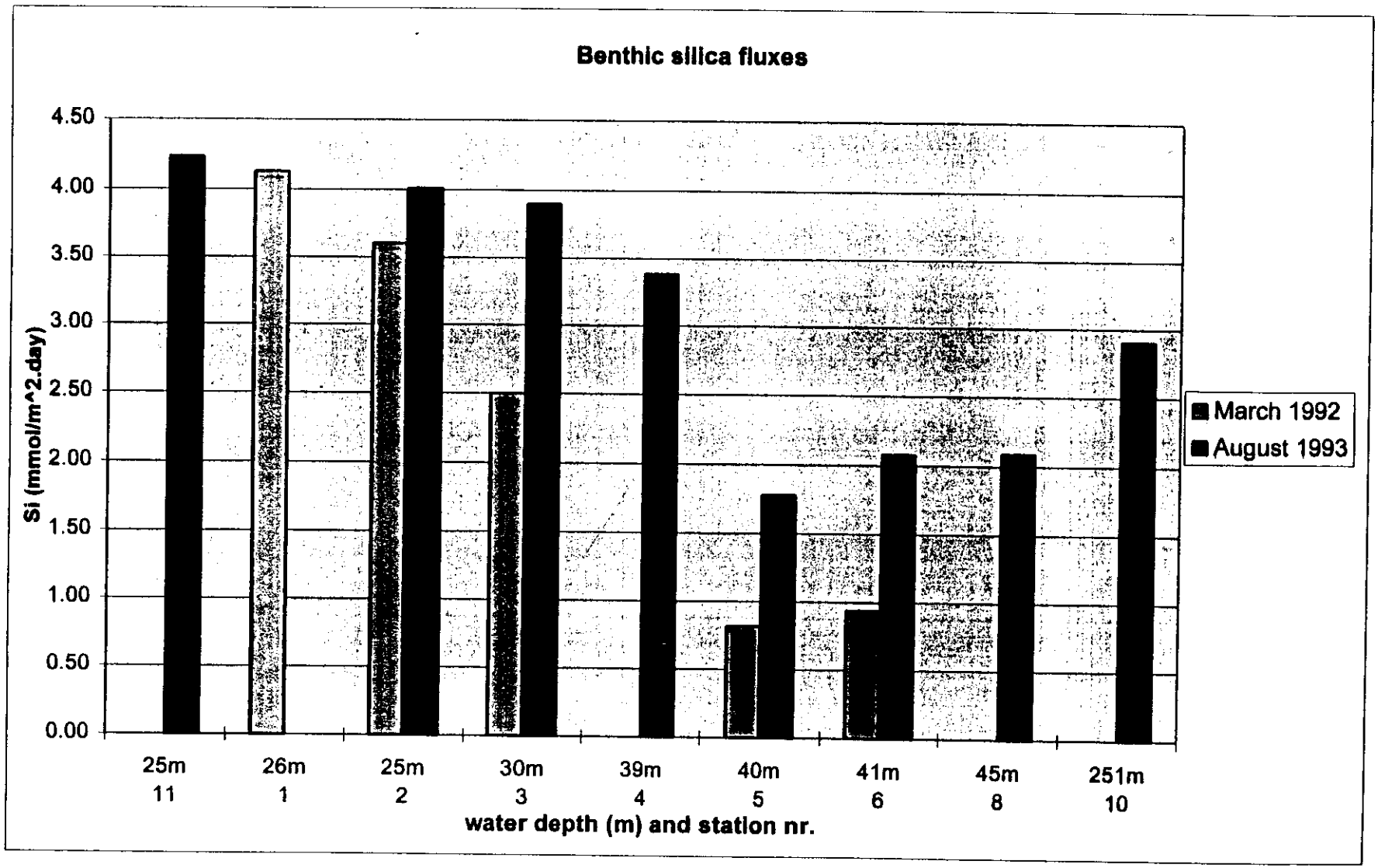
Epping + Kelder, 1998


Benthic O2 fluxes
mmol O2 m-2d-1
30
25
20
15
10
5
0
March 1992
August 1993
25 station 11
25 station 2
30 station 3
39 station 4
40 station 5
41 station 6
45 station 8
251 station 10
Waterdepth (m) and station nr.

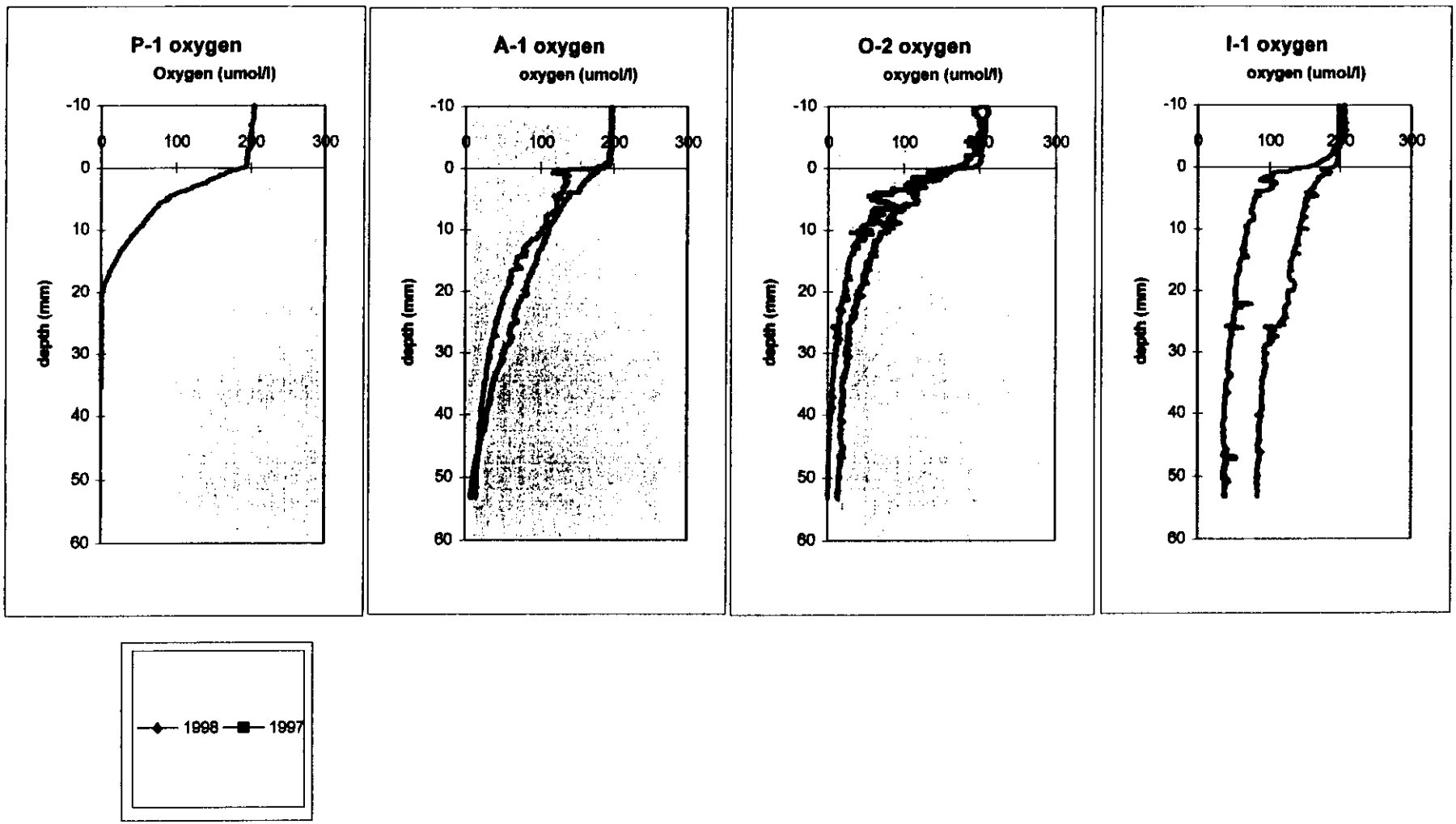
Benthic oxygen fluxes (mmol O_2 m^{-2} d^{-1}) in the shallow Northern Adriatic Sea

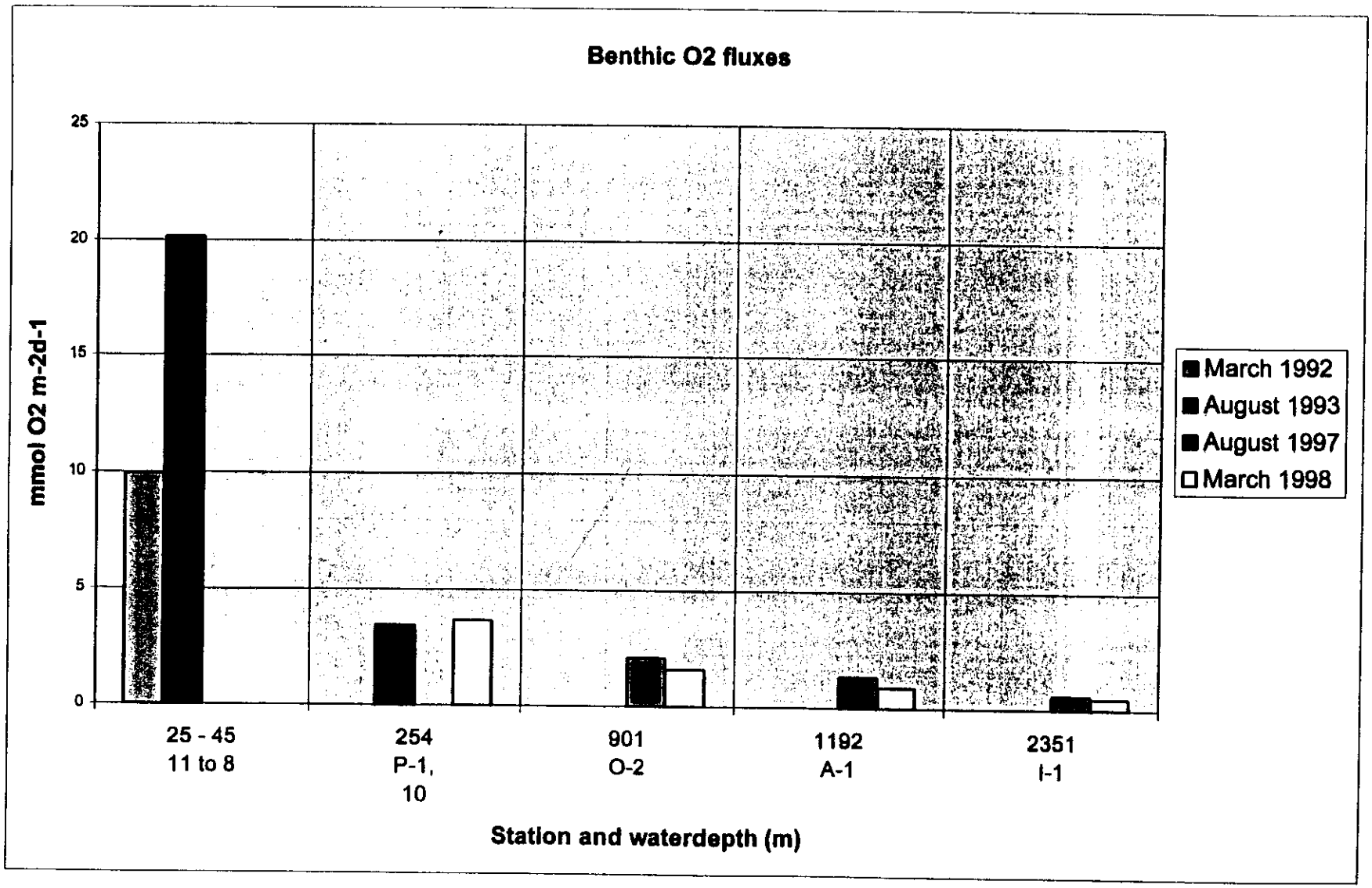
	Febr-March	August-Sept.
Giordani et al. (1992)	-	11.9 - 19.9
Tahey et al. (1996)	8.4 - 24.4	15.0 - 34.8
Epping and Helder (1997)	6.4 - 17.1	16.3 - 30.0
Moodley et al. (in press)	2.8 - 16.8	22.7 - 47.5

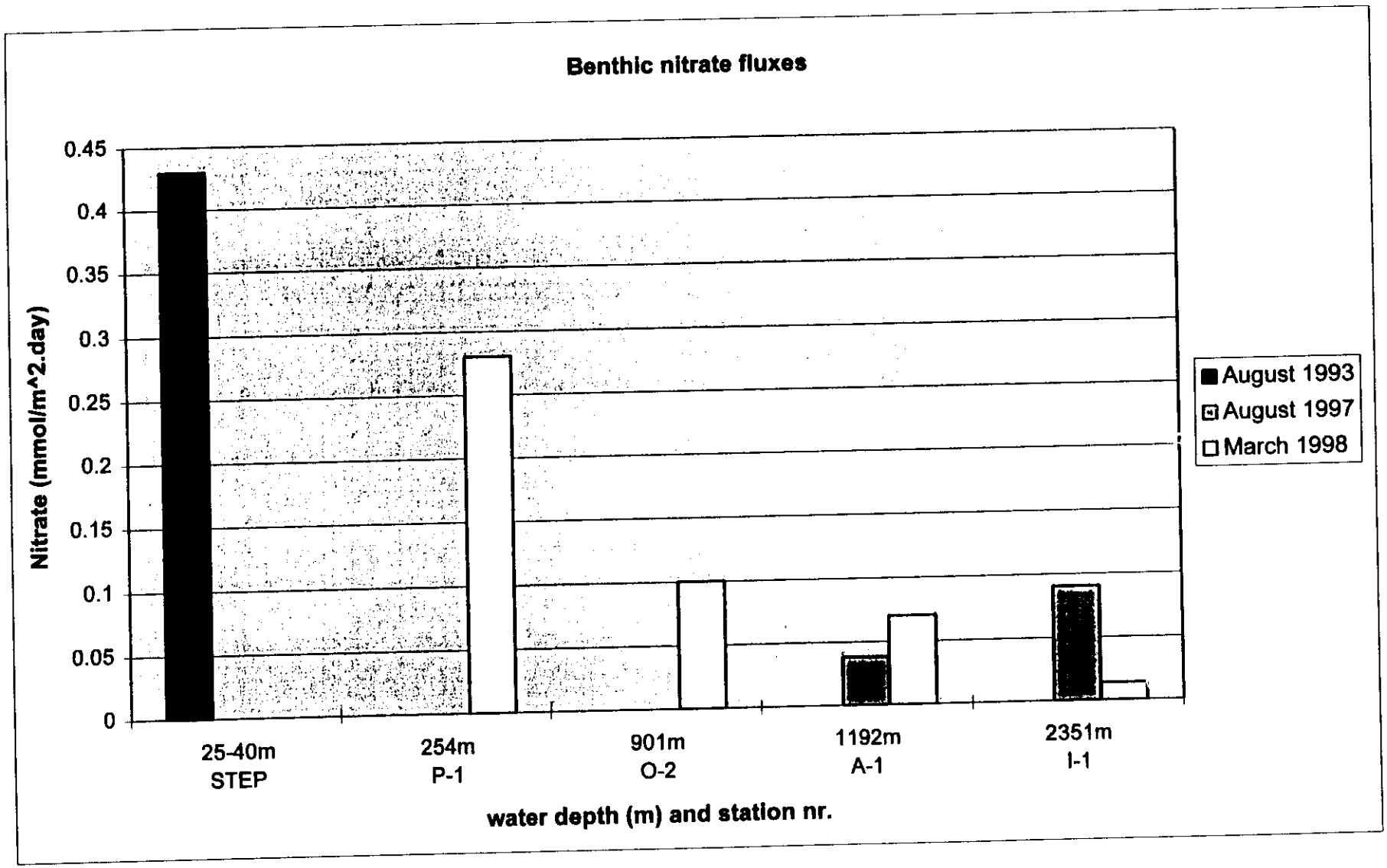

Benthic nitrate fluxes, STEP program
Nitrate (mmol/m^2.day)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
25m 11
26m 1
25m 2
30m 3
39m 4
40m 5
41m 6
45m 8
water depth (m) and station nr.
August 1993


Benthic silica fluxes
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Si (mmol/m^2.day)
March 1992
August 1993
25m
11
26m
1
25m
2
30m
3
39m
4
40m
5
41m
6
45m
8
251m
10
water depth (m) and station nr.

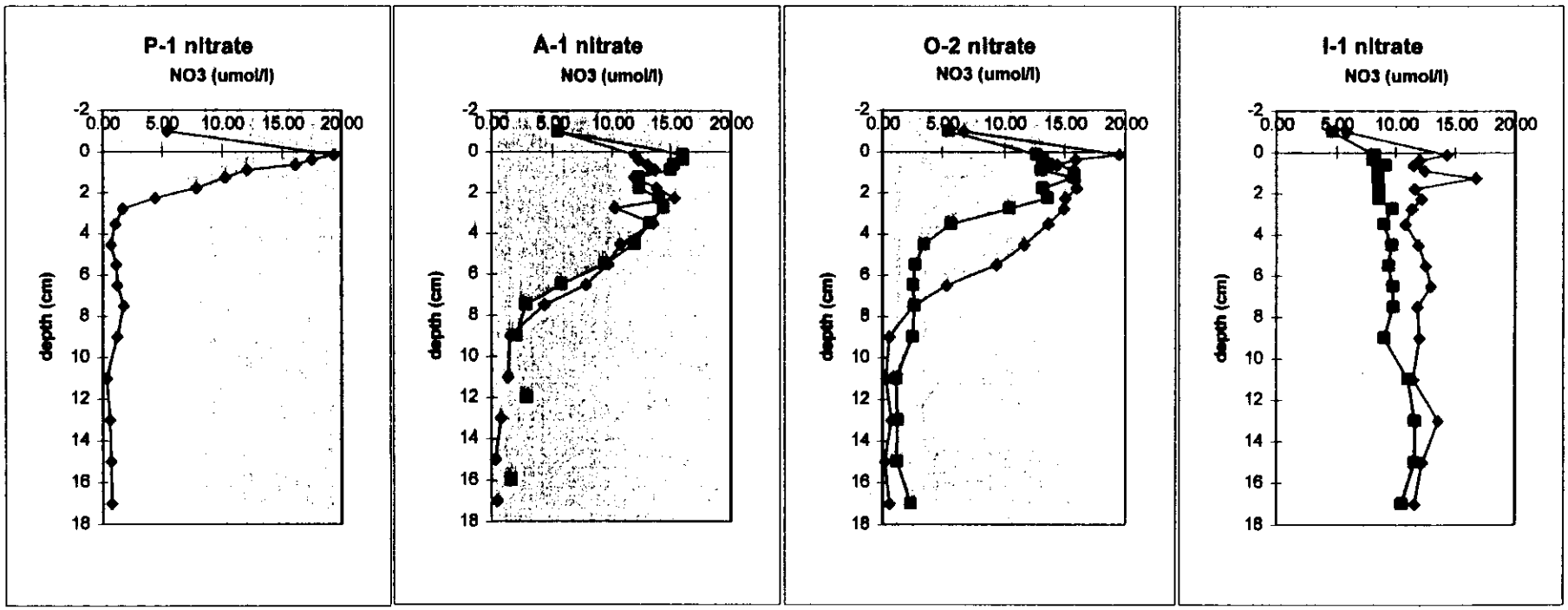
oxygen pore water profiles



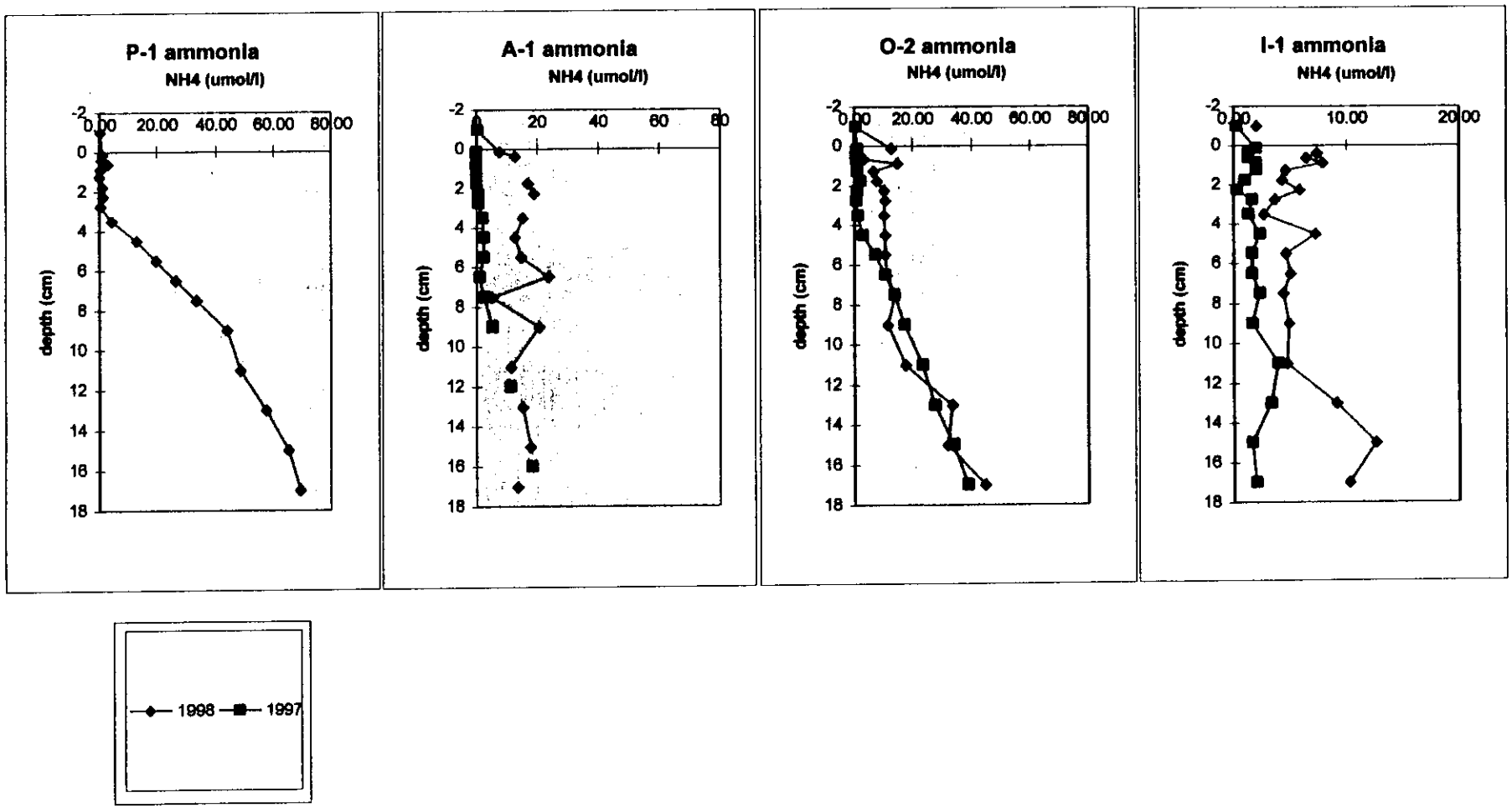

Benthic O2 fluxes
mmol O2 m-2d-1
25
20
15
10
5
0
25 - 45
11 to 8
254
P-1,
10
901
O-2
1192
A-1
2351
I-1
Station and waterdepth (m)
March 1992
August 1993
August 1997
March 1998

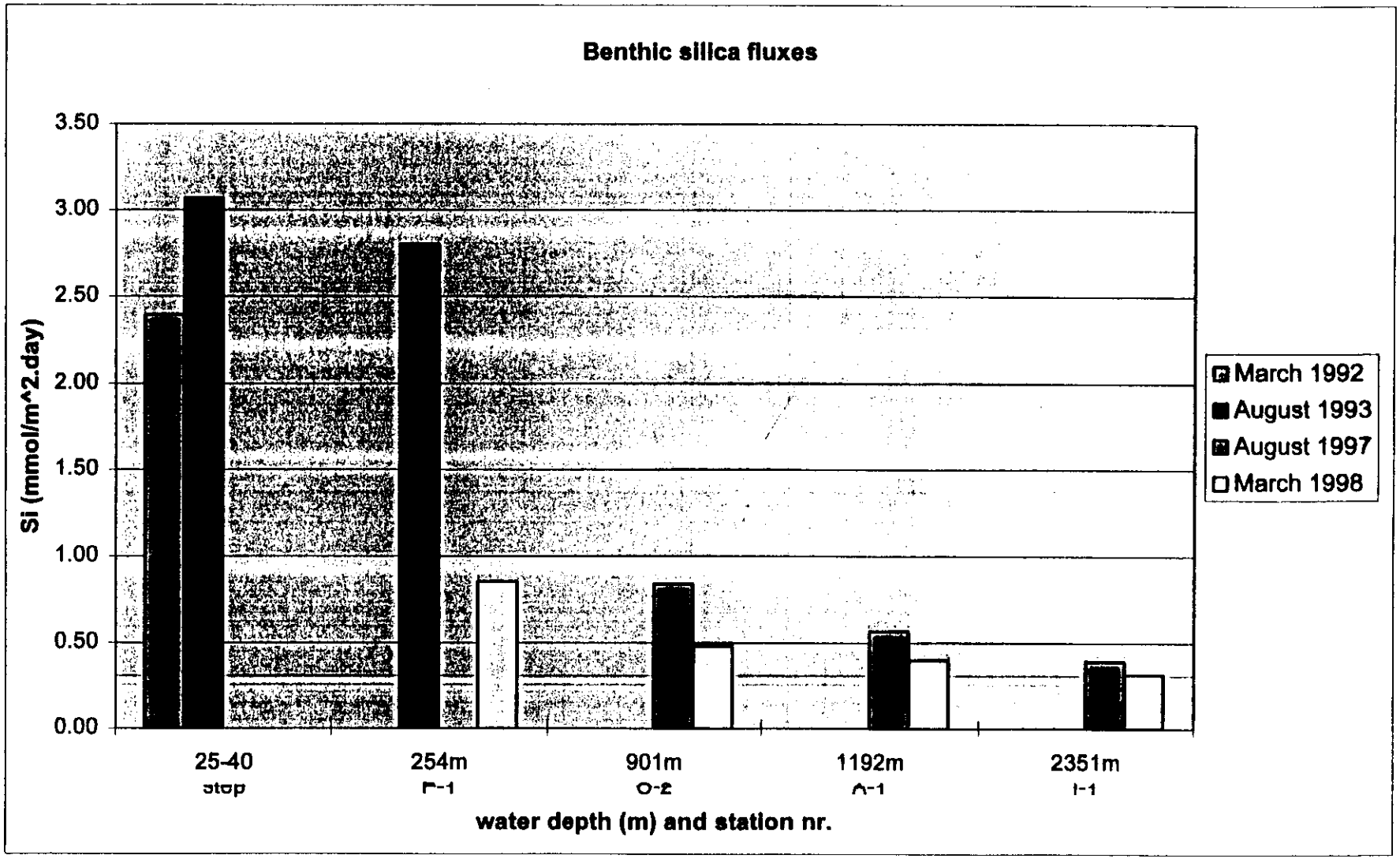

Benthic nitrate fluxes
Nitrate (mmol/m^2.day)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
August 1993
August 1997
March 1998
25-40m
STEP
254m
P-1
901m
O-2
1192m
A-1
2351m
I-1
water depth (m) and station nr.

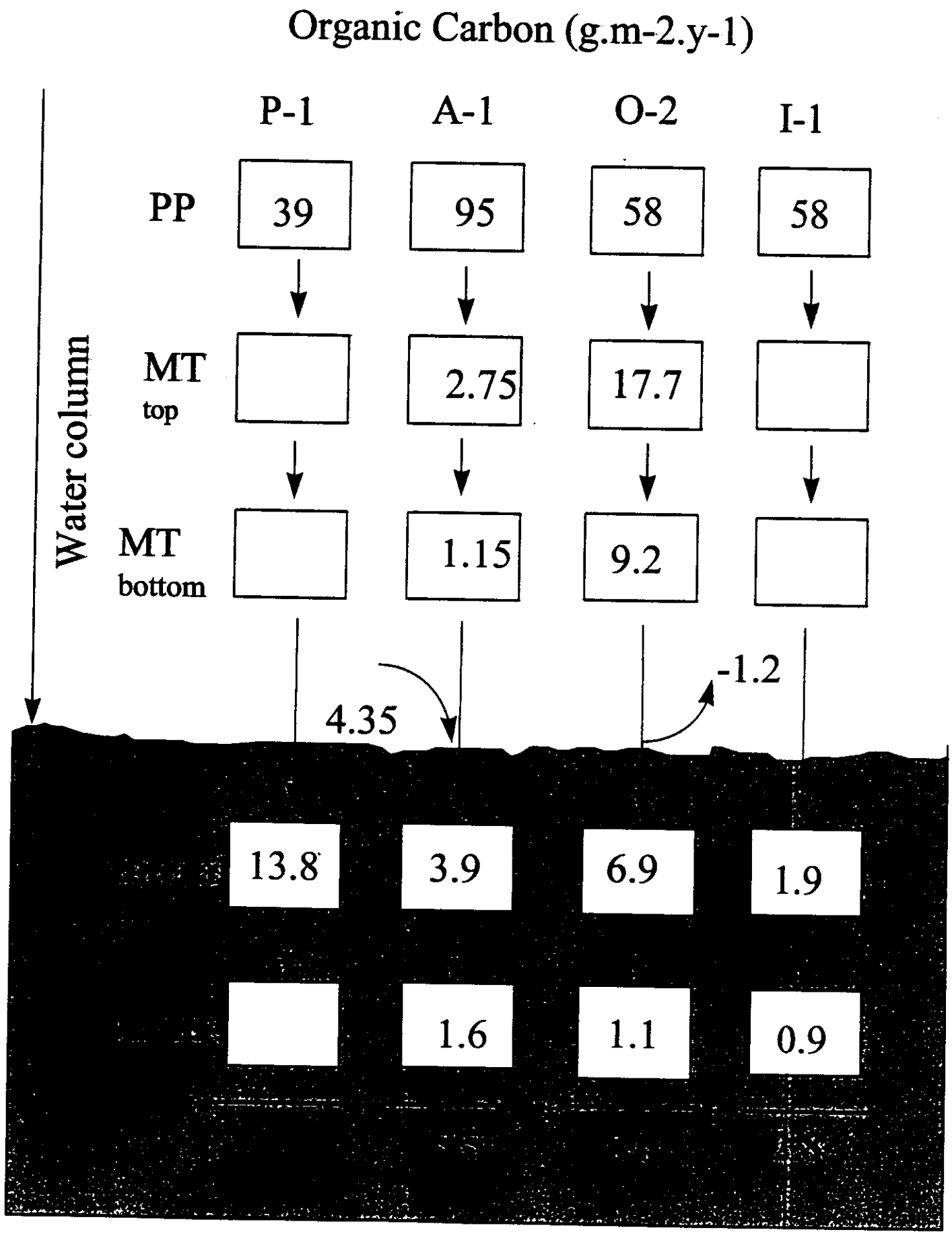
nitrate pore water profiles



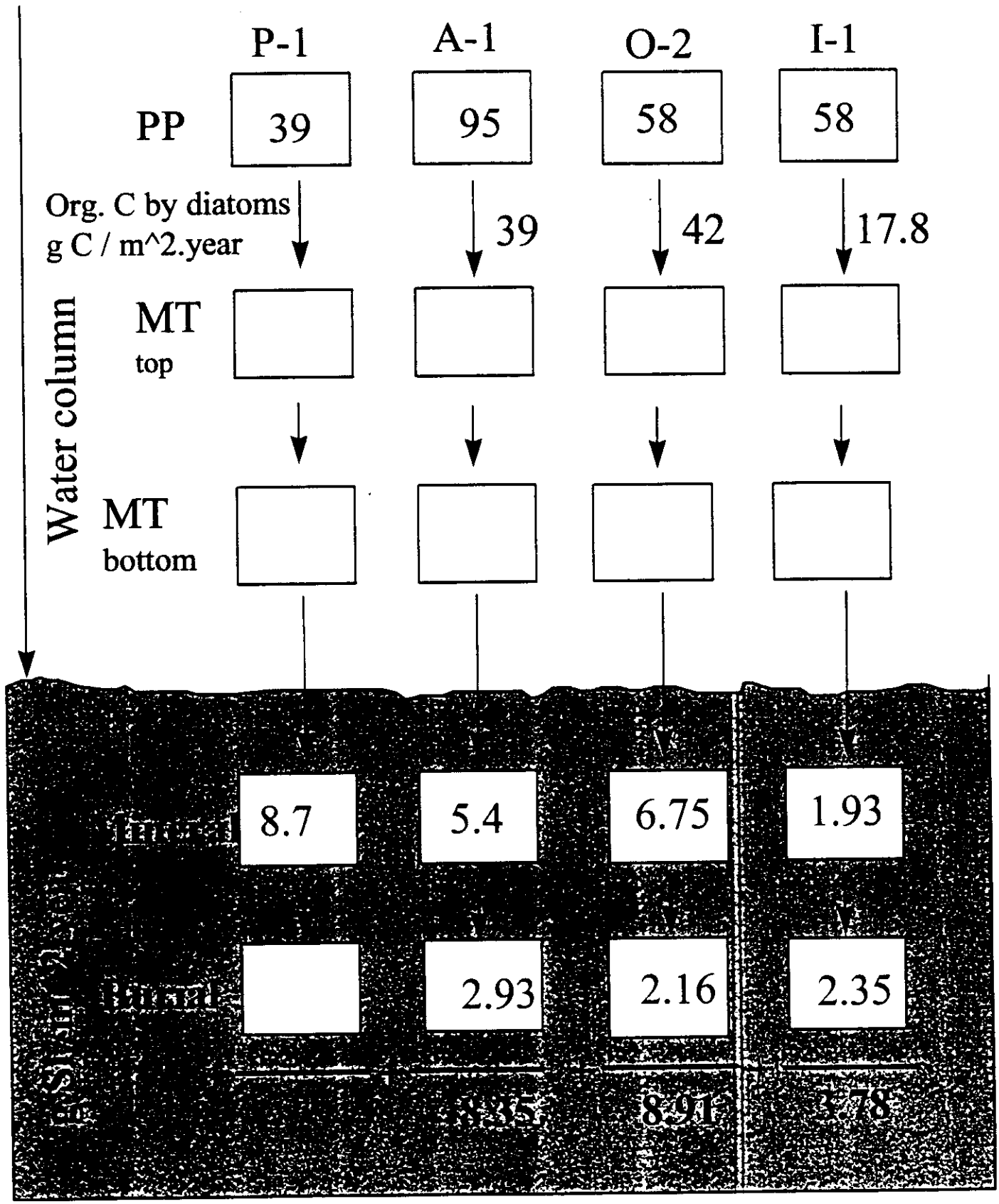
ammonia pore water profiles




Benthic silica fluxes
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Si (mmol/m^2.day)
March 1992
August 1993
August 1997
March 1998
25-40
stop
254m
F-1
901m
O-2
1192m
A-1
2351m
I-1
water depth (m) and station nr.


Organic Carbon (g.m-2.y-1)
P-1
A-1
O-2
I-1
PP
39
95
58
58
MT
top
2.75
17.7
MT
bottom
1.15
9.2
Water column
4.35
-1.2
13.8
3.9
6.9
1.9
1.6
1.1
0.9

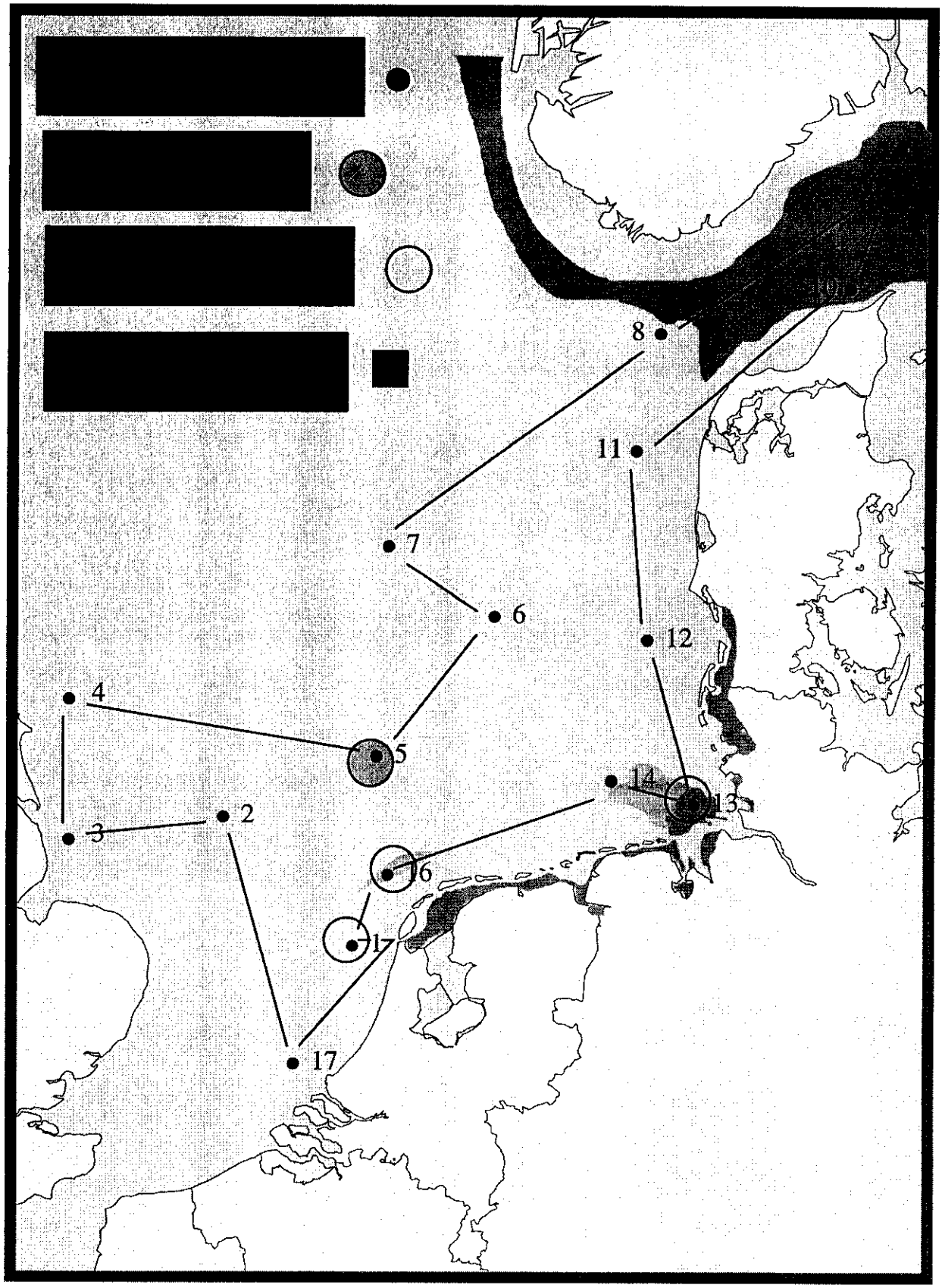
Contribution to org.C-budget by silicious organisms
Conversion of BioSi to org.C by C/Si=4.7 (w/w)



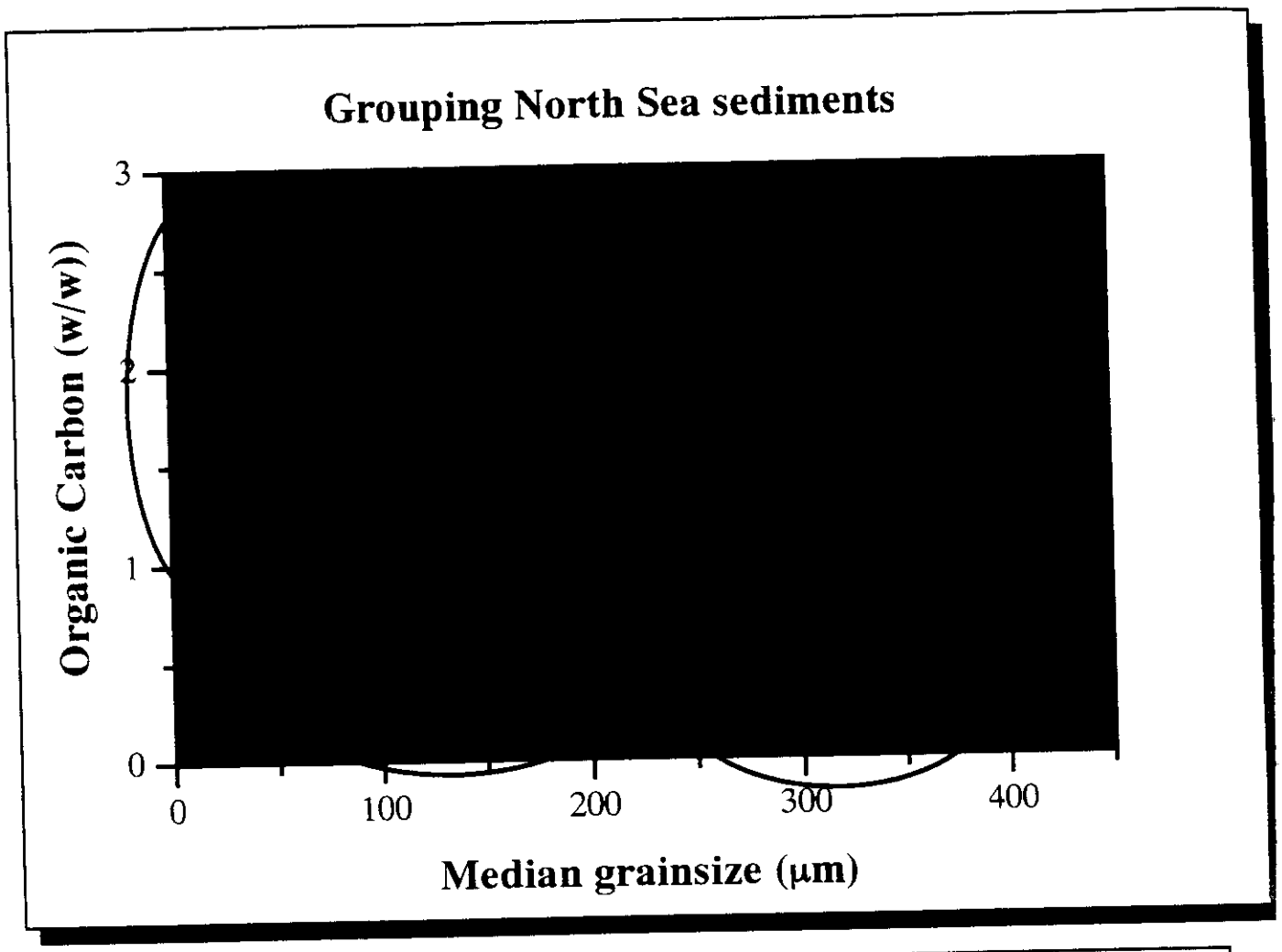
The Adriatic Sea: Conclusions

- *Benthic oxygen consumtion in the Northern Adriatic shows a clear seasonal variation*
- *Oxygen budgets of these sediments indicate the occurrence of benthic primary production in Northern Adriatic sediments*
- *Benthic oxygen consumtion rates accounts for 11 to 26% of the pelagic primary production in Winter. In summer, between 27 to 50% of the primary production is mineralised in the sediment, indicating the tight benthic-pelagic coupling*
- *In the mid-Adriatic depression, 15% of the primary production is mineralised in the sediment*
- *Sediments located in the southern Adriatic Sea account for 3 to 12 % of the pelagic primary production*
- *Benthic processes clearly affect the chemical composition of Adriatic water masses.*

Lohse et al. Benthic Mineral Cycling, ITCP, Nov 1998

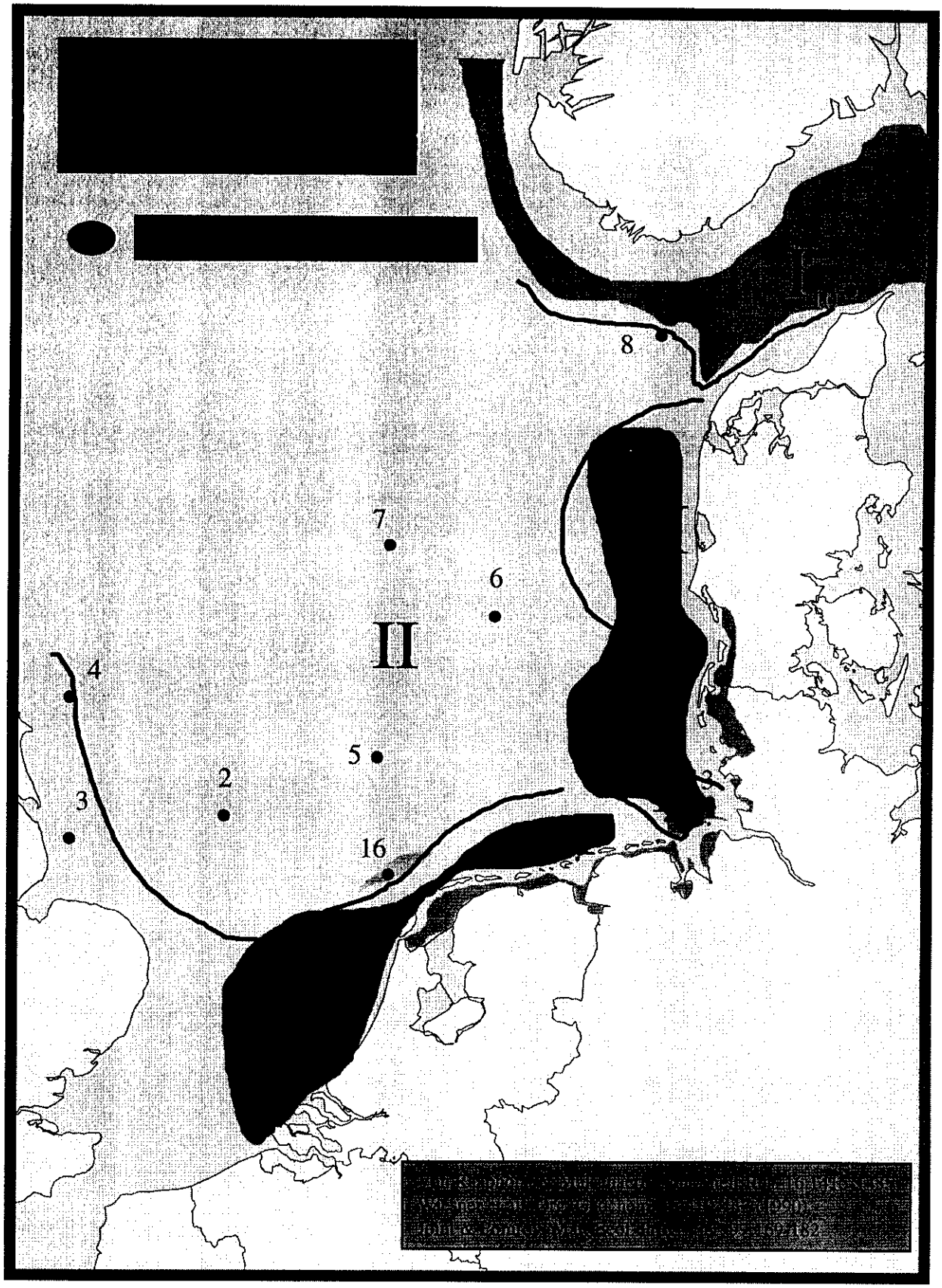


NIOZ Oct. 96

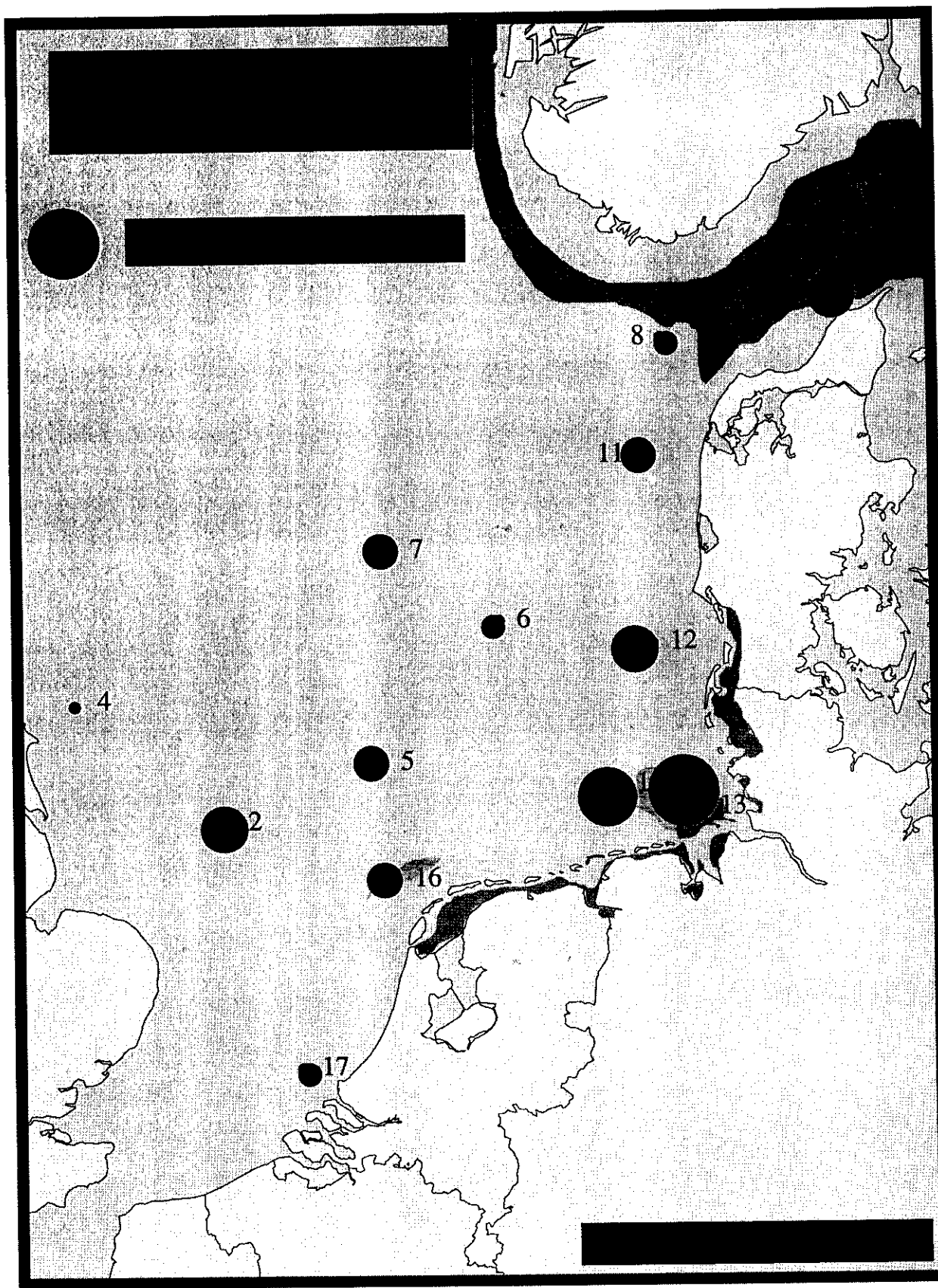


Lohse et al. Ophelia 42: 173-198 (1995)

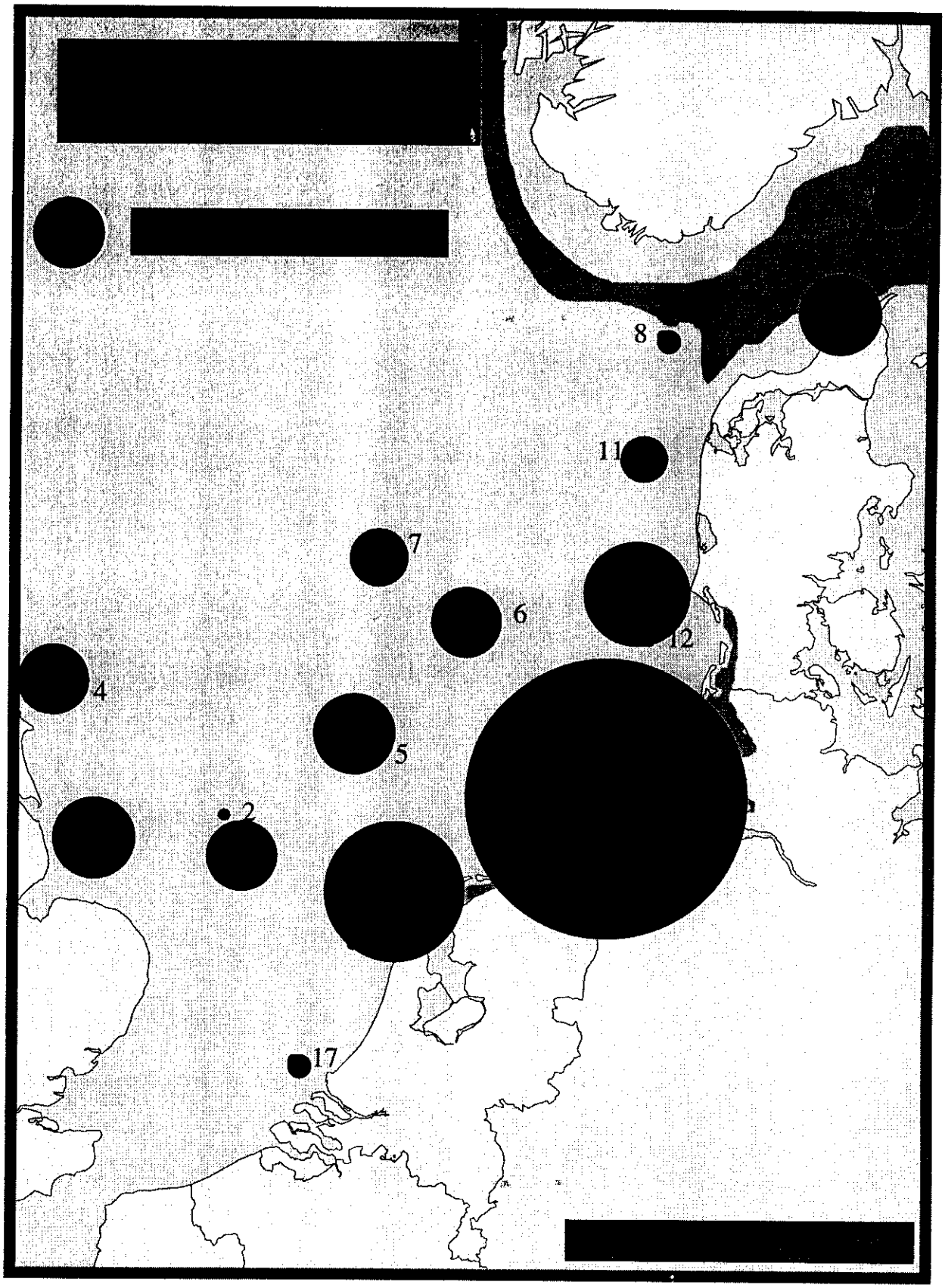
NIOZ Oct. 96



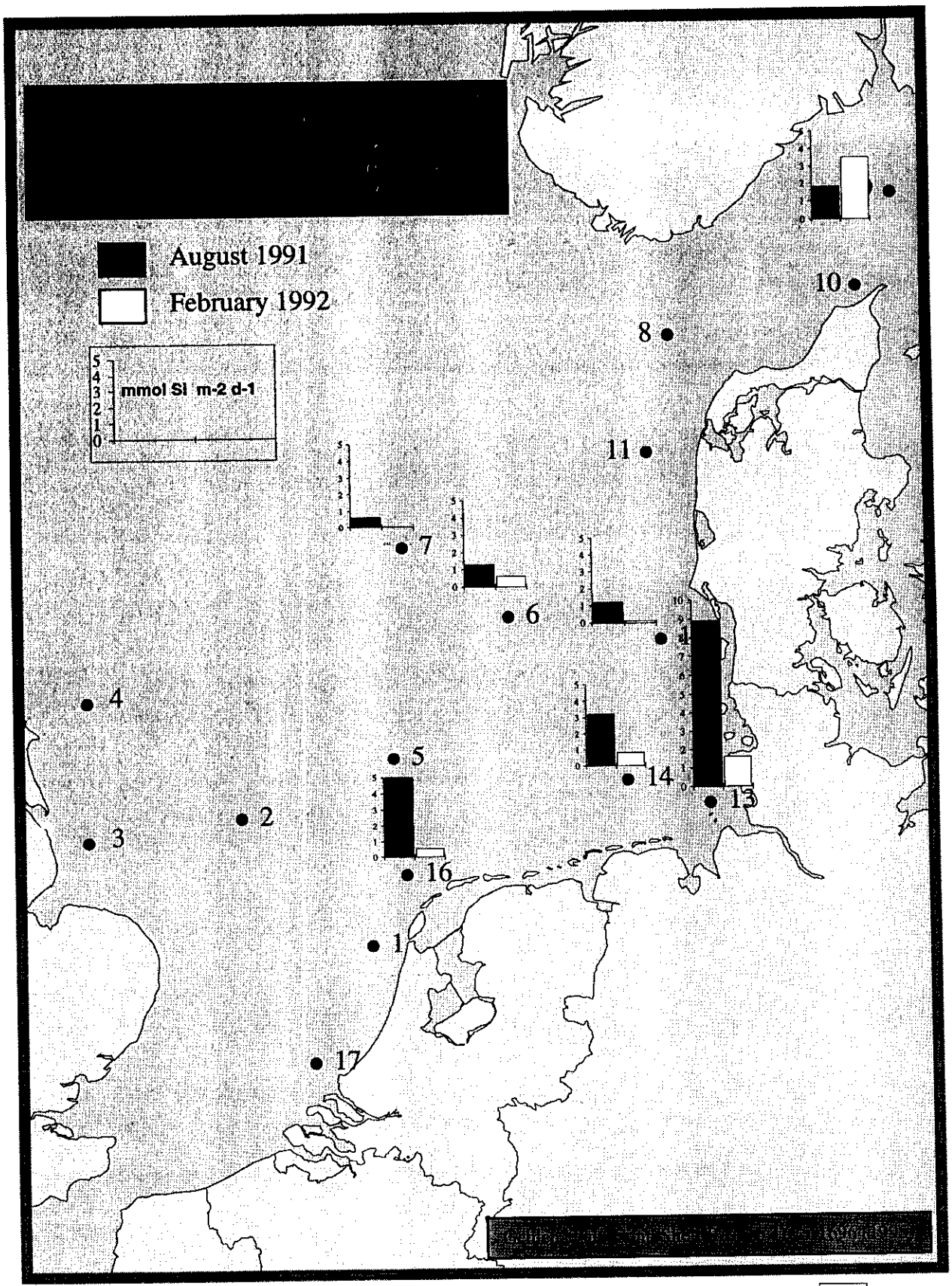
NIOZ Oct. 96



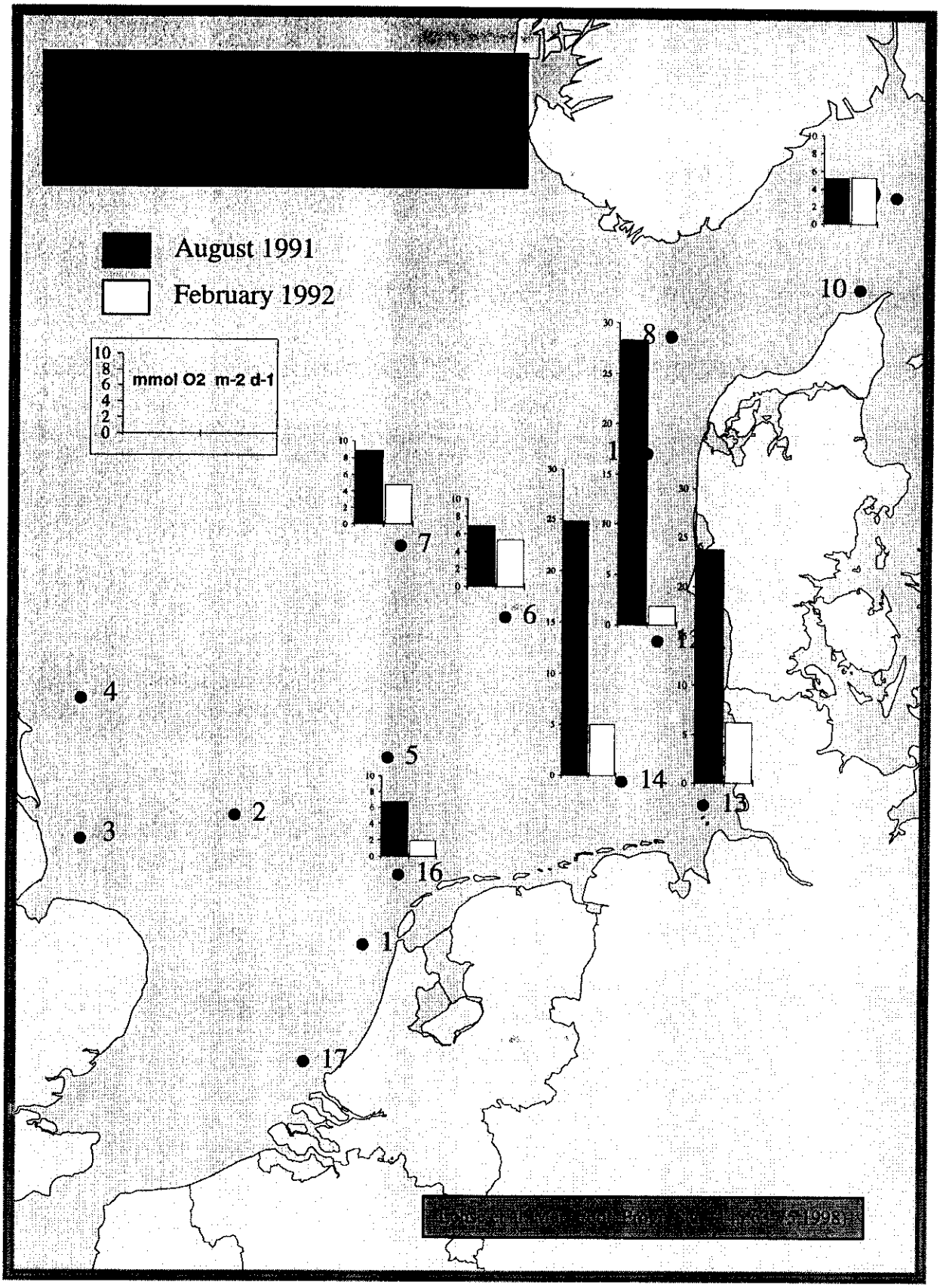
NIOZ Oct. 96



NIOZ Oct. 96


August 1991
February 1992
mmol Si m-2 d-1
0
1
2
3
4
5
10
8
11
7
6
4
5
2
3
16
1
17
14
13

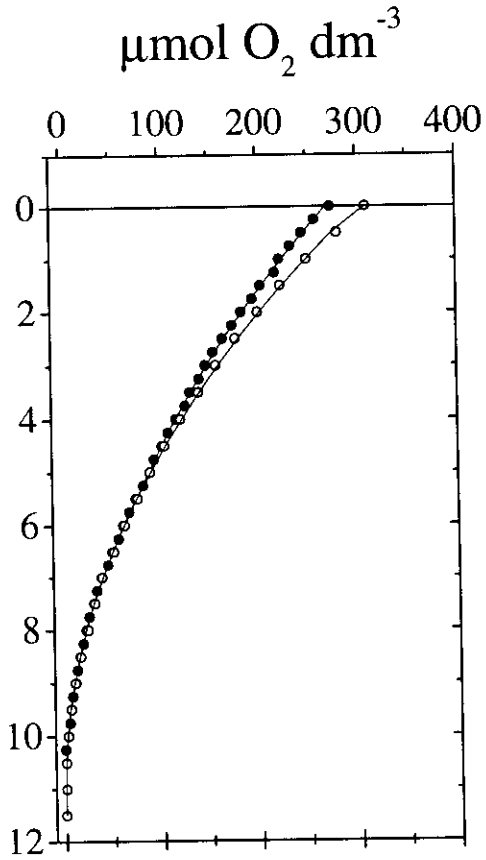
Oct. 96


August 1991
February 1992
mmol O2 m-2 d-1
10
8
6
4
2
0
1
2
3
4
5
6
7
8
10
12
13
14
16
17

Oct. 96

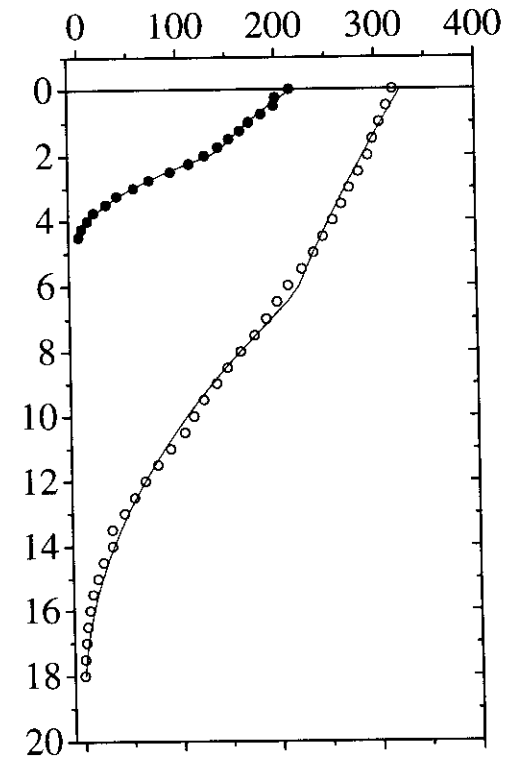
Skagerrak
water depth: 330 m

med. grainsize :
20 µm
(medium silt)



Frisian Front
water depth: 39 m

med. grainsize :
80 µm
(very fine sand)

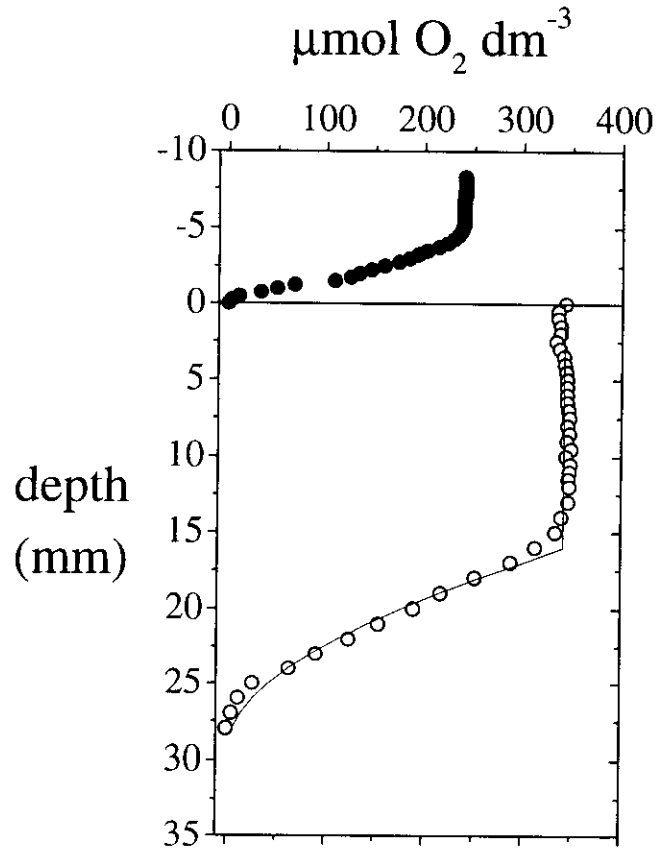


Danish coast

water depth: 12 m

medium grainsize:
190 µm

(fine sand)

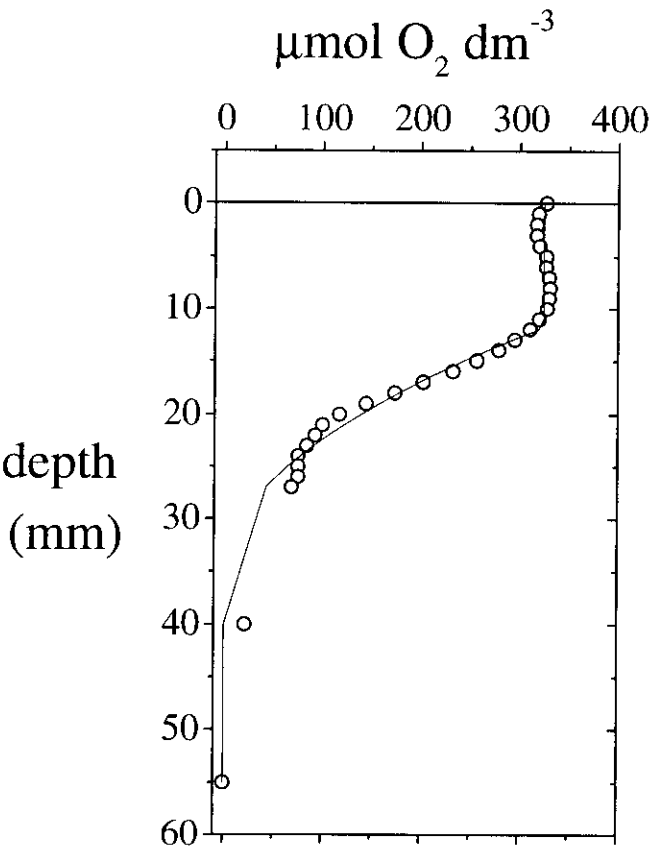


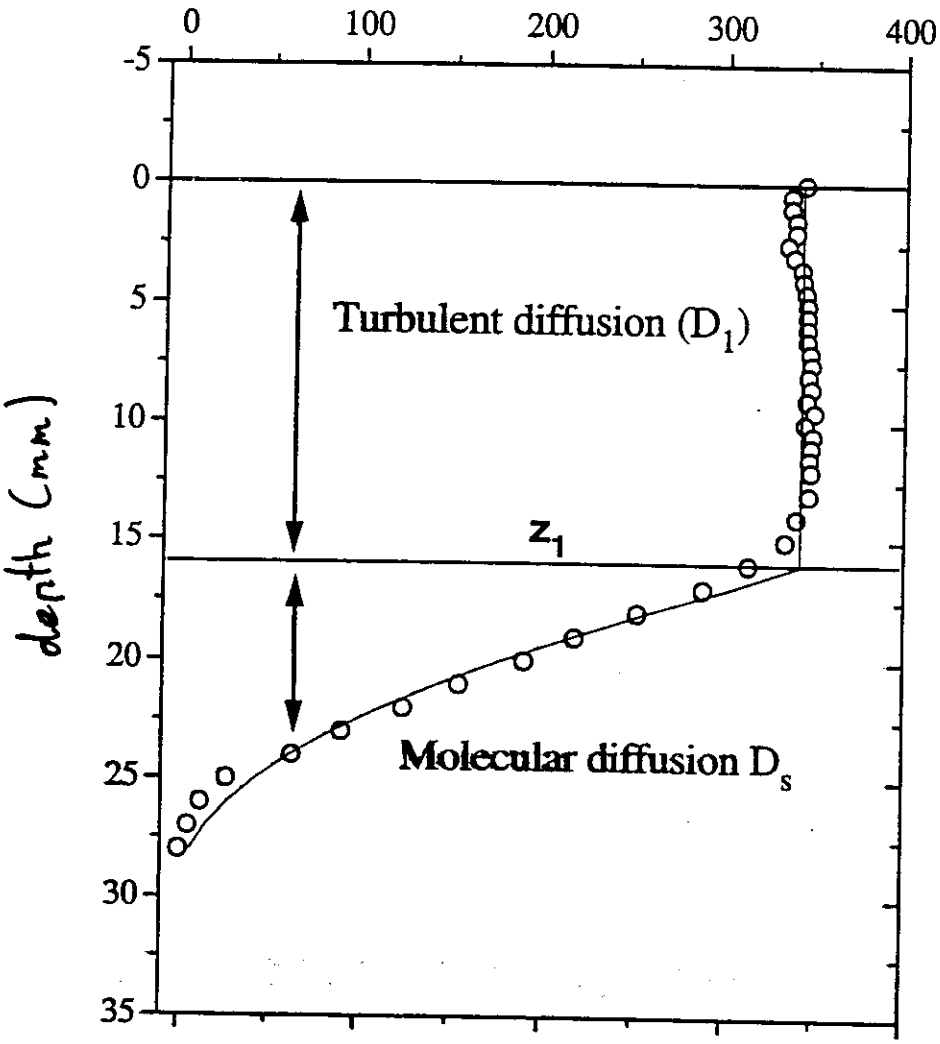
Doggerbank

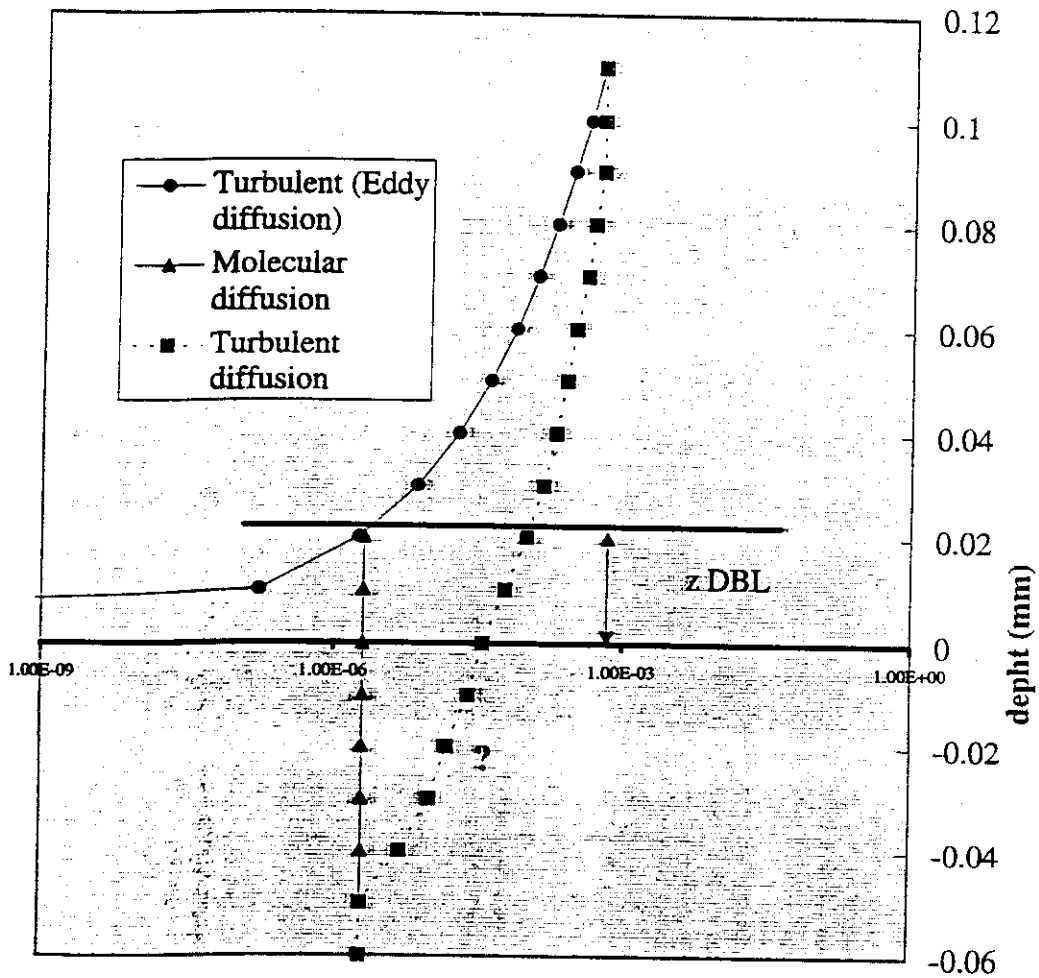
water depth: 60 m

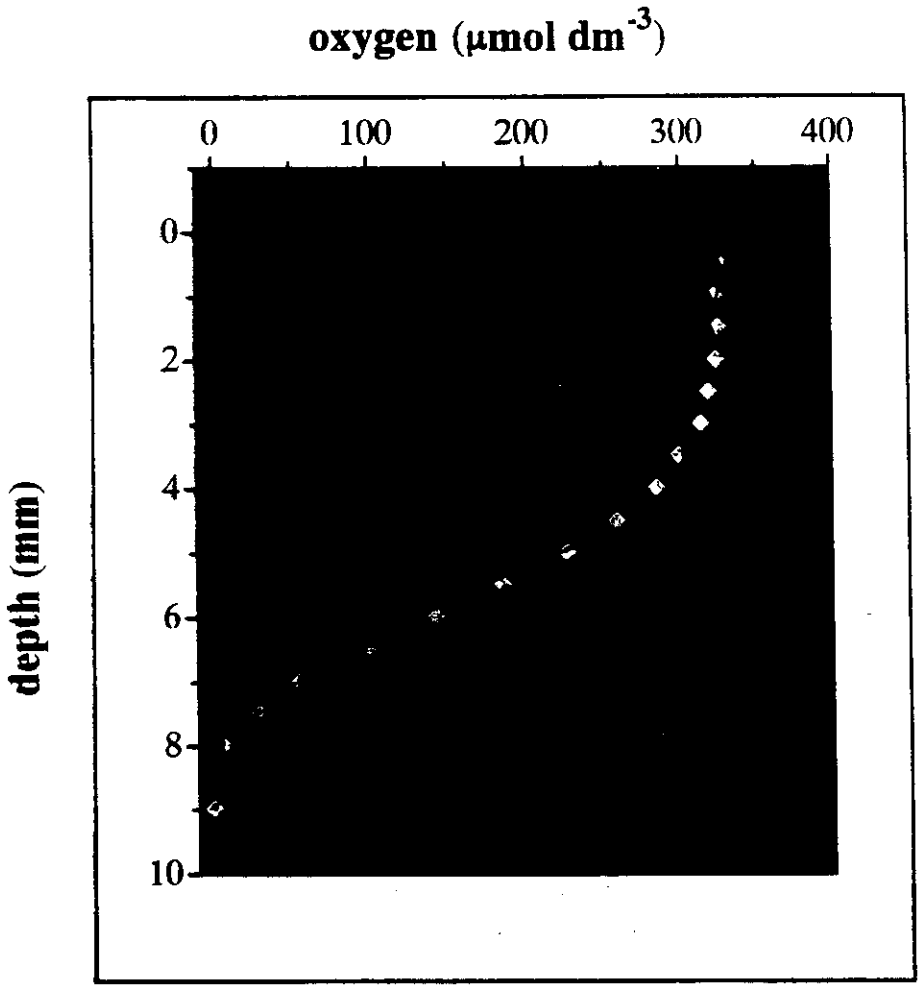
medium grainsize:
300 µm

(medium sand)




0
100
200
300
400
-5
0
5
10
15
20
25
30
35
depth (mm)
Turbulent diffusion (D_1)
z_1
Molecular diffusion D_s


Turbulent (Eddy diffusion)
Molecular diffusion
Turbulent diffusion
z DBL
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
depht (mm)
1.00E-09
1.00E-06
1.00E-03
1.00E+00
log Diffusion coefficient (cm-2 sec-1)


oxygen (µmol dm-3)
0
100
200
300
400
depth (mm)
0
2
4
6
8
10
10 minutes
20 minutes
25 minutes
30 minutes
after box core retrieval

Time scales for molecular and turbulent diffusion

$$t = z^2 / 2D_s$$

at $T = 9°C$, $S = 32$ ‰, $\phi = 0.5$

Distance (z) (cm)	Molecular diffusion coefficient	Turbulent coefficient
	6.4	429
	(x 10^{-6} cm^{-2} sec^{-1})	
0.01	7.8 sec	0.12 sec
0.05	3 min	2 sec
0.1	13 min	11 sec
0.5	5 h	5 min
1	21 h	19 min
5	23 d	8 h

nclusions

- Near bottom pressure fluctuations caused by tidal currents and wave action may induce turbulent transport processsses in "non-depositional" continental shelf sediments.
- Oxic/anoxic oscillations may lead to a more complete mineralisation of organic matter

Further studies

- Lander technologies to study the processes under in-situ conditions
- Calibration of stirring regimes in incubation chambers
- Laboratory experiments (thin-plug techniques)

NIOZ Dec. 96

Conclusions

North Sea sediments act as link rather than sink.

Temporal deposition of relatively fresh material causes large seasonal diffferences of biogeochemical processes in mid-shelf sediments. These sites and particularly those with more constant deposition (e.g. German Bight) are key areas for benthic mineralisation.

Before reaching the final depocentre in the Skagerrak, most of the organic matter has been decomposed. The material deposited and buried here is largely refractory.

NIOZ

Adriatic vs North Sea
Biogeochemical characteristics of **depositional** areas

Summer	*Adriatic (Po Plume)*	*North Sea (German Bight)*
Primary production (mmol C m^{-2} d^{-1})	50	110
Sedimentation rate (cm yr^{-1})	0.24-0.29	0.5-0.8
Sediment composition	clay-silt	medium silt
Oxygen uptake (mmol O_2 m^{-2} d^{-1})	15-25	50-70
Nitrogen mineralisation (mmol N m^{-2} d^{-1})	2-3	12
% primary production recycled in sediments	40	80
burial efficiency (%)	50	20

8

Lohse et al, Benthic Mineral Cycling, ITCP Nov 1998

Adriatic vs North Sea
Biogeochemical characteristics of **non-depositional** areas

Summer	*Adriatic (>30m)*	*southern North Sea*
Primary production (mmol C m^{-2} d^{-1})	40	26
Sedimentation rate (cm yr^{-1})	0	0
Sediment composition	medium sand	medium sand
Oxygen uptake (mmol O_2 m^{-2} d^{-1})	5	10-15
Nitrogen mineralisation (mmol N m^{-2} d^{-1})	0.2	0.5
% primary production recycled in sediments	20	30-50
burial efficiency (%)	0	0

16

Lohse et al, Benthic Mineral Cycling, ITCP Nov 1998

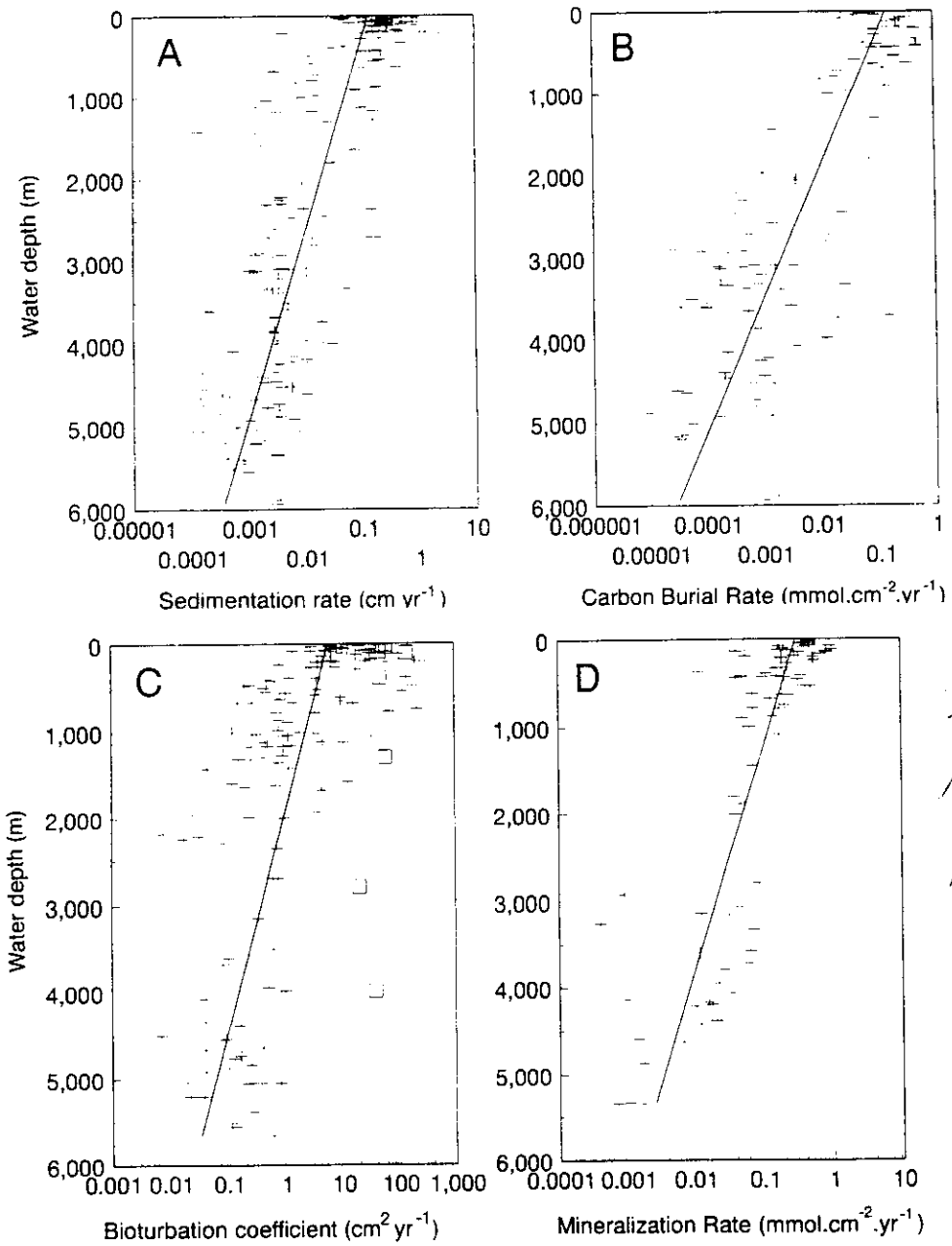


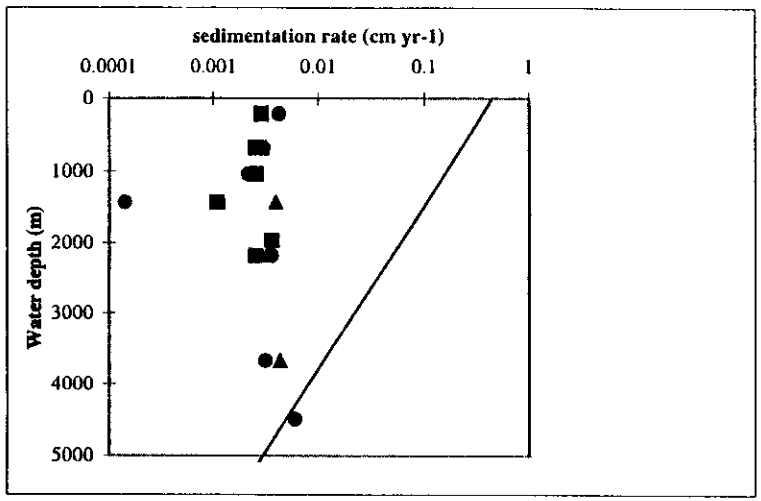
Fig. 3. Parameter versus water depth (m) plots. The regression curves based on the coefficients listed in Table 3 are included as well (solid lines).
(A) Sediment accumulation rate (ω; cm year^{-1}).
(B) Organic carbon burial rate (F_b; mmol C cm^{-2} year^{-1}).
(C) D_b-^{210}Pb (crosses; cm^2 year^{-1}) and D_b-^{234}Th (open squares; cm^2 year^{-1}).
(D) Total mineralization rate (F_c; mmol C cm^{-2} year^{-1}).

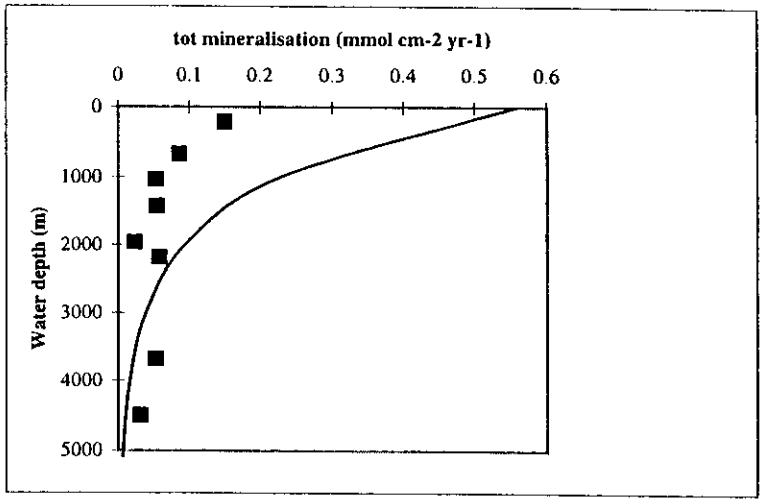
Middelburg et al 1997 J. Exp. Mar. Ecol. 214 327-342

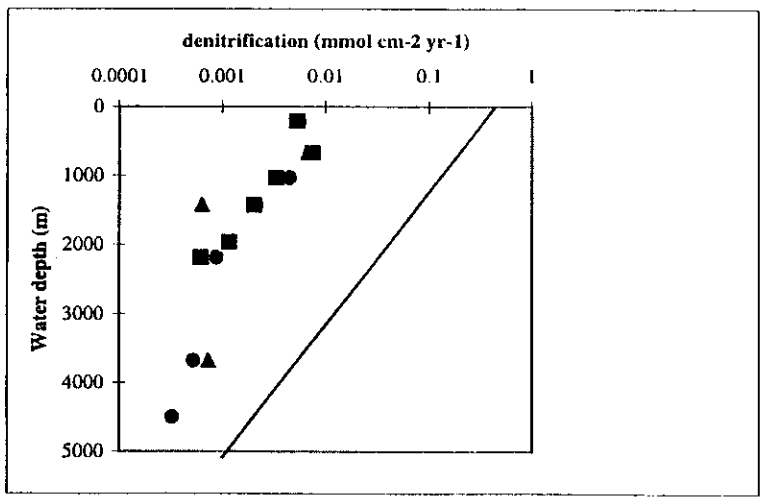
Table 4. Global depth distribution of burial and mineralization rates

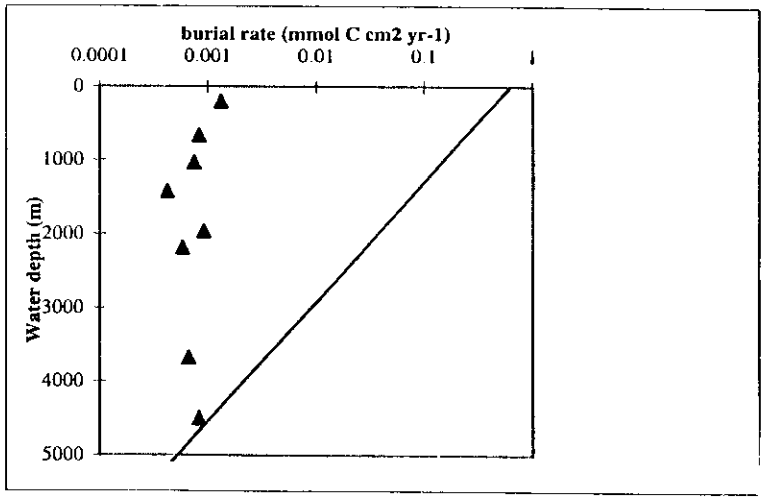
Depth range	Area (m)	ω	F_b	F_c	AEROBIC	DEN	SRR
			%				
0–200	7	56	68	52	42	63	64
200–2000	9	30	27	30	30	29	29
> 2000	84	14	5	18	28	8	7

Middelburg et al. Deep Sea Res.

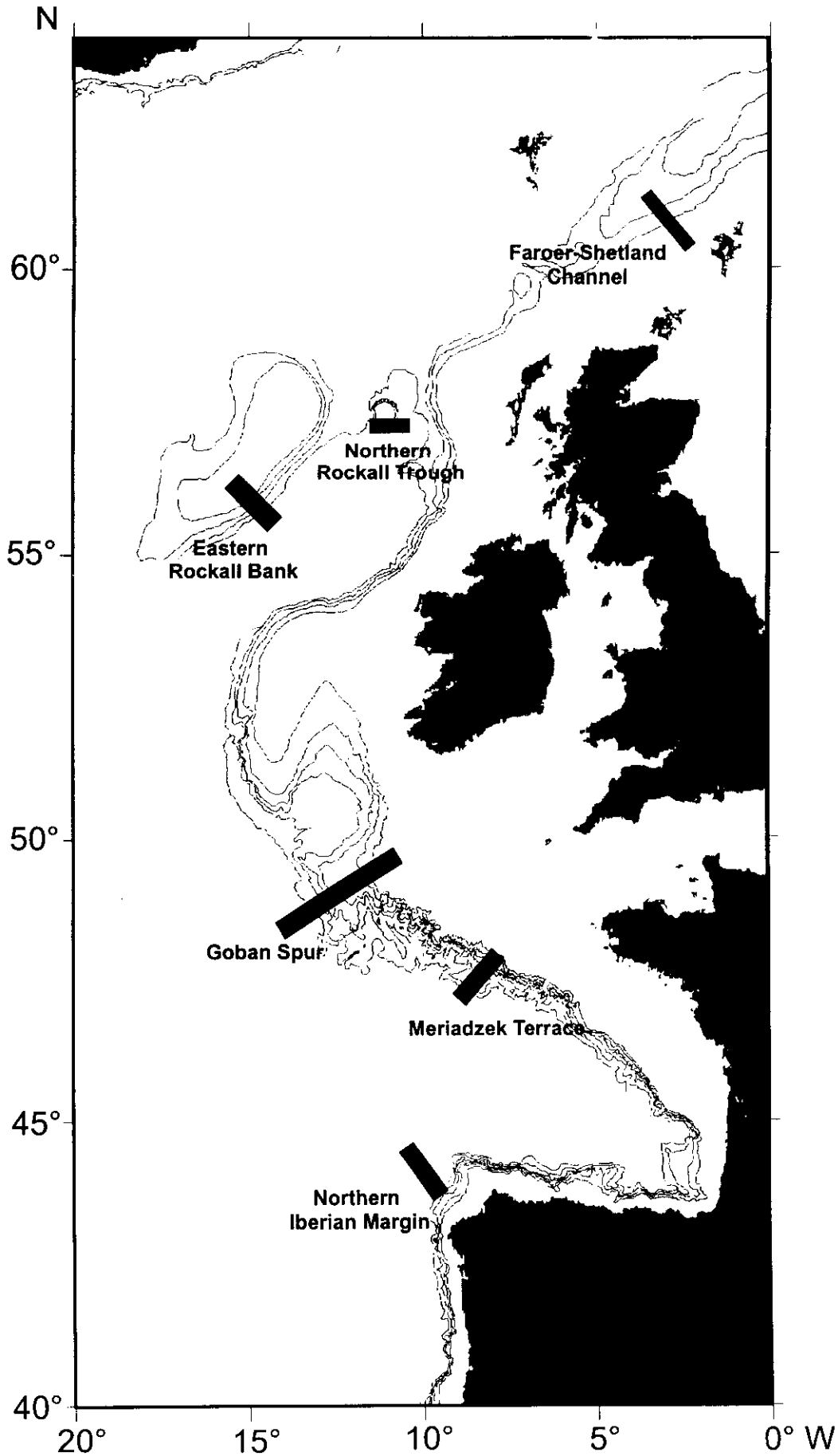








Data points from Lohse et al: Progr. in Oceanogr. (press)
Regression lines from Middelburg et al.


N
60°
55°
50°
45°
40°
20°
15°
10°
5°
0° W
Faroer-Shetland Channel
Northern Rockall Trough
Eastern Rockall Bank
Goban Spur
Meriadzek Terrace
Northern Iberian Margin

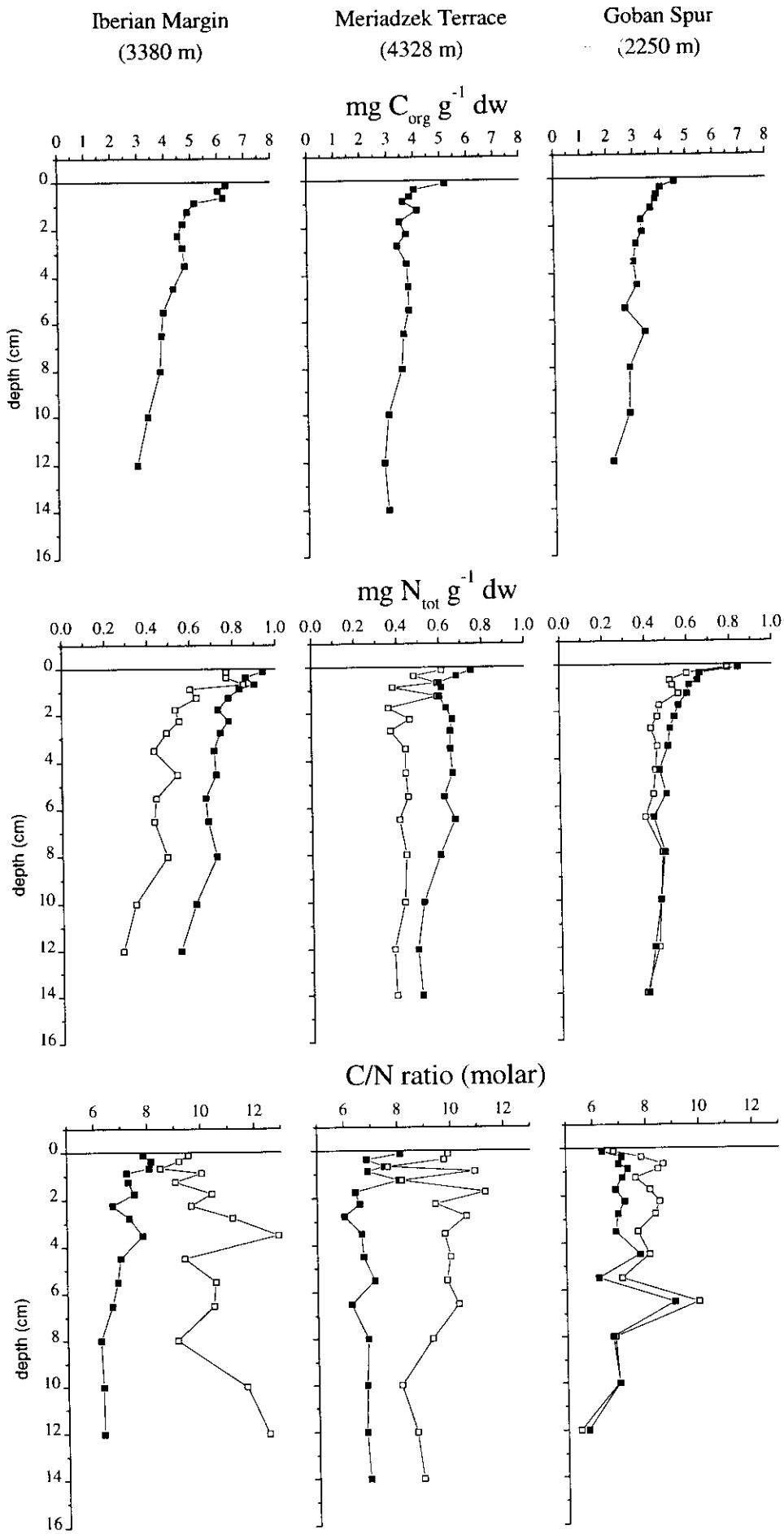


Figure 2
Lohse et al.

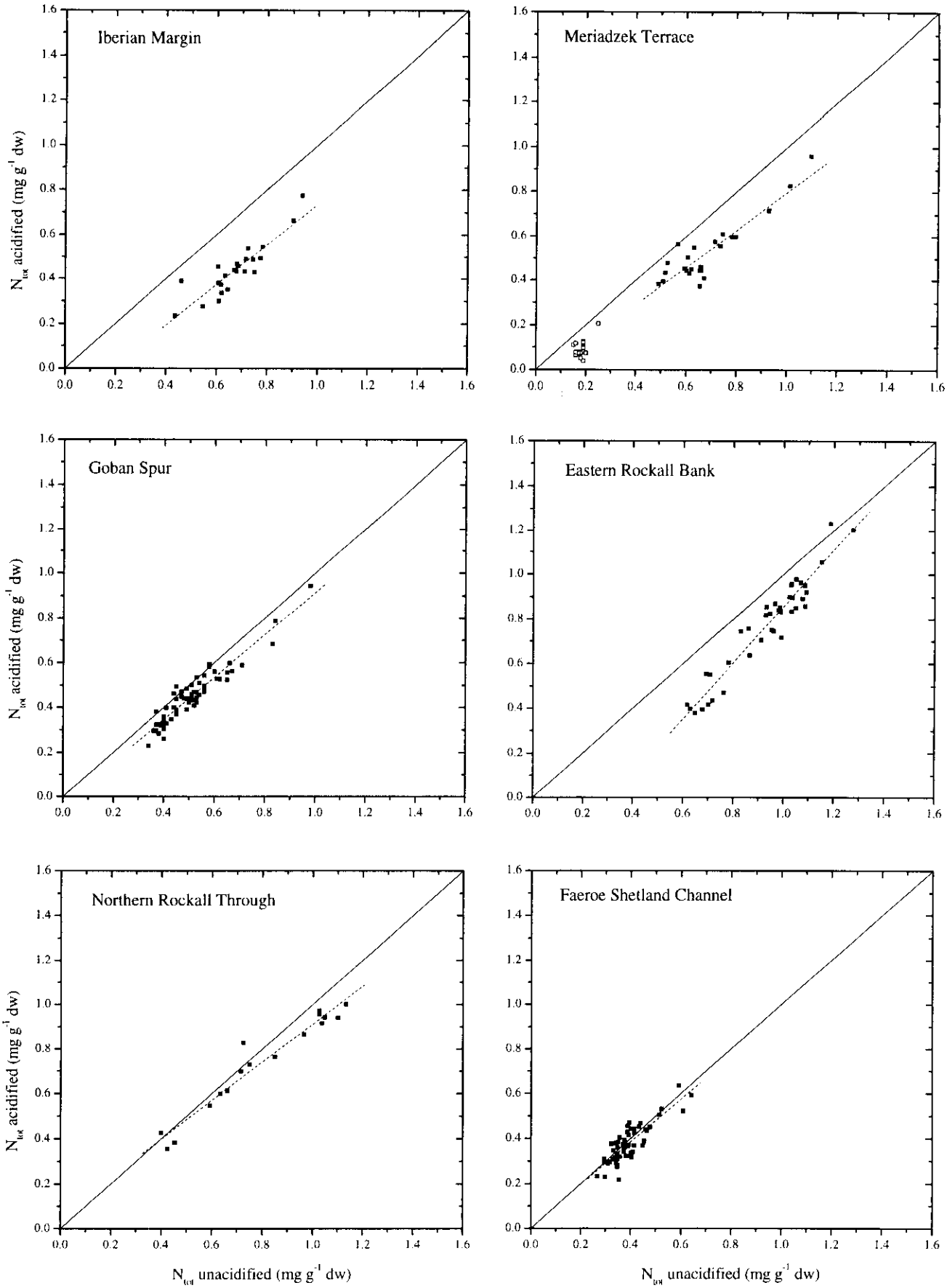


Figure 3 Lohse et al.

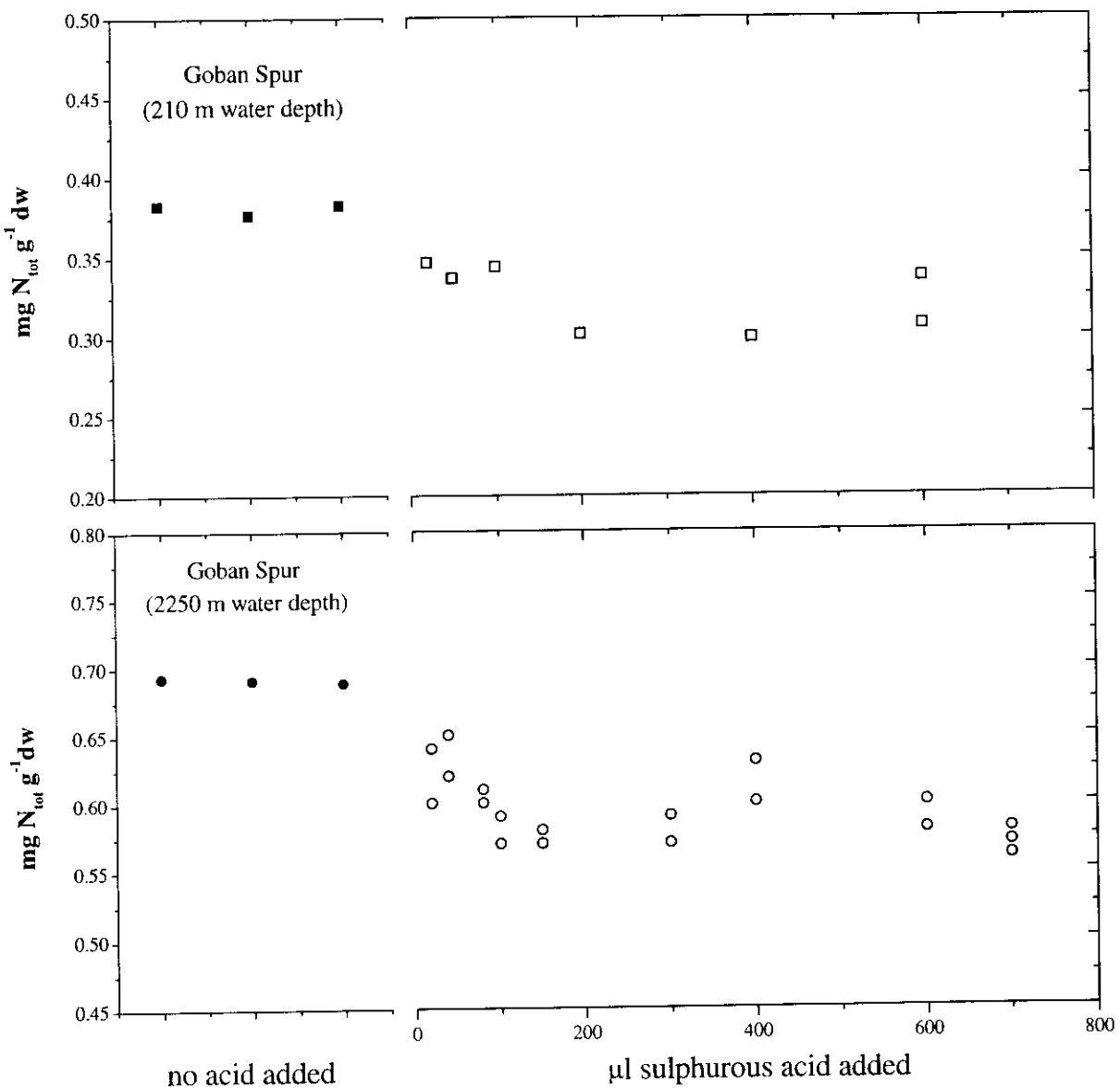


Fig. 4
Lohse et al.

Water depth (m)	Thickness oxic zone (cm)	Sedimentation rate (cm x 1000 yr^{-1})	Exposure time to Oxygen (yrs)	C_{org}/SFA (mg / m^2)
600	0.8	2.8	279	0.3
1400	1.4	1.8	841	0.16
1900	9.6	4.3	2242	0.17
3600	14.2	6.0	2367	0.07

Lohse et al, Benthic Mineral Cycling, ITCP, Nov. 1998