



# Particulate Organic Matter in Permeable Marine Sands—Dynamics in Time and Depth

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In a North Sea intertidal sandflat sediment, depth profiles of dissolved and particulate compounds were measured and evaluated with respect to transport and degradation of particulate organic matter (POM). Bimonthly from July 1997 to July 1998, the amount was measured of fine-grained (<70 μm) material in the permeable sand matrix, its N, C<sub>org</sub> and chlorophyll content as well as porewater DIC, NO<sub>x</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> concentrations. Depth profiles of fine particle concentrations indicated hydrodynamic influence down to 4–8 cm below the sediment surface. Worst-case calculations on the macrofaunal contribution to particle transport resulted in a biodiffusion coefficient of  $D_B \leq 1.85 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ , corresponding to less than 50% of total transport. Chl and POC contents and DIN concentrations exhibited summer/autumn and winter/spring characteristics in their profiles, revealing the seasonal importance of early diagenesis and advective transport, respectively. Areal inventories of POC, PN and Chl indicated the dominance of degradation and hydrodynamic removal of organic material during autumn/winter and fresh POM input throughout spring and summer. In the upper 5 cm, seasonal variation in the particle, POC, PN and Chl concentrations of the sediment was 1.4–5.3 times as large as below. Calculations based on POC loss or short-term DIC accumulation yielded estimates of annual carbon turnover rates ranging between 55 and 123 g C m<sup>-2</sup> yr<sup>-1</sup>. Possible implications of POM dynamics on the role of permeable sands in the marine carbon cycle are discussed.

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**Keywords:** sediment–water interface; organic matter; vertical exchange; mineralization; seasonal variations; particle transport; intertidal sandflat; North Sea

## Introduction

Permeable sands, a dominant sediment type on continental shelves (Emery, 1968; Riedl *et al.*, 1972), usually contain a relatively small amount of organic matter. Nevertheless, low organic carbon and nutrient concentrations in non-accumulating coastal sands may reflect high turnover rates rather than low activity (Huettel *et al.*, 1998).

Particulate matter passes through many cycles of settling and resuspension during transport over the shelf (van Raaphorst *et al.*, 1998) and is seized by ripple migration (Jenness & Duineveld, 1985), bio-irrigation and bioturbation, thus facing progressive degradation alternately by planktonic and benthic organisms. Moreover, advective co-transport of fluid and particles across the sediment–water interface is caused by the interaction of topography and bottom flows over permeable sediments (Huettel *et al.*, 1996; Pilditch *et al.*, 1998). The shallow coastal zone is an extremely dynamic region, where the fluid motions associated with both surface waves and currents reach down to the sea floor and interact with the bottom

sediments (Nittrouer & Wright, 1994). Recent investigations indicate that advectively accelerated solute exchange across the sediment–water interface (Lohse *et al.*, 1996; Huettel *et al.*, 1998) causes high oxygen consumption rates of organic-poor sands (Reimers *et al.*, 1996) and makes early diagenetic processes in non-accumulating sediments very active and variable (Jahnke *et al.*, 1996; Gätje & Reise, 1998).

Shelf seas, especially their intertidal areas, are subject to large variations in waves, currents, temperature, salinity, seston and nutrients on the time scales of hours to months (Kristensen *et al.*, 1997; Gätje & Reise, 1998). The mineralization of organic matter in shallow water sediments, therefore, can be expected to be highly variable both in time and in space (Shum & Sundby, 1996). However, little attention has been paid to the dynamics of suspended particles following interstitial flows in these sediments, thus far studied mainly in laboratory experiments (Huettel *et al.*, 1996; Pilditch *et al.*, 1998). In natural sands, particulate organic matter (POM) constitutes the most fine-grained and easily suspendable part of the sediment and is therefore likely to follow pore water flows through the sand matrix.

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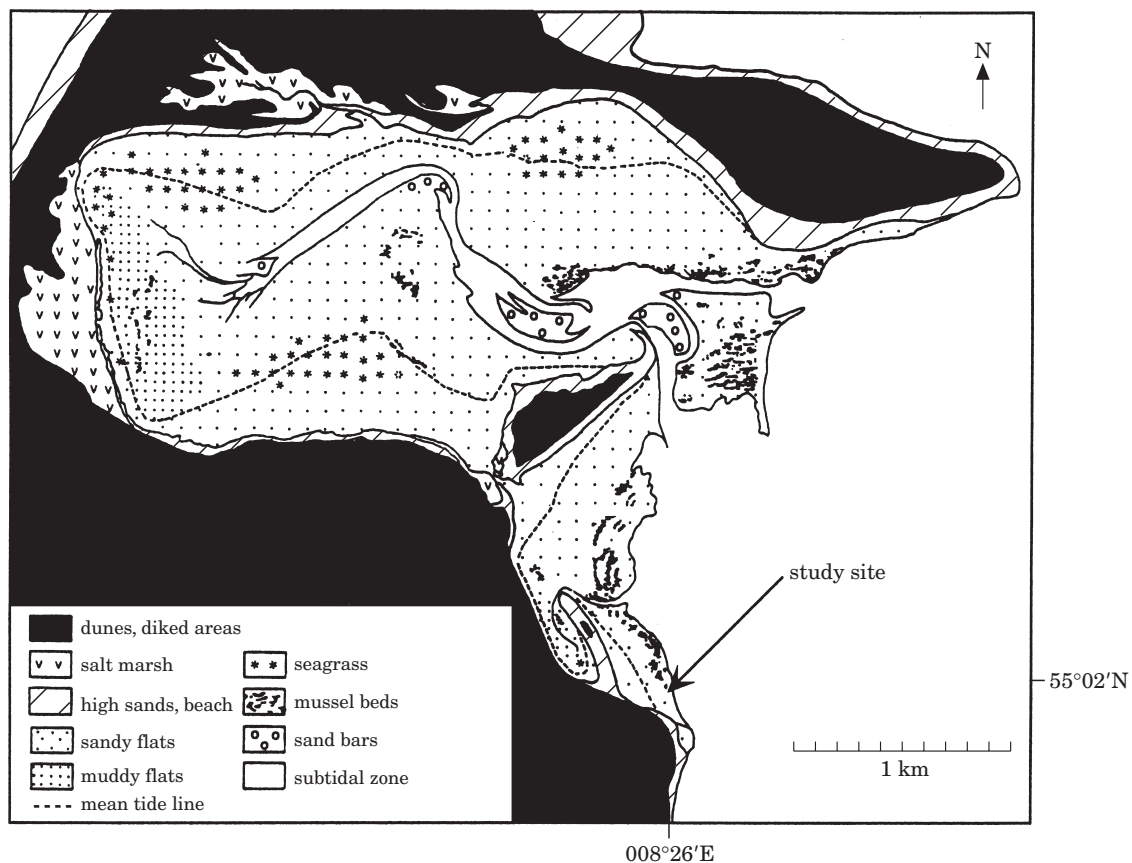


FIGURE 1. Intertidal habitats of Königshafen, as classified by [Reise \*et al.\* \(1994\)](#). Arrow indicates the study site in a sandflat below the mean tide level.

Results are presented here of a one-year field study in an intertidal sandflat that addressed particulate organic matter (POM) dynamics. Its vertical distribution, that does not obey the classically applied exponential decay law, and its seasonally varying composition are explained as a consequence of hydrodynamically induced transport and biogeochemical processes. Carbon turnover rates are estimated and compared to data from different marine sediments.

## Materials and Methods

### Study site

Our study site was located in the southern North Sea near Sylt island (55°02'N, 008°26'E). Near-bottom residual currents above the sandy tidal flats of Königshafen Bay are weakly flood-dominated ([Austen, 1994](#)); semidiurnal tides have a mean range of 1.8 m ([BSH, 1997](#)), and the study site was exposed on average for 2.5 h during low tide. Königshafen is sedimentologically relatively stable ([Austen, 1994](#)). Water temperatures in this area range from  $-2^{\circ}\text{C}$  to  $23^{\circ}\text{C}$  ([Reise, 1985](#)), and salinities range from 23 to 33

in winter and summer, respectively ([Kristensen \*et al.\*, 1997](#)). [Reise \(1985\)](#) and [Gätje and Reise \(1998\)](#) give a more detailed description of the study area.

The study site ([Figure 1](#)) was exposed to waves of less than 20 cm height and to currents of  $0\text{--}0.32\text{ m s}^{-1}$  (for details see [Table 1](#)), measured 2 cm above the crest of up to 2 cm high ripples forming on the sediment surface. The upper 15–20 cm of the sediment column consisted of moderately well sorted medium to coarse quartz sand (median grain size:  $400\text{--}750\ \mu\text{m}$ ), with permeabilities, as measured by the constant head method ([Klute & Dirksen, 1986](#)), ranging between  $3 \times 10^{-12}\text{ m}^2$  and  $20 \times 10^{-12}\text{ m}^2$ . Benthic macrofauna was typical for Königshafen sandflats with short exposure time at low tide, that were thoroughly studied by [Reise \*et al.\* \(1994\)](#). Benthic diatom blooms at the sediment surface were never observed during our study.

### Sampling

Sampling dates were: 17 July 97, 17 September 97, 18 November 97, 13 January 98, 15, 17, 19, 23, 25, 27 March 98, 12 May 98 and 7 July 98. Each time eight

TABLE 1. Weather conditions, water column Chl and algal cell concentrations on each sampling date. Wind speed, air temperature: data provided by Deutscher Wetterdienst (DWD). Phytoplankton, water column Chl concentrations: data provided by P. Martens. Current speed, water temperature: 1–1.5 h before low tide, 2 cm above the ripple crests. Algal species in last column: *Rhizosolenia imbricata* B, *Chaetoceros* sp. E, *Brockmanniella brockmannii* (H) H, S & S, *Skeletonema costatum* (G) C, *Phaeocystis globosa* (H) L

Date	Wind speed (daily mean) (m s <sup>-1</sup> )	Current speed (m s <sup>-1</sup> )	(air) T (°C)	(water) T (°C)	[Chl] (water) (µg dm <sup>-3</sup> )	Algal cells (cm <sup>-3</sup> )	Recent development
17 Jul 97	7.3		15.9	17	4.07	56	T constant, wind rising, start of bloom ( <i>Rhizosolenia imbricata</i> )
17 Sep 97	9.0	0.24	14.1	14	6.44	103	Gradually calming and cooling, shortly after bloom ( <i>Chaetoceros</i> sp.)
18 Nov 97	10.8	0.13	3.4	4	6.87	16	After mild weather suddenly stormy and colder
13 Jan 98 March 98	4.7	0.21	4.3	2	3.47	26	T constant, wind unsteady T and wind unsteady, spring bloom ( <i>Brockmanniella brockmannii</i> , <i>Skeletonema costatum</i> )
15 Mar 98	6.8	0.15	5.7	4			
17 Mar 98	6.7	0.05	5.9	5			
19 Mar 98	10.4	0.12	5.1	6			
23 Mar 98	9.1	0.16	3.0	8	10.77	805	
25 Mar 98	7.2	0.07	5.9	3			
27 Mar 98	7.1	0.07	7.0	5	9.67	511	
12 May 98	8.5	0.10	13.2	13	5.17	121	Wind rising, start of bloom ( <i>Phaeocystis globosa</i> )
7 Jul 98	11.2	0.17	12.0	12			Slowly calming after gale

sediment cores were taken of 60 mm i. d. and one core of 36 mm i. d., with core lengths of at least 20 cm, with 400 ml of overlying water. The respective sampling locations (0.5 m diameter) were chosen within a selected circular area of 4 m radius (Figure 2). All cores were carefully transported to the nearby laboratory and sectioned in depth intervals of 0.25 cm (down to 1 cm depth), 0.5 cm (down to 2 or 4 cm depth) and 1.0 cm (down to 15 cm depth).

#### Extraction of porewater

Equivalent slices of three parallel cores (60 mm diameter) were pooled. Porewater was obtained by centrifugation (500 g, 10 min, 15 °C) through GF-F filters in a Beckmann TJ-6 centrifuge. Our centrifuge tubes were constructed according to Saager *et al.* (1990), with minor changes to improve tightness.

For DIC analysis performed shortly after extraction, 1.5 ml aliquots of porewater were kept at 4 °C in gas-tight glass vials containing 75 µl of NaMoO<sub>4</sub> (0.5 M). Molybdate reduces the interference of dissolved sulphides (Lustwerk & Burdige, 1995). Two more 1.5 ml aliquots were stored in polyethylene vials at -20 °C for NH<sub>4</sub><sup>+</sup> and NO<sub>x</sub><sup>-</sup> analysis.

#### Extraction of the fine fraction

Equivalent slices of three parallel cores (60 mm diameter) were pooled, carefully suspended in NaCl solution (32 g l<sup>-1</sup>, 3 ml per cm<sup>3</sup> of sediment), and allowed to settle. After 20 s, the supernatant was decanted and the remaining sediment treated again in the same way. The decanted suspensions, containing the particulate matter of an effective diameter less than 70 µm (hereafter referred to as 'fine fraction'), were centrifuged (1200 g, 5 min, 15 °C) using an Eppendorf 5416 centrifuge. The pellet was freeze-dried, weighed and stored at 4 °C in the dark.

#### Porewater analysis

Dissolved inorganic carbon (DIC) was measured according to Hall and Aller (1992) using a flow-injection system. Freshly prepared NaHCO<sub>3</sub> solutions were used for calibration. The detection limit was 0.05 mM, and the analytical precision was 0.01 mM.

Ammonium concentrations were measured using a similar flow-injection system (Hall & Aller, 1992), with NH<sub>4</sub>Cl solutions serving as calibration standards. The detection limit was 2 µM, and the analytical precision was 0.05 µM.

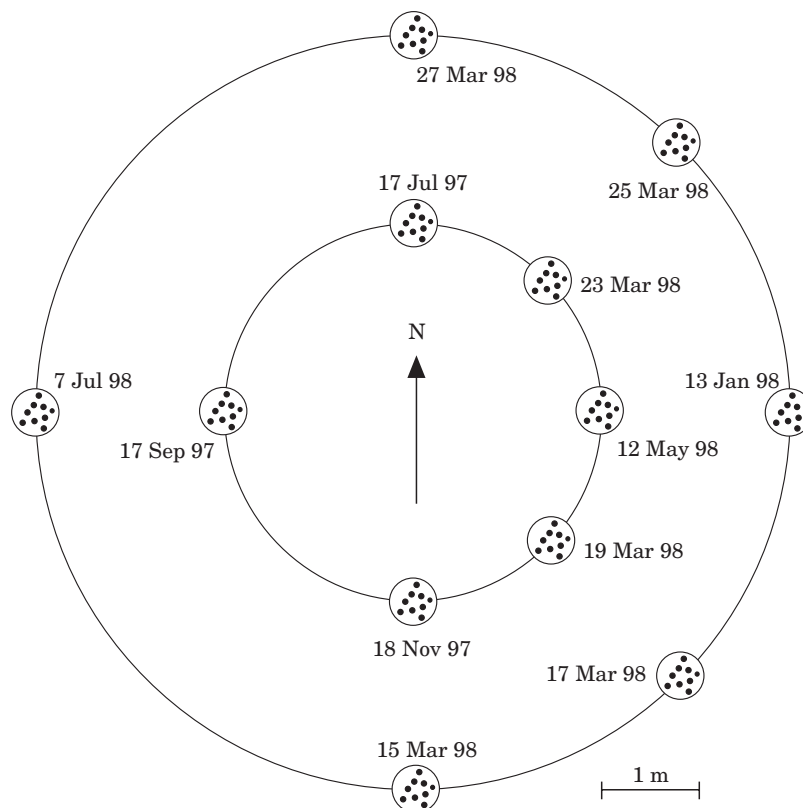


FIGURE 2. Study site and arrangement of the sampling locations (circles). Dots: approximate arrangement of the cores within the sampling location.

$\text{NO}_x^-$  (nitrate/nitrite) was determined by vanadium (III) reduction at 80 °C and subsequent chemiluminescence detection (Braman & Hendrix, 1989). A Thermo Environmental Instruments 42C  $\text{NO}_x$ -analyser and a HP3395 peak integrator were used. The detection limit was 1  $\mu\text{M}$ , and replicates agreed within 2%.

#### *Solid phase analyses*

Particulate carbon (PC) and nitrogen (PN) content was measured using a Fisons NA1500N elemental analyser with sulphanimide as the calibration standard. For particulate organic carbon (POC) determination, samples were pre-treated with 6N HCl for 15 min, washed twice with distilled water and dried. Weight loss by this pre-treatment was calculated assuming complete conservation of nitrogen, and POC contents were corrected accordingly.

For chlorophyll analyses, we prepared extracts from the fine fraction by dark incubation with 90% acetone at 4 °C for 16 h and subsequent centrifugation (1620 g, 7 min, 4 °C) using a Heraeus Metafuge 1.0 R. The supernatant was syringe-filtered through 0.45  $\mu\text{m}$  pores (Nalgene 199-2045 PTFE). Chloro-

phyll equivalent concentrations were determined fluorimetrically without acidification using a Hitachi F-2000. Solutions of Chl *a* in 90% acetone were used for calibration.

#### *Auxiliary measurements*

Daily data on the local weather conditions throughout 1997 and 1998, in particular wind speed and air temperature, were kindly provided by Deutscher Wetterdienst (DWD).

On all sampling days, we recorded the temperatures of air, water and sediment at the sampling site. Current velocities 2 cm above the sediment surface were measured 1–1.5 h before low tide using a Schiltknecht turbine anemometer.

Königshafen Bay was monitored throughout the study period with respect to phytoplankton cell numbers and species as well as Chl concentrations in the water column. P. Martens (Wadden Sea Station Sylt, AWI Foundation for Polar and Marine Research) kindly placed these unpublished data at our disposal.

Smear slides of the fine fraction were prepared according to Haq and Boersma (1978) using filtered

Balsam Canada as a fixative. We inspected them by light microscopy to qualitatively survey the types of particles found in the sediment samples.

## Results

### Fine fraction

The fine fraction extracted from the cores consisted mainly of silt-sized quartz grains, detritus, and fragments of diatom and foraminifera shells. On average, it constituted 0.6% (dry wt.) of the sediment. As an overall feature of the depth profiles of fine particles, we observed a minimum mostly located between 1.0 and 2.5 cm depth, and a subsurface maximum in 4 to 8 cm depth, in most cases close to the visually localised interface between oxidized and reduced sediment (Figure 3). The bandwidth, i.e. the difference between maximum and minimum, of concentrations within a profile amounted to 42–87% of the corresponding maximum value, and gradients from the minimum both towards smaller and towards greater depths were steep (Figure 3). Weighted average concentrations of the fine fraction in the depth intervals 0–1.0 cm (surface), 1.0–2.5 cm (minimum), 2.5–5 cm, 5–10 cm (subsurface maximum), and 10–15 cm of each profile were compared applying a Wilcoxon matched pairs signed rank test (Sachs, 1997). Fine particle concentrations in 1.0–2.5 cm depth were significantly lower ( $\alpha=0.1\%$ ) than those in 2.5–5 cm depth, which in turn were significantly lower ( $\alpha=1\%$ ) than concentrations in 5–10 cm depth. No significant difference in concentrations of the fine fraction could be detected ( $\alpha=5\%$ ) between the 5–10 cm depth interval and deeper down, nor between the 1.0–2.5 cm depth interval and the uppermost cm.

### Impact of bioturbation

Bioturbating macrofauna species found in the sliced cores were the polychaetes *Nereis* sp. and *Scoloplos armiger* M. Additionally, not more than one lugworm (*Arenicola marina* L.) was presented per sampled area (0.24 m<sup>2</sup>). In March 1998, wet-sieved sediment contained 647 ind m<sup>-2</sup> *Nereis*, 117 ind m<sup>-2</sup> *Scoloplos* and <11 ind m<sup>-2</sup> *Arenicola*. Judged from the species occurring during the study period, their approximate abundances in spring, location (Figure 1), organic content, grain size and exposure time of the sediment, our study site belonged to the lower sandy lugworm flats of Königshafen, according to the habitat classification of Reise *et al.* (1994) and Gätje and Reise (1998), however, with exceptionally low lugworm densities. Macrofaunal biomass data from those more

comprehensive studies were used for the following calculations constraining biological particle transport.

Species-specific biodiffusion coefficients at 15 °C and the corresponding biomasses were taken from Huettel (1988). Conversion based on the biomasses given by Reise *et al.* (1994) resulted in biodiffusion coefficients of  $D_B$  (*Arenicola marina*) =  $1.43 \times 10^{-6}$  cm<sup>2</sup> s<sup>-1</sup>,  $D_B$  (*Nereis diversicolor* M) =  $0.18 \times 10^{-6}$  cm<sup>2</sup> s<sup>-1</sup>, and  $D_B$  (*Scoloplos armiger*) =  $0.24 \times 10^{-6}$  cm<sup>2</sup> s<sup>-1</sup>. The particle flux ( $\mathcal{J}$ ) in the sediment is related to porosity ( $\phi$ ), biodiffusion coefficient ( $D_B$ ) and the vertical component of the particle concentration gradient ( $\partial/\partial z B$ ) by Equation 1 (Boudreau, 1997):

$$\mathcal{J} = -(1 - \phi) D_B \frac{\partial}{\partial z} B \quad (1)$$

With  $\phi \approx 0.34$  (Rusch *et al.*, pers. comm.) and  $\partial B/\partial z \approx -6$  mg cm<sup>-4</sup> in our study, biogeochemical transport of fine particulates would account for 6.33 g m<sup>-2</sup> day<sup>-1</sup>. The amount of fine particles in the top 5 cm varied between 146 g m<sup>-2</sup> in winter and 2533 g m<sup>-2</sup> in summer. To accumulate the difference within half a year, a net particle flux of 13.1 g m<sup>-2</sup> day<sup>-1</sup> was needed. Less than half of it could be explained by biogeochemical transport.

### Biochemically labile components

To characterize the composition of the fine fraction, its Chl content and molar C:N ratio was measured. The summer and autumn (July 97, September 97, May 98, July 98) chlorophyll equivalent concentration profiles (Figure 4) could in major part be described by the following equation:

$$[\text{Chl}] (z) = [\text{Chl}]_0 e^{-\lambda z} \quad (2)$$

with  $[\text{Chl}]_0$ : content at sediment surface,  $z$ : depth and  $\lambda$ : decay constant. Constants and correlation coefficients for the best fits are given in Table 2.

The winter and spring (January 98, March 98)  $[\text{Chl}]$  profiles (Figure 4) were shaped differently: relatively Chl-rich material penetrated down to 5–9 cm depth, below which Chl contents rapidly dropped to background values. Chl contents were highest in the depth interval of minimum C:N ratios. Intermediate profiles between the ‘summer shape’ and the ‘winter shape’ were recorded in November 97 (data not shown).

C:N ratios of the fine fraction ranged between 9 and 13, in the total sediment between 16 and 42. The latter values may be slightly overestimated, as the N content of the sand fraction was close to the detection limit.

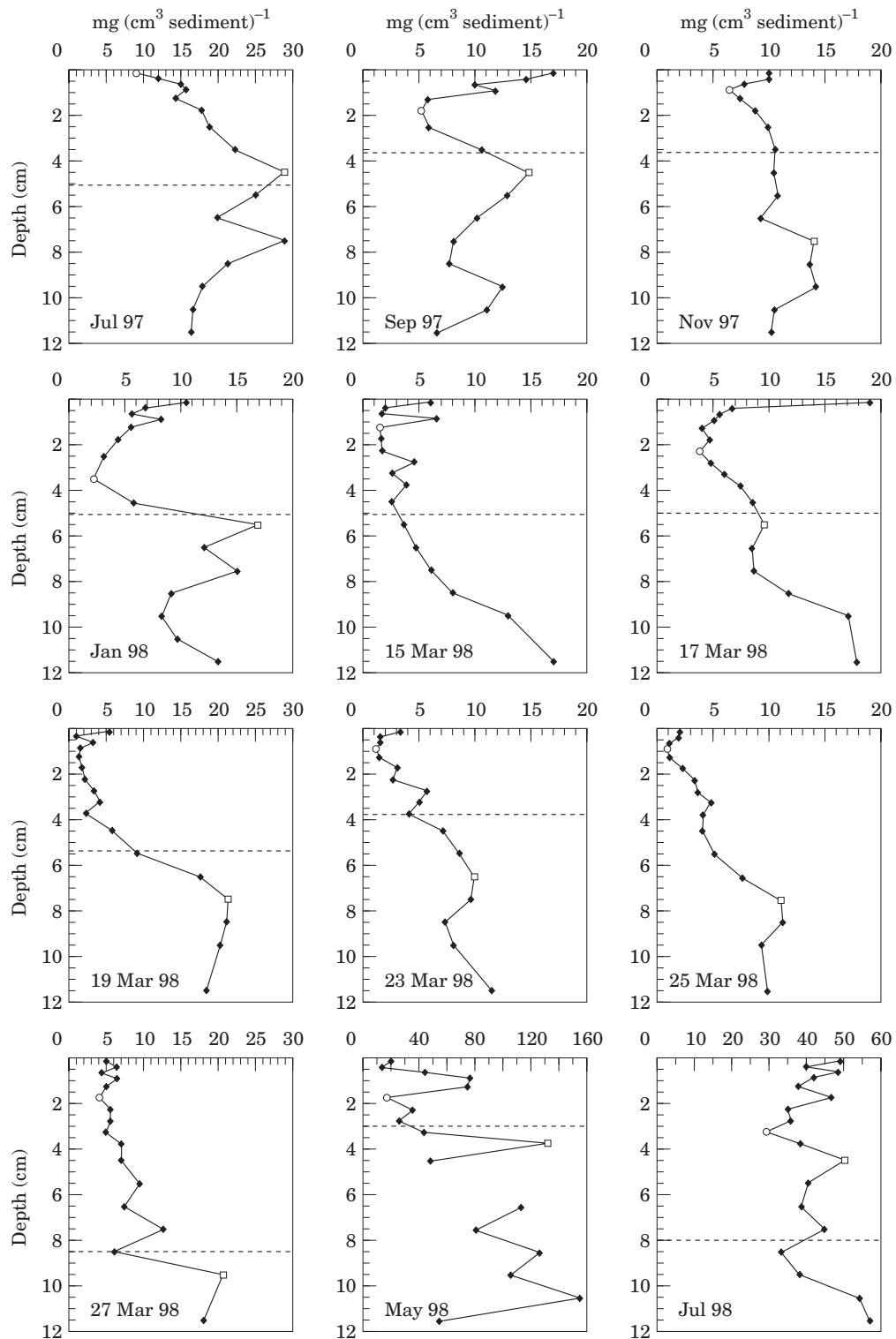


FIGURE 3. Depth profiles of the concentration of fine fraction extracted from the sediment. Circles: minimum; squares: subsurface maximum. Broken line: depth of changing colour between oxidized and reduced sediment.

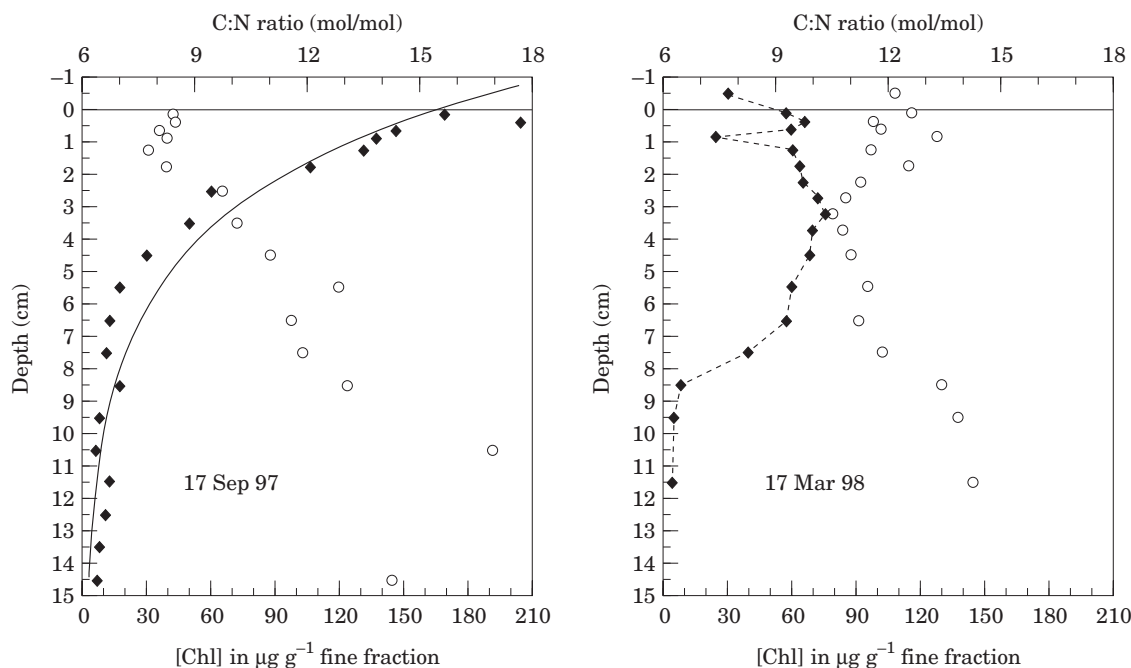


FIGURE 4. Depth profiles of Chl content (diamonds) and C:N ratio (circles) of the fine fraction. Solid line: data fit according to Table 2. Values in  $-0.5$  cm depth refer to particles suspended in the water column. Left: summer/autumn, represented by 17 September 97; right: winter/spring, represented by 17 March 98. The complete data set for all profiles is available from the authors.

### Carbon

The fine fraction was  $47 \pm 34$  ( $N=15$ ) times as rich in POC (by weight) as the sediment it was extracted from. It contained  $(28 \pm 28)\%$  of the sedimentary organic carbon.

Fine POC as the starting-point of decomposition and porewater DIC as its final product are shown in Figure 5(a,b). Most DIC profiles could be described as the superposition of a linear increase with depth and a local, cap-shaped surplus within the top 5 cm. The slope of the gradient and the depth-integrated size of the 'cap' varied seasonally.

TABLE 2. Parameters of the summer/autumn [Chl] profile fits according to Equation 2: surface concentration, decay constant, correlation coefficient. Last column: depth interval, if not all data were included

	$[\text{Chl}]_0$ ( $\mu\text{g g}^{-1}$ )	$\lambda$ ( $\text{cm}^{-1}$ )	$R^2$	
17 Jul 97	259	0.207	0.9532	
17 Sep 97	164	0.278	0.8607	
18 Nov 97	176	0.175	0.9233	$z > 2.5$ cm
12 May 98	102	0.269	0.8240	$z > 1.5$ cm
7 Jul 98	141	0.222	0.9831	$z \leq 6$ cm v $z \geq 11$ cm

POC contents markedly decreased towards greater depths in summer and autumn [Figure 5(a): July 97, September 97, July 98], whereas in winter and spring [Figure 5(a): November 97, January 98, Figure 5(b)] they appeared constant or slightly increasing with depth. In the May profile, the value at 11–12 cm depth was an outlier due to locally higher amounts of fine particles that were rich in POC and PN, but poor in Chl. Several profiles showed a POC minimum within the uppermost 2–3 cm.

### Nitrogen

The fine fraction was  $19 \pm 10$  ( $N=94$ ) times as rich in nitrogen (by weight) as the sediment it was extracted from. It contained  $(12 \pm 11)\%$  of the sedimentary nitrogen.

Figure 6 compares the profiles of different nitrogen species: fine particulate nitrogen (PN), oxidized DIN (nitrate/nitrite) and reduced DIN (ammonium). As examples for the summer and winter situations, September 97 and 17 March 98, are shown, respectively.

Below 5 cm depth, the PN content of the fine fraction remained constant or slightly decreased with depth. Temporal changes virtually affected only the top 5 cm. All winter profiles showed a local PN minimum in the uppermost 2 cm.

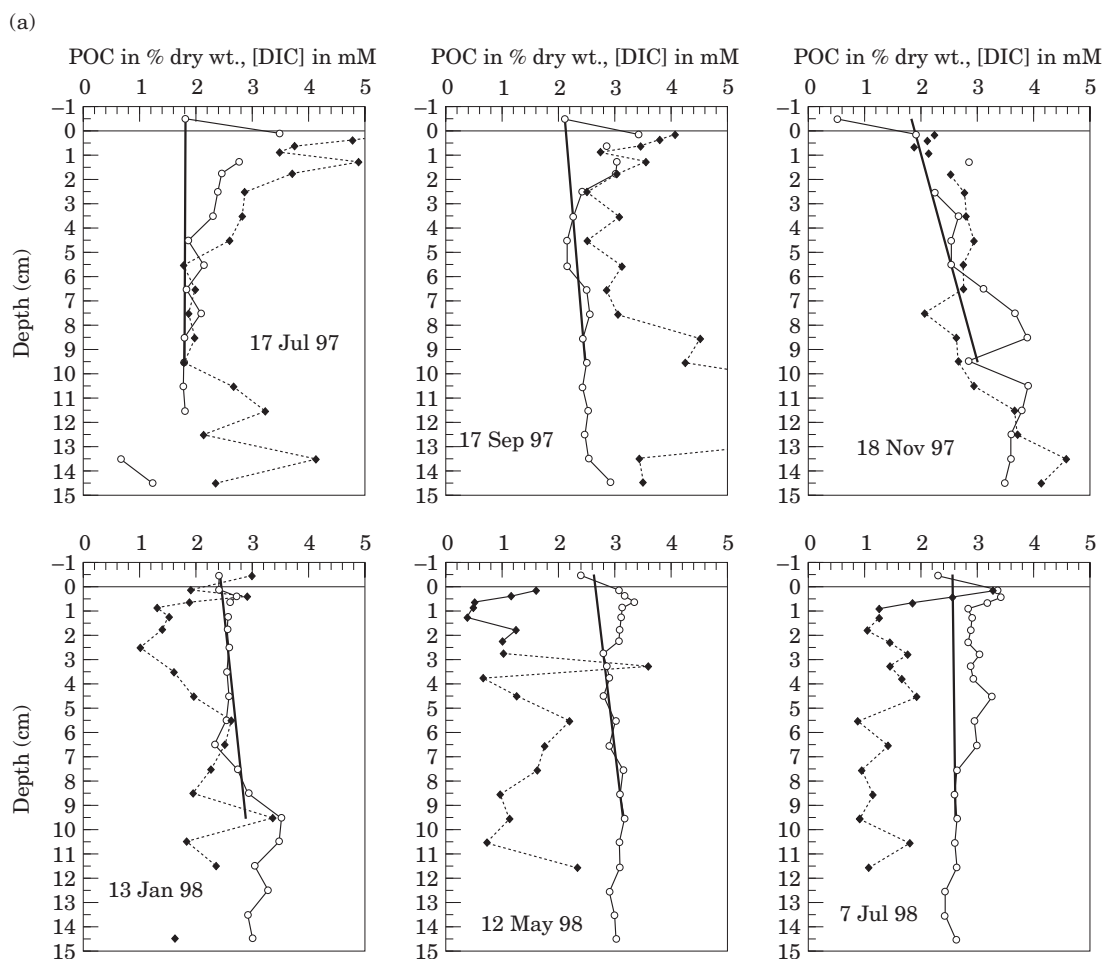


FIGURE 5. (a).

Except for occasionally a very narrow peak in the top 1–2 cm, porewater nitrate/nitrite ( $\text{NO}_x^-$ ) concentrations during summer and autumn were mostly below  $5\text{--}10\ \mu\text{M}$  throughout the sediment column and overlying water. Comparatively high concentrations of up to  $70\ \mu\text{M}\ \text{NO}_x^-$  were recorded in winter and spring, with porewater profiles appearing dominated by oxidant supply from and DIN release into the water column.  $\text{NO}_x^-$  penetrated 3 to 8 cm into the sediment, and down to the same depth  $\text{NH}_4^+$  concentrations were low.

#### Seasonal variation

The phytoplankton and weather conditions for each sampling date are compiled in Table 1. During increases in wind speed—generally related to rougher seas—the top cm of the sediment was depleted in the fine fraction, e.g. in July 97 and May 98 (Figure 3). With wind and water calming, recently suspended

material re-entered the uppermost sediment layers, e.g. in September 97, March 98 and July 98 (Figure 3). Chl-rich material was entered in September 97 and March 98 (Rusch *et al.*, pers. comm.), when phytoplankton bloomed (Table 1).

Throughout the year, only minor changes occurred below 5 cm depth, whereas the upper 5 cm showed marked seasonal variation in the profiles of fine particulates, POC, PN, and Chl, with concentrations decreasing from summer 1997 to winter and increasing again until summer 1998. The mean concentrations between 5 and 10 cm depth over all seasons are listed in Table 3. Assuming the same mean background concentrations for the whole sediment column, we define a dimensionless ‘relative variation’ according to Equation 3:

$$\text{relative variation} = \frac{\text{summer concentration} - \text{winter concentration}}{\text{mean background concentration}} \quad (3)$$

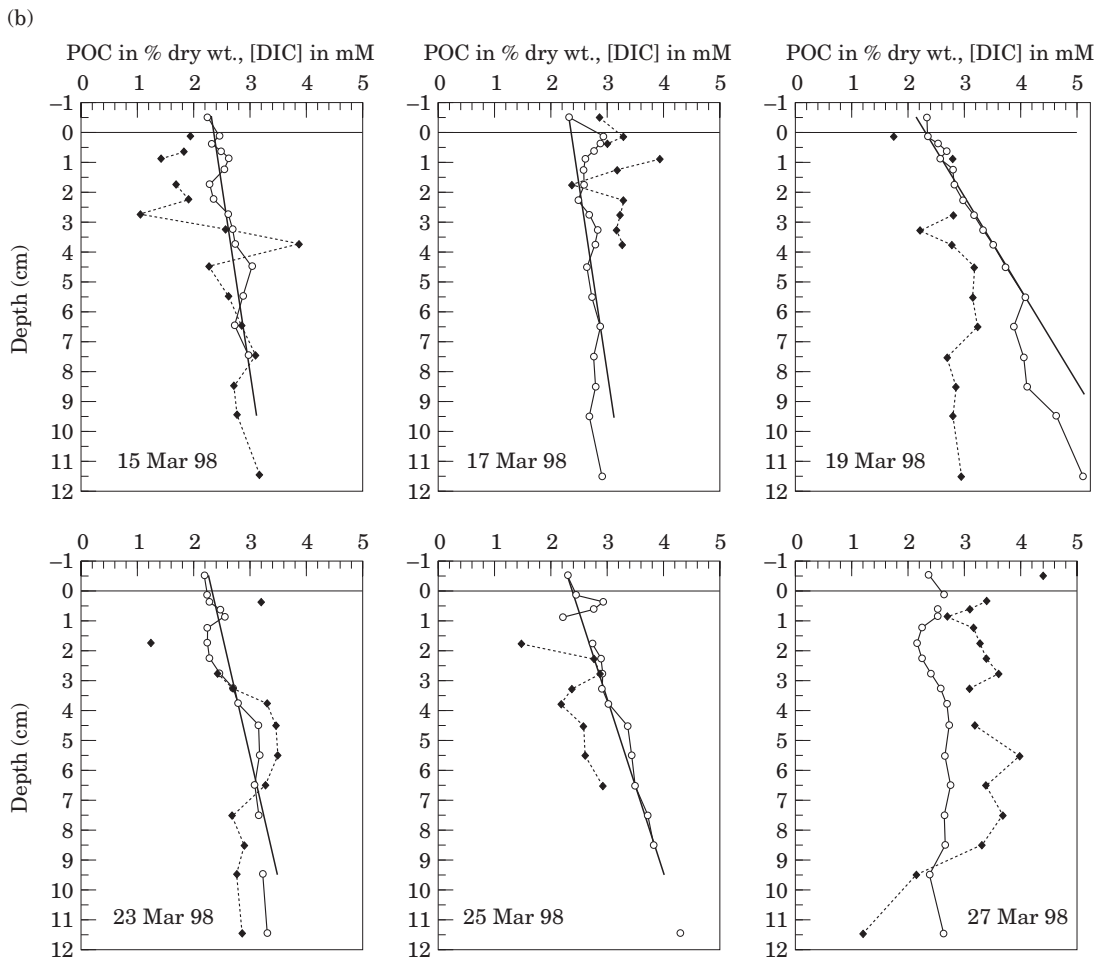


FIGURE 5. (b).

FIGURE 5. Depth profiles of POC content of the fine fraction (diamonds) and porewater DIC concentration (circles). POC values in  $-0.5$  cm depth refer to particles suspended in the water column. Bold lines: supposed DIC gradient (for explanations see text). (a) July 97 through to January 98, May 98, July 98. (b) March 98.

with winter meaning January 98 and summer the mean of July 97 and July 98. The resulting depth profiles of the relative variations are compared in Figure 7. The amount of fine particles did not vary significantly more in the upper 5 cm than it did below ( $\alpha > 5\%$ , Lord test; Sachs, 1997). In contrast, the relative variation of POC and PN concentrations abruptly and significantly decreased at 5 cm depth ( $\alpha < 1\%$ , Lord test), with the variation of PN generally exceeding that of POC. The most pronounced seasonality was found in Chl concentrations, with relative variations of up to 12 near the surface. Unlike the other parameters, Chl variations decreased with depth rather exponentially than abruptly at a certain depth. Significant differences between the depth intervals 0–1 cm were found for Chl ( $\alpha < 1\%$ ), but not ( $\alpha > 5\%$ ) for fine particle, POC and PN variations (Lord test).

The concentrations of POC, PN and Chl in the upper 5 cm exceeding the mean background part were integrated separately for each sampling date (March: mean). The resulting areal inventories are listed in Table 3. The pool sizes gradually decreased from summer 1997 until January 1998 and afterwards increased again. Negative inventories show that part of the background organic matter was removed during winter.

#### Mineralization rates

Annual carbon mineralization rates of the studied sandy sediment were estimated using four different approaches, A–D. In approach A, the loss of POC between maximum inventory in summer and minimum inventory in winter was divided by 0.5 years,

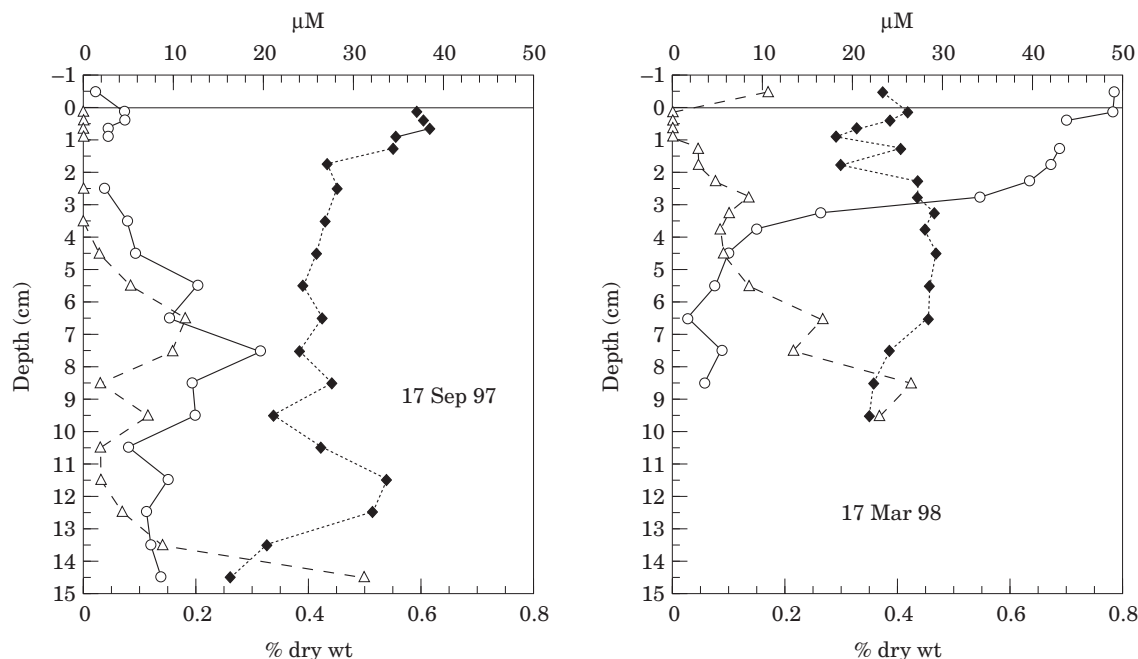


FIGURE 6. Depth profiles of PN content of the fine fraction (diamonds) and pore water DIN concentrations ( $\text{NO}_x^-$ : circles;  $\text{NH}_4^+$ : triangles). PN values in  $-0.5$  cm depth refer to particles suspended in the water column. Left: summer/autumn, represented by 17 September 97; right: winter/spring, represented by 17 March 98.

resulting in  $55 \text{ g C m}^{-2} \text{ yr}^{-1}$  (summer: July 1997) or  $64 \text{ g C m}^{-2} \text{ yr}^{-1}$  (summer: July 1998). More elaborate approaches treated each DIC profile separately, integrating the amount of accumulated mineralization product in the way schematically illustrated in Figure 8. Assuming seawater penetration down to 5 cm depth, there was a DIC background to be deducted from the total amount in the uppermost 5 cm. Annual mean ( $2.26 \pm 0.16 \text{ mM}$ ) and momentary seawater DIC concentrations were used in approach B and C, respectively. In approach D, the DIC gradient concentrations [Figure 5(a,b)] were regarded as background, and only the superimposed surplus DIC was depth-integrated. We assumed that the maximum time for DIC accumulation was the span between highest near-bottom tidal current velocity in the first third of the flood cycle (Austen, 1994) and sampling, i.e. 7 h, and used this value in the calculation. The rates obtained that way for every second month were integrated over the year, yielding annual rates of  $123 \text{ g C m}^{-2} \text{ yr}^{-1}$  (B),  $116 \text{ g C m}^{-2} \text{ yr}^{-1}$  (C), and  $75 \text{ g C m}^{-2} \text{ yr}^{-1}$  (D), respectively.

## Discussion

### *Depth distribution of fine particles in a permeable sediment*

The studied marine sediment was exposed to near-bottom currents, and its relatively high permeability

facilitated hydrodynamic influence down to 4–8 cm depth. The sediment colour suggested that there was sufficient porewater flushing to keep the upper 3–5–9 cm of the sediment oxidized. This depth of porewater exchange was in many cases close to the horizon of maximum concentration of fine particles (Figure 3). With concentrations in the 2.5–5 cm depth interval significantly lower than in the 5–10 cm depth interval, it can be concluded that not only porewater but also small particles were hydrodynamically removed from the sediment. Fine-grained material could be displaced by advective flows or waves propagating into the sediment, and by winnowing during resuspension and redeposition of the uppermost sediment layers. Towards the surface, the sediment was increasingly depleted in fine fraction, as shown by significantly lower concentrations in 1.0–2.5 cm depth compared to below. By contrast, the uppermost cm was affected by surface deposition, ripple migration, erosion/redeposition cycles, microphytobenthic colonization etc., and due to this mixed influence, no significant overall feature of the top layer could be detected. Individual profiles, though, could be qualitatively related to short-term weather changes.

### *Contribution of biogeochemical particle transport*

Shallow water sediments are often densely populated by macrofauna (e.g. McCall & Tevesz, 1982;

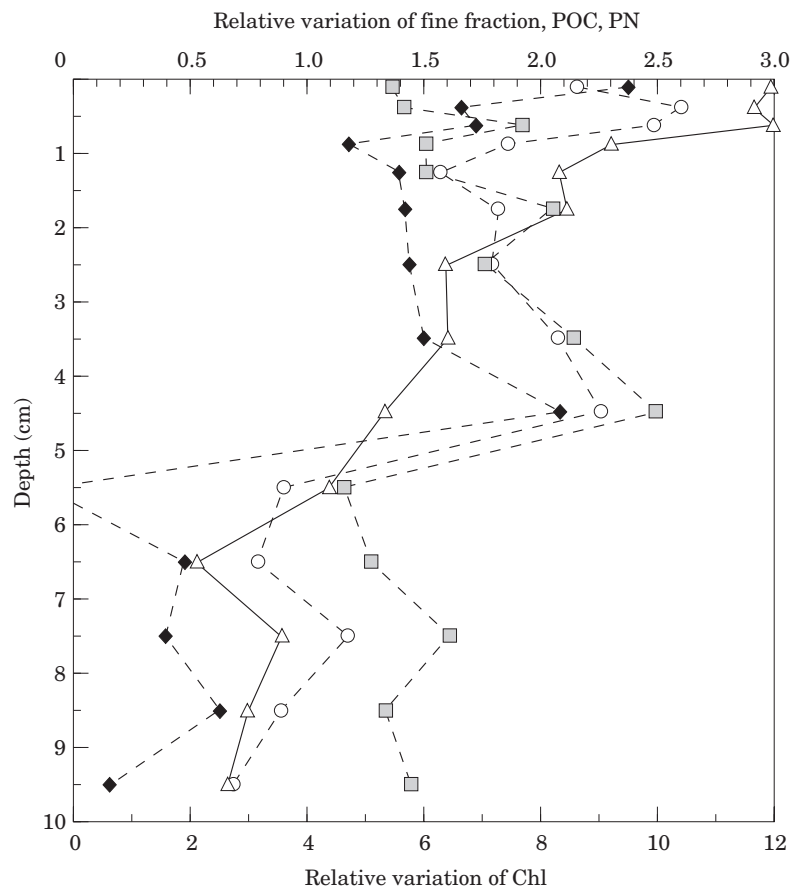


FIGURE 7. Depth profiles of the ‘relative variation’ (defined by Equation 3) of fine particle (squares), POC (diamonds), PN (circles) and Chl (triangles) concentrations in the sediment. The negative value at 5–6 cm depth resulted from a relatively high POC content in January 98 and an extremely low POC content in July 98 [see Figure 5(a)].

TABLE 3. POC, PN and Chl in the sediment: mean concentration in 5–10 cm depth (seasonally invariant), regarded as the refractory part, and areal inventories in the top 5 cm, refractory part deducted

	POC	PN	Chl
Mean concentration (5–10 cm) ( $\mu\text{g cm}^{-3}$ )	$363 \pm 89$ ( $N=55$ )	$48 \pm 19$ ( $N=25$ )	$0.41 \pm 0.41$ ( $N=51$ )
Inventory (0–5 cm) ( $\mu\text{g cm}^{-2}$ )			
17 Jul 97	1349	279	11.4
17 Sep 97	-303	-2	2.2
18 Nov 97	-507	-78	2.6
13 Jan 98	-1411	-175	-1.1
March 98	-1137	-151	-0.8
12 May 98	874	72	5.4
7 Jul 98	1774	344	17.2

Wheatcroft *et al.*, 1990; Marinelli & Boudreau, 1996), so bioturbation is expected to contribute to particle transport across the water–sediment interface. For that reason, a study site was chosen that belonged to

an intertidal habitat type lowest in macrofauna abundance and biomass within Königshafen, except for some sandbars (Reise *et al.*, 1994). Interannual biomass variabilities of North Sea intertidal communities

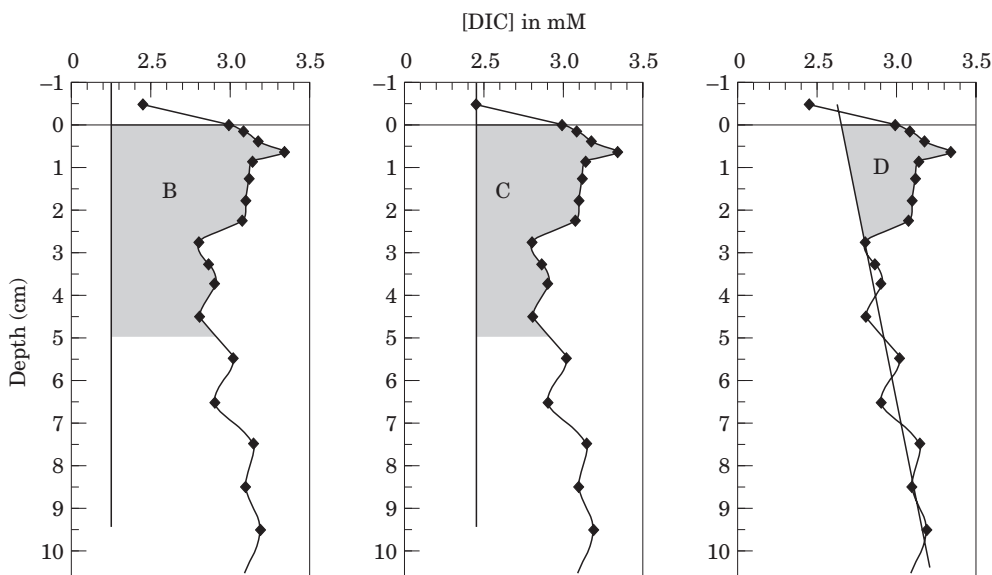


FIGURE 8. Schematic of the DIC integration approaches B (left), C (centre) and D (right), performed on the May 98 profile as an illustrative example.

are about 10–30% (Beukema *et al.*, 1993; Reise *et al.*, 1994), low enough to base our rough estimate of biogenic particle transport on older data from the same location. According to these data, more than three-quarters of the calculated biodiffusion was due to *Arenicola marina*, however, as throughout the study period we observed lower lugworm densities than Reise *et al.* (1994), the biodiffusive fine particle flux may be overestimated. As commonly found in the literature, our worst case calculations were based on bioturbation modelled as a diffusive process acting along concentration gradients. Although deposit feeding moves particles in a rather non-local manner (e.g. conveyor-belt-like), non-diffusive mechanisms of sediment displacement can combine to produce apparently diffusive profiles (Wheatcroft *et al.*, 1990). In most shallow water environments, mixing rates exceed  $0.32 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$  (Wheatcroft *et al.*, 1990), so our estimate of  $D_B \leq 1.85 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$  was in a typical range. Notwithstanding this relatively high biodiffusion coefficient, less than half of the net particle flux could be attributed to biogenic transport. We therefore conclude that in our study physical transport processes had a stronger impact than macrozoobenthos.

#### Organic matter in fine and coarse particles

Compared to the sediment total, the fine fraction was distinguished as markedly richer in  $C_{\text{org}}$  and N and having smaller C:N ratios. Fresh organic matter preferentially associated with the silt and even more with

the clay fraction has been reported of various marine sediments (Bordovskiy, 1965; Tanoue & Handa, 1979; deFlaun & Mayer, 1983; Wiesner *et al.*, 1990; Anton *et al.*, 1993; Mayer, 1994; Lohse *et al.*, 1995). In sandy sediments, fine particles are subject to intense dynamics, because they represent not only the biogeochemically labile fraction, but at the same time also the most mobile part of the sediment. At our study site, 28% of the organic carbon and 12% of the sedimentary nitrogen were associated with the easily moveable fine particles that comprised *c.* 1% (v/v) of the sediment. The remaining organic material was adsorbed to the coarse sand matrix and therefore moved much less. Moreover, it could be partly sheltered from microbial degradation by the microtopography of the sand grains (Mayer, 1994). Considering mobility and bioavailability, the adsorbed fraction of organic matter presumably contributed less to the spatial and temporal dynamics we observed than the fine particles.

#### Interfacial transport of fine-grained POM

In winter and spring, relatively strong currents could cause advective flow through the permeable, rippled sediment, carrying labile POM from the water column down to 5–9 cm depth (Figure 4), where retention and adsorption (Huettel *et al.*, 1996) trapped the fine particles. As temperatures and benthic activity were still low at that time of the year, the decomposition of freshly entered material could not keep step with the transport processes. During summer and early

autumn, though, increased degradation activity and moderate current velocities apparently reduced the net penetration of labile POM (Figure 4), and exponential [Chl] profiles (Table 2) suggest that transport was relatively slow compared to decomposition.

#### *Dynamics of sedimentary carbon*

The spatial and temporal variability observed in the POC contents and DIC concentrations [Figure 5(a,b)] reflected carbon mineralization that depended on seasons and sediment depth. In summer, POC contents decreased with depth by the combined effects of organic-rich particle input from the surface and intense degradation in deeper layers. In winter, with particle supply poorer in organics and sedimentary decomposition slowed down, POC contents stayed constant with depth. All POC contents were corrected for changes in sample weight due to the acid pre-treatment, basing on the assumption that acidification did not change the nitrogen content. This premise might have introduced slight errors, as acid treatment can generate volatile nitrogen compounds, especially in carbonate-rich samples (Lohse *et al.*, 2000). Compared to even the nearly unaffected, low-carbonate samples of that study, our sediment contained an order of magnitude less carbonate (data not shown). Therefore, errors in our POC data that may be attributed to nitrogen loss appear insignificant.

Gradients in the DIC profiles were influenced by diffusive and advective export counteracting production by fermenting and mineralizing bacteria. A balanced situation in summer 1997, with gradients almost vertical, gave way to a gradually increasing dominance of DIC removal, indicated by a marked decrease of concentrations towards the sediment surface. During spring and summer 1998, the transport/production steady state equilibrium was gradually re-established. The upper 2–3 cm of our sediment were characterized by a POC minimum and DIC maximum [Figure 5(a,b)] as well as a PN minimum (Figure 6). Benthic microbial activity seemed especially high in this horizon, apparently fuelled by a recurrent supply of both labile organic matter and oxidants from the water column. Moreover, possible inhibition by metabolic end products could be minimised by advective removal. Remarkably, bacterial counts from the same site (Rusch *et al.*, pers. comm.) indicated that the microbiologically most active zone was not at the very surface, but rather in 1 to 4 cm depth, depending on the season. Bacteria living close to the water–sediment interface experience strong mechanical stress due to harsh hydrodynamic conditions and grazing by meiofauna, making the top cm

unfavourable to dwell in in spite of optimal food supply.

#### *Dynamics of sedimentary nitrogen*

The narrow  $\text{NO}_x^-$  peaks close to the water–sediment interface, occasionally occurring in the summer and autumn profiles (Figure 6), were probably related to single ragworms (*Nereis* sp.). These polychaetes stimulate subsurface nitrification in their burrow walls (Kristensen & Blackburn, 1987; Huettel, 1988). Apart from the presumably *Nereis*-caused peaks, the summer and winter DIN profiles (Figure 6) were basically similar to those obtained by Lohse *et al.* (1993) at a North Sea coastal station with a fine sandy bottom as organic-poor as our study site. In summer, subsurface nitrification rates and interfacial DIN fluxes were high (Lohse *et al.*, 1993), providing nutrients for primary production and electron donors for OM mineralization. As nitrification appears more strictly limited by ammonium availability than by oxygen penetration, lower nitrification rates were measured in winter (Lohse *et al.*, 1993). Neither primary production nor OM mineralization are major nitrate sinks during winter and early spring in Königshafen (Gätje & Reise, 1998), so  $\text{NO}_x^-$  could accumulate in spite of relatively slow production. Deep-reaching exchange of oxygen and DIN with the water column, in the cold season favoured by particularly strong currents and high permeabilities, closely linked benthic and pelagic nitrogen turnover.

#### *Influence of the seasons*

Seasonally varying extents of hydrodynamic and biogeochemical influences became obvious in the effects on the labile fine fraction (Figure 4), POC/DIC [Figure 5(a,b)] and PN/DIN profiles (Figure 6), with a physically dominated winter situation and a microbologically dominated summer situation. Direct and indirect impacts of medium-term weather changes (Table 1) affected mainly the top 5 cm, whereas below the sediment approached steady-state conditions, indicated by small seasonal variations (Figure 7). Relative variations of concentrations decreased in the order  $\text{Chl} > \text{PN} > \text{POC} > \text{fine fraction}$  in accordance with the order of biochemical lability. The time series of the areal inventories of Chl, PN and POC (Table 3) coherently showed a continuous net removal of POM from the sedimentary pool throughout the second half of 1997, as well as the net accumulation of freshly entered POM during spring and summer 1998. Zero inventories were defined as correspondence to the

background concentrations below 5 cm depth, where POM supply and early diagenesis seem to balance each other throughout the year. Negative areal inventories in 0–5 cm depth (Table 3) were unlikely to be due to enhanced degradation alone, as they occurred in winter. Additionally, better POM supply to upper sediment layers than to deeper ones pushes the balance rather towards positive inventories. Thus, an additional explanation for the removal of POM from the sediment is required. We suggest particle efflux by resuspension and/or advective processes. Interannual variation, roughly estimated from the differences in pool size between July 97 and July 98, was small compared to the seasonal variation (Table 3), thus making the results of our one-year study to some extent transferable to other years.

#### *Carbon turnover rates in a permeable sandflat sediment*

The determination of mineralization rates by core incubations or *in situ* measurements using benthic chambers is not appropriate for sands exposed to waves and currents, as these methods cannot include hydrodynamic effects and therefore underestimate turnover rates. Our approach A is an underestimation as well for the reason that POC inputs during autumn, e.g. from the *Rhizosolenia* and *Chaetoceros* blooms (Table 1), were ignored. On the other hand, POC loss was not purely diagenetic, leading to an overestimation of carbon mineralization. The problem of overestimation is by-passed by considering and treating the tightly coupled benthic and near-bottom pelagic environment as a unit. From the DIC approaches, D agreed best with the result of the POC approach A. Approach D could be taken as a rough estimate for oxic and suboxic mineralization, but by deduction of the upward diffusing DIC it disregards sulphate reduction as an important degradation process in deeper layers and therefore underestimates the total sedimentary mineralization. B and C were nearly equal with respect to both the approaches themselves and their results on an annual basis. They would only be prone to slight overestimation, if porewater exchange were incomplete during the preceding flood cycle, or to underestimation, if accumulation were incomplete due to some extent of interfacial exchange during the accumulation period. All our approaches fail to consider horizontal heterogeneity as a typical feature of intertidal sediments and three-dimensional advective flow patterns (Huettel *et al.*, 1998). Nevertheless, we consider a turnover rate of  $120 \text{ g C m}^{-2} \text{ yr}^{-1}$  to serve well as a first, preliminary estimate for temperate intertidal sandflats. It is in the same order as mineralization rates in another

Königshafen sandflat and the estimated planktonic primary production in the bay (Gätje & Reise, 1998). Further studies should focus on more detailed carbon budgets, including DOC fluxes and benthic primary production, and quantify the degree of coupling between bottom water and permeable sediments at various sandy shelf sites. Annual carbon turnover rates have been measured in different North Sea sediments, and results ranged between  $24$  and  $131 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Upton *et al.*, 1993; Nedwell *et al.*, 1994; Osinga *et al.*, 1996; Boon *et al.*, 1998; Boon & Duineveld, 1998). Median grain sizes were  $100$ – $250 \mu\text{m}$  and TOC contents one order of magnitude higher than in our sediment, which yet proved to be equally active.

#### Conclusions

Life in our sandflat had to cope with an environment variable both in time and in space. Below 5 cm depth, conditions changed only slightly and slowly, and a constantly small bacterial population fed on rather refractory POM or depended on occasional DOM supply from above. The zone between 1 and 5 cm depth was characterised by steep gradients (Figure 3) and strong seasonal variation (Figure 7), and tight coupling to the water column provided rich supply for many microbes. Since advective transport enhances the oxygen utilisation of permeable sediments, particularly when easily degradable organic carbon is available (Forster *et al.*, 1996), it may as well provide a mechanism to enhance carbon mineralization (Ziebis *et al.*, 1996). The sediment studied here met all requirements for advective particle and solute exchange, like surface roughness, high permeability and relatively strong near-bottom currents, and in this paper we have presented several clear signs of advective influence on the organic matter budget of the uppermost 5 cm. Our results support the conclusion that the high-energy environment on the continental shelf enhances biogeochemical dynamics in permeable sands. With 30% of the oceanic primary production (Jørgensen, 1996), shallow coastal waters have a high potential of OM mineralization, in which sandy sediments may contribute far more than to be expected from grain size and TOC content. Since permeable sands cover 43.5% of the world's continental shelves (Riedl *et al.*, 1972), they should be reconsidered with respect to quantitative importance in the marine carbon cycle.

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