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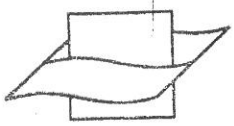

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The seafloor as the ultimate sediment trap—using sediment properties to constrain benthic–pelagic exchange processes at the Goban Spur

Peter M.J. Herman[a,*], Karline Soetaert[a], Jack J. Middelburg[a], Carlo Heip[a], Lutz Lohse[b], Erik Epping[b], Wim Helder[b], Avan N. Antia[c], Rolf Peinert[c]

[a] *Netherlands Institute of Ecology, Centre for Estuarine and Coastal Ecology, P.O. Box 140, NL-4400 AC Yerseke, Netherlands*
[b] *Netherlands Institute for Sea Research, P.O. Box 59, NL-1790 Den Burg-Texel, Netherlands*
[c] *Institut für Meereskunde, Universität Kiel, Düsternbrooker Weg 20, D-24105 Kiel, Germany*

Abstract

The benthic diagenetic model OMEXDIA has been used to reproduce observed benthic pore water and solid phase profiles obtained during the OMEX study in the Goban Spur Area (N.E. Atlantic), and to dynamically model benthic profiles at site OMEX III (3660-m depth), with the sediment trap organic flux as external forcing. The results of the dynamic modelling show that the organic flux as determined from the lowermost sediment trap (400 metres above the bottom) at OMEX III is insufficient to explain the organic carbon and pore water profiles. The best fitting was obtained by maintaining the seasonal pattern as observed in the traps, while multiplying the absolute values of the flux by a factor of 1.85.

The "inverse modelling" of diagenetic processes resulted in estimates of total mineralisation rate and of degradability of the organic matter at the different stations. These diagenetic model-based estimates are used to constrain the patterns of lateral and vertical transports of organic matter. Using the observed degradability as a function of depth, we show that the observed organic matter fluxes at the different depths are consistent with a model where at all stations along the gradient the same vertical export flux occurs at 200 m, and where organic matter sinks with a constant sinking rate of around 130 m d^{-1}. If sinking rates were higher, in the order of 200 m d^{-1}, the observations could be consistent with an off-slope gradient in export production of approximately a factor of 1.5 between the shallowest and deepest sites.

The derived high degradability of the arriving organic matter and the consistency of the mass fluxes at the different stations exclude the possibility of a massive deposition, on the margin, of organic matter produced on the shelf or shelf break. However, other hypotheses to explain the patterns found in the sediment trap data of both OMEX and other continental margin study sites also suffer from

*Corresponding author. Tel.: +31-113-577475; fax: +31-113-573616.
E-mail address: herman@cemo.nioo.knaw.nl (P.M.J. Herman).

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different inconsistencies. Further, close examination of the flow patterns at the margin will be needed to examine the question.

1. Introduction

The role of continental margins in the global biogeochemical cycles is a matter of intense study. Previous studies have suggested that continental margin sediments may be active depocentres, where relatively high sedimentation rates cause the burial of substantial amounts of organic carbon (e.g., Anderson et al., 1994 and references therein). If it can be shown that this buried organic matter is derived from the shelf, it may represent a significant term in the carbon flux of the ocean, even if it is only a few percent of the shelf production (Anderson et al., 1994; Bacon et al., 1994; Falkowski et al., 1994).

Sediment trap studies have been and will remain an essential component of all studies focusing on the deposition of organic carbon in ocean margin and basin sediments. Material deposited in traps provides a wealth of quantitative and qualitative data about the settling matter. However, sediment trap deployments have their own methodological problems. In a vertical array of traps, a similar trap design is exposed to different hydrodynamic conditions, as actual current speeds tend to decrease with depth. Interaction between trap design and hydrodynamics may result in different trap efficiency. Near the bottom, resuspension of material in the benthic boundary layer may result in overtrapping. Lateral inputs, such as those resulting from deposition from intermediate nepheloid layers or other off-shelf transport mechanisms, may increase the amount of sediment trapped in intermediate traps in the array. Swimmers, and their interaction with poisoning of the traps, may bias the amount of material trapped. Extrapolating the flux caught in sediment traps to the flux actually arriving at the sediment surface therefore may be problematic. A common feature of trap deployments at continental margins is that deeper traps catch significantly more material than shallower ones in the same array (Etcheber et al., 1996). This is commonly ascribed to lateral inputs of settling material, although other processes may be important, such as particle focusing, hydrodynamic sorting of biogenous from heavier lithogenous resuspended sediment, horizontal advection or differences in trapping efficiency with depth (Timothy and Pond, 1997).

In this article we explore an alternative way to characterise the carbon flux by "looking up" from the diagenetic processes in the sediment, the ultimate sediment trap. This approach has been adopted before by Jahnke et al. (1990) and Reimers et al. (1992), who compared carbon fluxes based on sediment traps with those based on oxygen uptake and/or mineralisation rates along the eastern Pacific margin. They reported that the carbon demand by the sediments was significantly higher than that captured by sediment traps. Lateral inputs were invoked to reconcile the difference.

We forward their approach by considering not only the balance between the amount captured in traps and the quantity mineralised in the sediments, but also the degradability of the organic flux. Particulate organic matter is a complex mixture of numerous compounds with different reactivities which is best represented as a continuum of degradabilities (Middelburg, 1989; Boudreau and Ruddick, 1991). During decomposition microbial communities tend to sequentially

utilise organic substances, the more reactive substrates being consumed first (Westrich and Berner, 1984). As a result of the preferential consumption of reactive components, the reactivity of particulate organic matter decreases with time (Middelburg, 1989). Hence the average degradability of the organic matter delivered to the sediment contains information on the degradation history, i.e. age, of the organic matter. This information on the relative age of organic matter puts severe constraints on the possible transport pathway of the material to the sediment. High-quality young material is expected when rapid vertical transport dominates, whereas low-quality older material is anticipated in case of dominant lateral inputs.

During the OMEX project, considerable effort was spent in analysing profiles of pore water and solid phase concentrations in the sediment (Balzer et al., 1998; Lohse et al., 1998; van Weering et al., 1998). We analysed these profiles with a coupled diagenetic model (Soetaert et al., 1996a), which is a process-based predictive model. The model uses a number of site-specific parameters that express the bioturbation rate, the quantity of the organic flux and the quality (= degradability) of this flux as it arrives at the sediment surface. These site-specific parameters are unknowns that can be estimated (from the sediment profiles only) by using inverse modelling. Our basic approach consisted of simultaneously fitting the profiles of oxygen, ammonium, nitrate and organic matter with the model, while varying the site-specific free parameters. This process was executed for each station to derive the quantity and quality (hence age) of the organic matter delivered to the sediment. The magnitude and age of the organic matter flux as deduced from diagenetic modelling are then used to constrain the pattern of lateral and vertical transport of organic matter.

2. Material and methods

2.1. Benthic diagenetic model

The benthic diagenetic model used to fit the benthic profiles and extract the parameters of the benthic–pelagic exchange is extensively described in Soetaert et al. (1996a,b). The model is forced by a flux of organic carbon at the sediment surface. In order to represent the reactive continuum of organic matter in natural mixtures, this flux is described as consisting of three fractions: a "fast degrading" fraction, a "slowly degrading" fraction and a fraction that is not mineralised at ecological time scales. The two degradable fractions have different C/N ratios. In the sediment, organic matter is moved by advection (sediment accretion), compaction and bioturbation (represented as a depth-dependent diffusive mixing term—Boudreau, 1986). For each of the two organic matter fractions, mineralisation occurs at a fixed rate, independent of the electron acceptors present. Dissolved substances in the model are oxygen, nitrate, ammonium and "other reduced substances". Their transport is described by an advective and (molecular) diffusion term. Processes affecting the concentrations are mineralisation (consuming oxygen or nitrate and producing reduced substances and/or ammonium), nitrification, re-oxidation of the other reduced substances, and deposition of reduced substances.

The model basically describes the rates of change of the state variables over time and space. It can be used for steady-state calculations, where it predicts sediment profiles of the state variables under constant conditions of organic flux and bioturbation. This is the mode used for the isolated

stations, where profiles were obtained at one or two isolated points in time only. Alternatively, the model can also be used for a time-dynamic run, where time evolution of the depth profiles is calculated based on initial conditions and on a (time-varying) flux of organic matter. In the latter mode, the model was used to compute the sediment profiles that would result from the flux observed in the lowermost sediment trap at station OMEX III.

2.2. Available benthic data

Table 1 shows the available data on benthic profiles, as obtained by several workers in OMEX. We refer to Lohse et al. (1998) for the description of the field and laboratory methods used. The data are published on CD-ROM as part of the OMEX database (Lowry et al., 1997). Fitting of the profiles failed in the case of station OMEX II at 1400-m depth, where the model was unable to even nearly fit the nitrate profile in the top sediment layers. Balzer et al. (1998) discuss these high nitrogen concentrations in the top 1–1.5 cm, and interpret them as methodological artefacts, especially since they are not reflected in the profiles of other nutrients. Consequently, it is not warranted to adapt the model to represent these potentially misleading profiles.

2.3. Parameter estimation

Most parameters of the model are rate constants that either were derived from laboratory experiments or from calibration of the model on a literature database of benthic rates (see Soetaert et al., 1996a). For the application at a particular station, some parameters (temperature, advection rate, solute concentrations in the bottom water) were forced on the model from observations. A limited number of site-specific parameters were varied as free parameters to obtain an optimal fit to the available benthic profile data. The site-specific fit parameters are (1) the total flux of mineralisable organic matter, (2) the total flux of refractory organic matter, (3) the fraction of the fast degrading part in the flux of mineralisable organic matter (and its complement, the fraction of slowly degrading detritus), (4) the first-order degradation rates of fast and (5) slow

Table 1
Data used for the diagenetic modelling

Site	Depth (m)	Date	Profiles measured	Data originator
OMEX A	208	October 1993	O_2, NO_3, NH_4, orgC	W. Helder
OMEX I	670	October 1993	O_2, NO_3, NH_4, orgC	W. Helder
OMEX I	667	May 1994	O_2, NO_3, NH_4, orgC	W. Helder
OMEX B	1034	October 1993	O_2, NO_3, NH_4, orgC	W. Helder
OMEX B	1016	May 1994	O_2, NO_3, NH_4, orgC	W. Helder
OMEX C	1961	October 1993	O_2, NO_3, NH_4, orgC	W. Helder
OMEX III	3660	October 1993	O_2, NO_3, NH_4, orgC	W. Helder
OMEX III	3660	May 1994	O_2, NO_3, NH_4, orgC	W. Helder
OMEX III	3660	September 1995	O_2	W. Helder
OMEX III	3660	August 1995	NO_3	W. Balzer
OMEX III	3660	September 1994	NO_3	W. Balzer

detritus, and (6) the bioturbation coefficient. The choice of these parameters was based on extensive Monte-Carlo sensitivity analyses (Soetaert et al., 1996a; Middelburg et al., 1996; Soetaert et al., 1998). Fitting of these parameters was done by hand-tuning and visual inspection of the result. The fit results are generally a bit inferior to what can be obtained by fitting models for one component at a time. However, the advantage of fitting simultaneously all the curves available is that a consistent model is obtained, taking into consideration all the constraints offered by these different components. We refer to Soetaert et al. (1998) for extensive discussion of the methodological aspects of this form of "inverse modelling".

2.4. *Using parameters based on diagenetic modelling to constrain particle sinking rates*

The classical approach to the prediction of organic matter flux to the sediment at different water depths is to assume a prescribed (e.g., exponential) decrease of the quantity with depth or, equivalently, with travelling time through the water column. However, mineralisation of organic matter results not only in a decrease of the quantity, but also in a decrease of the lability (Westrich and Berner, 1984; Middelburg, 1989; Boudreau and Ruddick, 1991). Accordingly, the degradability of the organic matter as it arrives at the sediment surface provides an additional constraint on carbon fluxes.

To test the hypothesis of consistency between the fluxes at the different stations, we took into account both the quality and the quantity of organic flux. We imposed the quality (as based on inverse diagenetic modelling) and used the total mineralisation rates to constrain sinking rates. We assumed that the vertical flux at a depth of 200 m is the same for all stations, and we also assumed a constant vertical sinking velocity of organic matter between 200 m and the bottom. Moreover, the initial quality spectrum of organic matter is assumed to be the same at all stations. The essence of the test is to see whether the quantity and the quality of the organic flux, as determined at the different stations, can be consistent with these simplifying assumptions. If the fitted sinking velocity is not realistic, or if the flux at some stations is largely insufficient, additional mechanisms are necessary to explain the observations. Otherwise, the assumptions of no spatial gradient in flux at 200 m and of constant sinking velocity can be interpreted as the most parsimonious model for the observations.

The weighted mean degradability of the organic carbon ($\bar{k}$) arriving at the sediment surface was calculated as

$$\bar{k} = p_f k_f + (1 - p_f) k_s,$$

where p_f denotes the fraction of the total flux in the fast degrading component, and k_f and k_s are the first-order degradation constants of the fast and slowly degrading detritus fractions (at in situ temperatures), respectively. Values of the weighted mean degradability are available from the inverse diagenetic modelling at different water-depth stations.

We assumed that the degradation rate in the water at a given depth is the same as that estimated for the organic matter arriving on the sediment at that depth. The model for the fluxes can be stated as

$$F_j = F_{200} \exp\left(- \sum_{i=1}^{j} \frac{\Delta x_i}{u} \bar{k}_i \right),$$

where Δx_i, is the ith depth interval, $\bar{k}_i$ is the weighted degradation coefficient at the ith depth, u is the sinking velocity, F_{200} is the observed organic flux at 200-m depth (the shallowest station considered in this study) and F_j is the flux observed at other depths. The sinking speed, u, was obtained by regressing this model on the observed fluxes, using the estimated degradability constants.

3. Results

3.1. Steady-state fitting of benthic profiles

The benthic profile data at all stations, except station OMEX III (3660 m), were fitted with the steady-state version of the model, since no information on the time course of the organic matter influx was available. In general, the model fits were rather good (Fig. 1). Some problems were encountered in modelling the deep ammonium concentrations. At several stations, there is a hint of slow ammonium production in zones below the sampling depth, giving rise to almost straight diffusion profiles into the zone of active early diagenesis. The increase of ammonium at greater depth is probably due to mineralisation of relicts of labile organic matter from the last glacial (e.g., Wallace et al., 1988). This type of process is not incorporated into our model. However, it does not modify the estimates of parameters of concern here.

3.2. Dynamic run at station OMEX III

For station OMEX III (3660 m) we performed a time-dynamic run of the model, forced by the influx pattern of organic carbon derived from the sediment traps at this station (Antia et al., 2001). In contrast to the other model simulations, this run thus had a reduced number of free parameters, since the total influx of organic matter was imposed. The remaining free parameters were adjusted to optimise the fit, and kept constant over time. This run therefore critically tests whether the observed profiles can be modelled with fluxes based on the sediment traps. Fig. 2 (top panel) shows the time course of input at the station (trap data at 400 metres above the bottom (mab)) and the calculated oxygen flux over the benthic–pelagic interface. The panels underneath show the benthic profiles for a number of dates where data are available. Some of these dates are outside the period of trap observations; they are compared with the model output for the same day of the year, within the trapping period.

Two model runs are shown in Fig. 2. The run forced by the flux observed in the sediment trap is given in broken lines. This forcing resulted in a severe underestimation of the total organic carbon (TOC) concentrations in the sediment. It is possible to use other parameter sets (results not shown) that fit the TOC concentrations well, at the expense of the fit for the dissolved species in the pore water. However, the constraints offered by both TOC and dissolved species can never be met with the forcing directly derived from the trap observations. The solid lines in Fig. 2 present a different time-dynamic run, where the flux of organic matter was partly free: the flux values observed in the sediment traps were multiplied at all times by a constant, which was a free

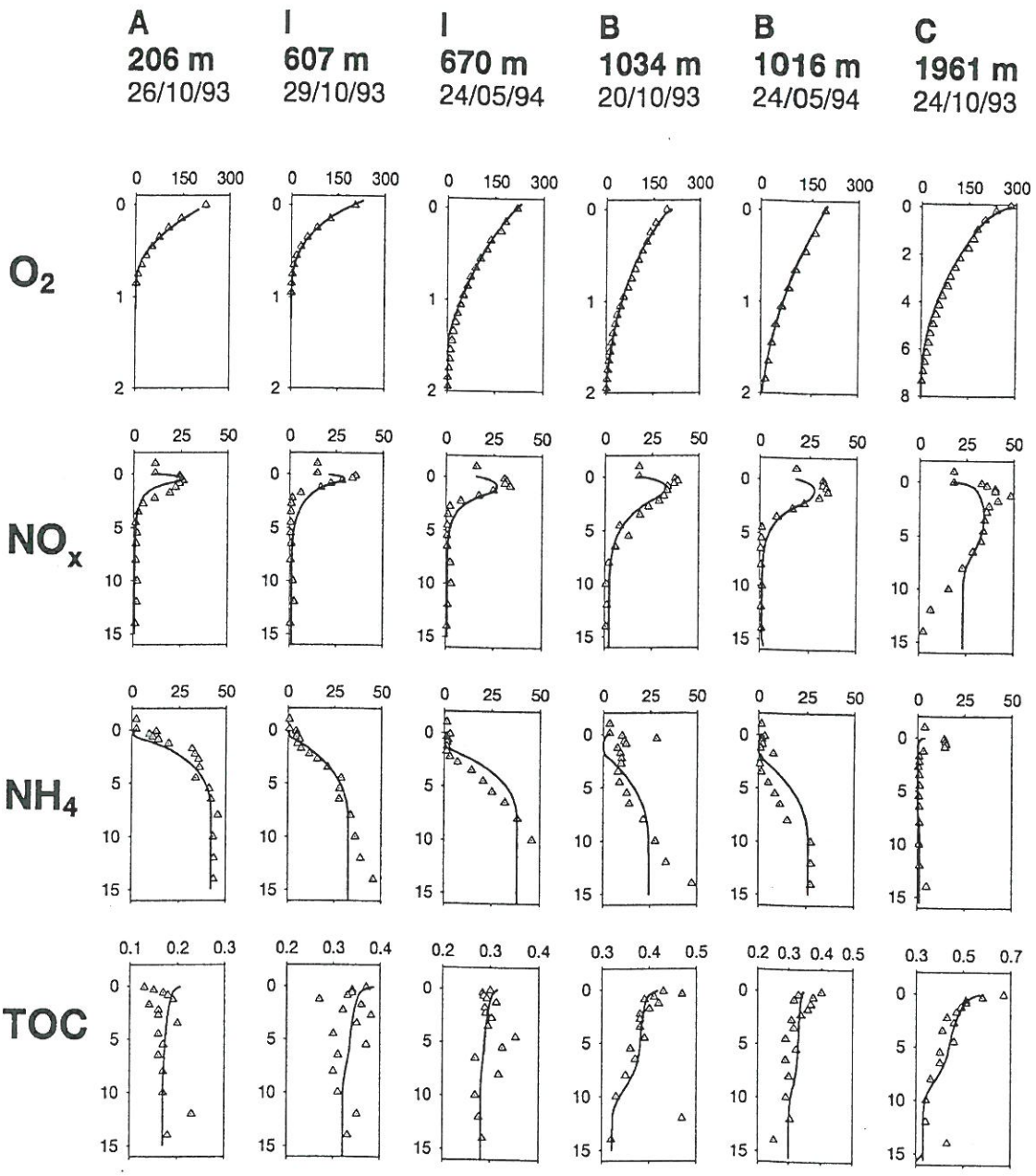
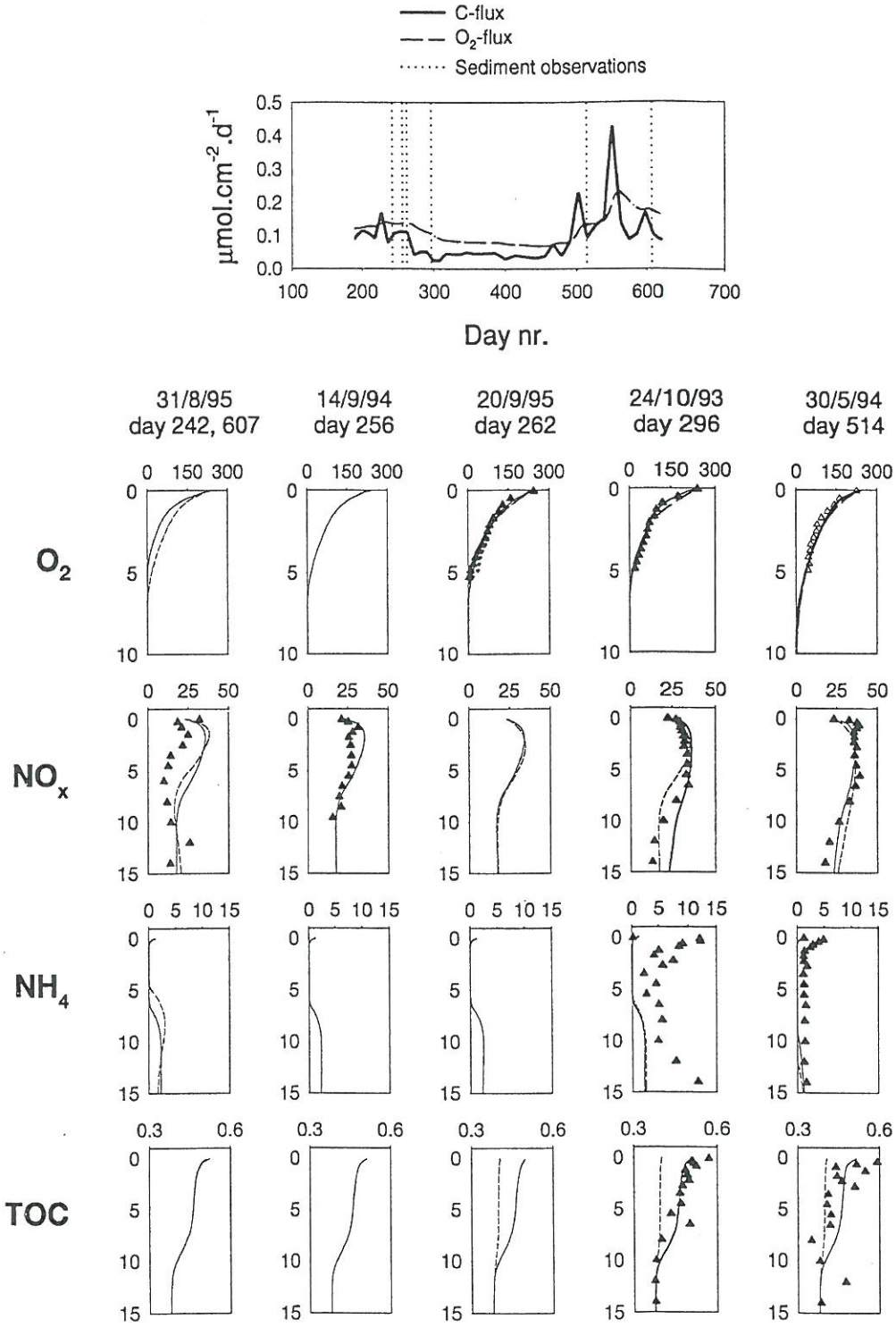


Fig. 1. Diagenetic modelling of the benthic profiles from the OMEX project. Concentrations of oxygen, nitrate and ammonium are in $\mu mol\,l^{-1}$; concentration of total organic carbon is in %. All concentrations are plotted versus depth in the sediment (cm). Continuous lines on the graphs are the fitted model values, points indicate the observations. Data from Lohse et al. (1998) and Balzer et al. (1998).

parameter in the estimation process. In this application, therefore, we kept the seasonal pattern of sedimentation as observed in the sediment traps, but adjusted the flux for some hypothetical undertrapping or lateral input. The optimal value of the constant was 1.85 and the fits of the model were satisfactory.


C-flux
O_2-flux
Sediment observations
µmol.cm^{-2}.d^{-1}
Day nr.
31/8/95 day 242, 607
14/9/94 day 256
20/9/95 day 262
24/10/93 day 296
30/5/94 day 514
O_2
NO_x
NH_4
TOC

3.3. Quantity and quality of organic flux at different depths

The fitted parameters (Fig. 3, Table 2), shown as a function of depth, indicate a general decrease in total mineralisation and degradability with water depth. The bioturbation rate is lower at the deepest stations, but shows no trend with depth in the 200–1000-m range. The bioturbation rates, and their relationship with the observed benthic assemblages, are discussed by Heip et al. (2001).

The consistency test of the total mineralisation rate, assuming a pelagic degradation rate equal to the degradation rate of the material arriving at the sea floor yields an acceptable fit to the data, with a sinking speed of $132\,m\,d^{-1}$ (Fig. 3). Part of the unexplained variation is likely to be the result of the effects of seasonality. However, no spurious deviations from the exponential model were observed. The fitted sinking speed is within an acceptable range.

4. Discussion

4.1. Degradability of the organic matter delivered to the sediments

The absolute magnitude of the weighted average degradability constants varies (at in situ temperatures) between $8\,a^{-1}$ at the deepest site and $48\,a^{-1}$ at the shelf site. Scaled to a common temperature of 10°C, the range is between 14 and $44\,a^{-1}$. Although considerable uncertainty around these values may be assumed (Soetaert et al., 1998; see below), all degradability constants are high, suggesting that the material arriving at the seafloor is freshly deposited and does not have a long history of degradation and transport in the water column. The value for the deepest OMEX site ($8\,a^{-1}$ at OMEX III, 3660-m depth) is very close to the degradability rate deduced for the Pacific N/M site (4100 m) by Soetaert et al. (1996b) using the same model: $7\,a^{-1}$ at an in situ temperature of 1.5°C. These values were based not only on fitting of benthic profiles, but also on simulating (with the same parameter values) the time series of sediment oxygen consumption. With a different model (1-G type with only one class of organic matter), Sayles et al. (1994) arrived at degradability rates of $5–10\,a^{-1}$ for the same N/M site. Lochte and Turley (1988) reported a degradability of $6.6\,a^{-1}$ at a depth of 4500 m in the North Atlantic. Hammond et al. (1996), using a 2-G model with bioturbation constrained by ^{210}Pb and ^{234}Th excess profiles in the central equatorial Pacific, found first-order rate constants for the fast fraction of $4–43\,a^{-1}$; for the slow fraction they were approximately three orders of magnitude lower. Rabouille et al. (1998) found degradability constants of $1.4–16\,a^{-1}$ in deep Pacific stations (3500–5000 m), These degradability constants are again in the same range as found in this study.

Fig. 2. Dynamic run of the benthic diagenetic model at station OMEX III (3660 m) forced by the time series of organic carbon input derived from the lowermost sediment trap in the array at this location (Antia et al., 1999). The top panel compares the input of organic carbon (multiplied with a factor 1.85—see text) with the modelled SCOC. Dotted lines denote the timing of the sediment sampling events. The lower panels compare model output with observed benthic profiles (as in Fig. 1). For the model run indicated with full lines, the input data were multiplied by 1.85. Runs with the actual sediment trap forcing data are indicated with a dashed line.

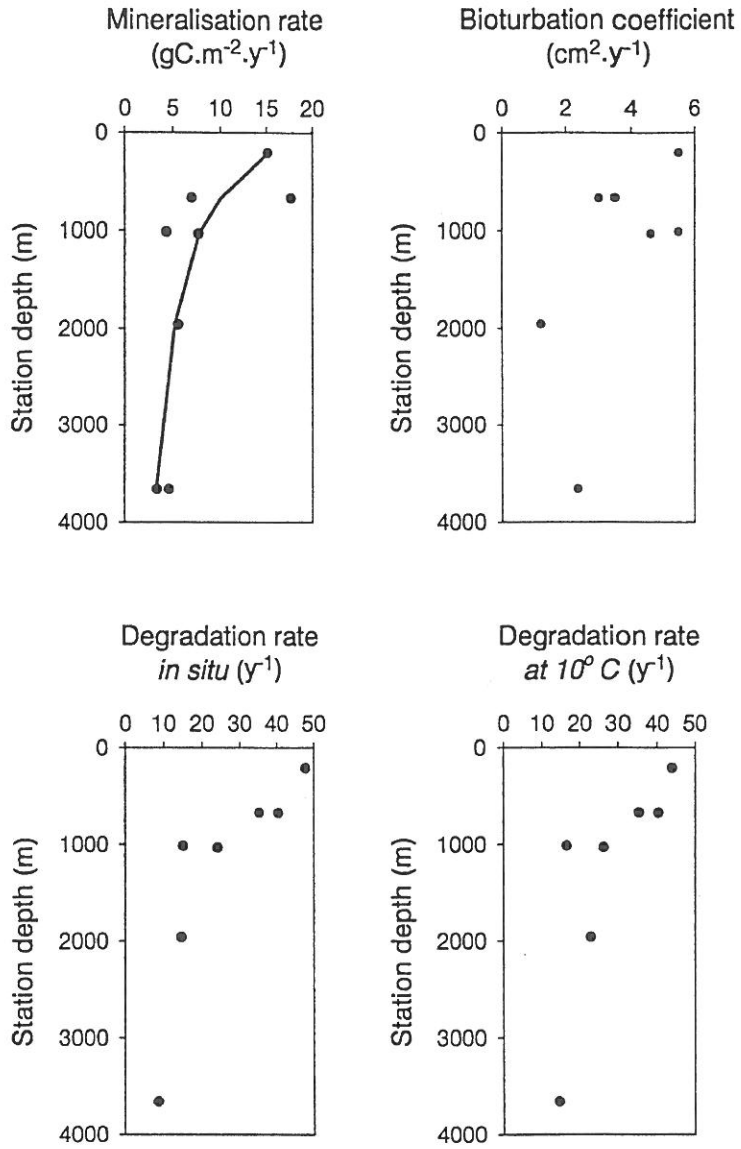


Fig. 3. Fitted parameters D_b (bioturbation coefficient), weighted average degradation coefficient k (at in situ temperature and reduced to 10°C) and total mineralisation rate for the OMEX stations on the Goban Spur transect, plotted as a function of depth of the station. Dots are the parameter values resulting from the fitting of the diagenetic model to the observed profiles. The line for the total mineralisation rate is obtained by assuming equal vertical input at 200 m at all sites, constant sinking rate (132 m d^{-1}) and degradation rate in the water column given by the degradation rate of the material arriving at the sediment surface for the specific depth.

We have estimated the degradability constants of the material arriving at the sediment surface with the explicit aim to deduce from these a measure of age of the material. As argued before, average degradability of an organic material mixture must decrease with age, since the most degradable fractions disappear first, and the slowly degrading fractions become relatively more

Table 2
Parameter estimates from the fitting of the diagenetic model to the sediment profiles[a]

Station	Time spent (a)	k_{avg} (a^{-1})	TotMin (g $C m^{-2} a^{-1}$)	D_b ($cm^2 a^{-1}$)
A93	0.16	47.7	15.1	5.5
I93	0.32	40.3	17.6	3.0
I94	0.57	35.2	6.9	3.5
B93	1.95	24.0	7.7	4.6
B94	2.30	15.0	4.3	5.5
C93	1.71	14.5	5.6	1.2
III93	2.90	8.6	3.4	2.4
III94	2.90	8.6	4.6	2.4

[a] Time spent: average time spent in the sediment by a particle at mineralisation; k_{avg}: average first-order degradability constant of the organic matter when it arrives at the sediment surface; TotMin: total mineralisation in the sediment; D_b: bioturbation coefficient.

important in the mixture. From the comparison of degradability between the OMEX III site and the open-ocean deep-sea sites, we conclude that the material deposited at the OMEX III site is of similar age. Therefore, it seems likely that the mechanisms of bulk organic matter transport towards the benthos may be similar, with (rapid) vertical transport dominating the organic flux. At least, any alternative pathway of mass transport should be approximately as fast as vertical transport.

One must be careful, however, with over-interpreting the significance of average degradability rates. These values not only have a relatively large uncertainty, but they also tend to give a biased view of the distribution of degradability in the natural mixture of organic carbon. These distributions were highly skewed (most material was in the relatively high degradation rate class, whereas a smaller fraction had much lower degradability) and the average degradability emphasises only the most degradable class. Based on degradability rates, we can therefore only conclude that vertical transport appears to be the major mechanism for the (fast decaying) majority of the organic carbon flux. However, the fraction in the slowly degrading class of organic material (between 9% and 22% of the total flux of organic matter) may have a different origin, fate and transport pathway. This fraction has little influence on the weighted average degradation rate. Additionally, the quality of material sedimenting (vertical flux to the benthos) varies seasonally, as seen by strong variations in the ratio of bulk POC to the more labile phytopigments in the sediment traps (Antia et al., 2001), and this is likely to induce a response in benthic community activity.

Our estimates of degradability of the organic matter as it arrives at the sea floor are much higher than those of Lohse et al. (1998), yet they are partly based on the same data set. Their estimates of degradability rates vary between $22.6\,a^{-1}$ at OMEX station A (200 m), $0.9\,a^{-1}$ at station I (650 m) and then declining with station depth to $0.002\,a^{-1}$ at station E (4500 m). The large discrepancy between these estimates and ours is caused by three major differences in approach.

Firstly, Lohse et al. (1998) calculated their degradability rates assuming only one degrading fraction of organic matter with a fixed degradation rate, in contrast to our approach assuming two fractions of degrading organic matter. In their approach, the degradability cannot change

with age of the material, and no difference can be made between the degradability of the material as it arrives at the sediment surface, and its degradability after having resided in the sediment for a long time. Naturally then, one expects the estimate of the degradability to be dominated by the old material left over in the sediments and not by the rapidly disappearing, fast degrading material that arrives. In our estimates, based on two classes of degradable organic matter, there is a large difference between the degradability of the material as it arrives at the seafloor, and of the average degradability of the (degradable) organic matter present in the sediment. The latter is almost exclusively made up of the slowly degrading fraction.

Secondly, Lohse et al. (1998) imposed a bioturbation coefficient D_b derived from ^{210}Pb profiles. As noted by these authors themselves, estimates of D_b may differ considerably with the tracer used (Smith et al., 1993; Hammond et al., 1996; Middelburg et al., 1997; Soetaert et al., 1998). Their argument that the ^{210}Pb derived bioturbation rates are the right choice here because no high degradabilities have been observed is quite circular; the argument that no seasonality has been observed in the benthos is weak, as shown by the correspondence between our time-dynamic run for OMEX III and the sediment profile data, which used high degradability rates.

Thirdly, Lohse et al. (1998) based their estimations on the oxygen profiles only. As shown by Soetaert et al. (1998) for OMEX station B, the oxygen profile taken alone sets a strong constraint on the total mineralisation rate in the sediment, but no constraints at all on bioturbation and degradation rates. For all the combinations of D_b and k tried, it was possible to find values for the other parameters so that the oxygen profile was adequately fitted. The information content of the oxygen profile for bioturbation and degradation rates was the lowest of all single profiles tested.

4.2. *Uncertainty of the parameter estimates from the diagenetic modelling*

For the interpretation of the parameters derived from diagenetic modelling, consideration of the estimation uncertainty is a crucial issue. From a Monte-Carlo analysis. Soetaert et al. (1998) concluded that, firstly, the parameter ranges are much more reduced by the simultaneous fitting of all four available profiles (oxygen, nitrate, ammonium, organic carbon) than by the fitting of a subset of them (even though the goodness-of-fit of a single profile fitted by a single-component model may be better than that obtained by a coupled model). Secondly, the total mineralisation rate is better constrained than the degradability and bioturbation rates. The statistical uncertainty interval of bioturbation and degradability rates is an order of magnitude larger (factor 3) than for total mineralisation rate (factor 0.25). The main cause for the larger intervals on degradability and bioturbation rates is the importance of the factor $\sqrt{k/D_b}$ (where k is the degradability and D_b is the bioturbation coefficient) in determining the shape of the organic carbon and mineralisation profiles (Boudreau, 1996). The constraint on this combined factor is much stronger than on the individual parameters k and D_b.

The statistical uncertainty intervals indicate that, given this model, parameter values outside the uncertainty interval produce significantly worse fits than values inside the interval. Their meaning is therefore dependent on the validity of the model and the model assumptions. Comparison of our estimates of degradability with the ones derived by Lohse et al. (1998) is a clear illustration of this dependency on the model formulation. Their estimates fall far outside our uncertainty intervals, but are based on a different model approach.

A more objective way to appraise the uncertainty in our estimates of total mineralisation rate is to compare them to measured sediment community oxygen consumption. For the six comparisons we could make with Duineveld et al. (1997) (using a respiratory quotient (RQ) of 1), the linear correlation coefficient equals 0.77 and the regression line does not differ significantly from the 1 : 1 line. Considering that SCOC measurements are also subject to variation, this comparison confirms the previously estimated order of magnitude of the uncertainty in our estimates.

4.3. Differences between benthic and pelagic degradability coefficients

For the purpose of estimating the sinking velocity and of testing the consistency of the fluxes and degradabilities as a function of station depth, we have assumed that the degradability of the organic material as it arrives at the sediment surface is the same as its degradability in the water column. In fact we assume that the compositional quality of the organic matter is the major determinant of its degradability, and that interaction with the environment is only of minor importance. This assumption may be false for numerous reasons. If, beside the inherent quality of the organic matter, degradability is also determined by the availability of grazers, bacteria, nutrients, reaction products, electron acceptors or other mineralogical factors, the degradability may be higher or lower in the water column than in the sediment. Our assumption of equal degradability is the most parsimonious; in addition we have some independent evidence to test its validity. The empirical power model is based on a uniform degradability–time relation, irrespective of whether degradation occurred in the water column or in the sediment, or oxic and anoxic environments (Middelburg, 1989). Similarly, compositional changes in organic matter upon degradation are systematic over a range of systems including sediment traps and surficial sediments (Dauwe and Middelburg, 1998; Dauwe et al., 1999). If the degradability were lower in the water column than in the sediment, our estimates of sinking velocity would be too high, and vice versa. However, as long as a reasonably constant relation between degradability in water column and sediment can be assumed, our conclusion that the fluxes at different depths are consistent with a model of constant sinking velocity and a vertical flux of the organic matter would remain valid.

4.4. Discrepancies between sediment trap fluxes and fluxes estimated from benthic modelling

From the dynamic model runs at the deep OMEX III station, it appears impossible to fit the benthic profiles at the station with the organic fluxes derived from the sediment traps deployed 400 m above the sediment at the same station. These fluxes were used without (1) correction for any further degradation between the trap and the sediment surface and without (2) inclusion of any benthic boundary layer degradation. Both aspects would only widen the gap. The most reliable of our parameter estimates, total mineralisation rate, is definitely higher than the organic flux measured by the sediment traps. A similar discrepancy (at the same station OMEX III) is found when comparing the sediment trap fluxes with directly measured benthic oxygen consumption rates (Duineveld et al., 1997) or with requirements of the benthic fauna (Heip et al., 2001). The benthic oxygen consumption rates were well reproduced by our model.

Discrepancies between carbon demands, determined from benthic measurements, and carbon supply determined from sediment traps are not exceptional, especially at ocean margin sites.

Lampitt et al. (1995) reported for a slope station in the Porcupine Bight (N.E. Atlantic) at 2000 m a vertical supply that was only sufficient for 20% of the measured sediment community oxygen demand. Similarly, Jahnke et al. (1990) found the strongest deviation between benthic metabolism and sediment trap estimates of vertical organic matter flux at North Pacific continental slope stations, where demands exceeded supply by threefold. Rowe et al. (1990), for western North Atlantic sites ranging from the shelf to the abyssal plain, in general found sediment community oxygen demands in excess of measured POC fluxes. This was especially true at stations with a high input of refractory (terrestrial) material. In contrast to these findings at slope stations, agreement is generally better for abyssal sites. Lampitt et al. (1995) found good agreement at an abyssal station (4000-m depth) in the Porcupine Bight between the sediment community oxygen demand and the vertical flux estimates in a nearby JGOFS station. In the North Pacific open-ocean station N/M, the discrepancy is also relatively small (Sayles et al., 1994; Soetaert et al., 1996b). In the deep central Pacific Ocean, Murray and Kuivila (1990) found a close agreement between organic matter deposition estimated from sediment traps and sediment community oxygen demand.

Anderson et al. (1994) concluded that a considerable lateral flux of organic carbon occurs in the Mid-Atlantic Bight (SEEP program). This lateral flux resulted in enhanced carbon deposition rates in the mid-slope region. These authors reviewed other continental margin experiments and found a general agreement with this pattern. All these studies show high organic carbon contents (several weight percent) in the sediments below the bioturbated zone. This is typically to be expected in sediments receiving old and refractory organic carbon. In the Mid-Atlantic Bight, for example, 38% of the organic carbon arriving at the sediment at the 1000-m site is buried. From the organic carbon profiles in the sediment, Anderson et al. (1994) conclude that the remainder of the carbon is relatively fresh. The results at the Goban Spur transect are in clear contrast to these results. The high flux and burial of old, refractory organic carbon was not observed at the Goban Spur margin sites (van Weering et al., 1998). In general, the organic carbon profiles have low background concentrations deep in the sediment and a clear curvature in the upper centimetres, clearly different from the profiles observed in the Mid-Atlantic Bight.

The problem of discrepancies between benthic fluxes and sediment trap fluxes is mirrored by the problem of (apparent) inconsistencies in vertical trap arrays, where in many cases the lowermost traps collect more material than the shallower ones (e.g., Biscaye and Anderson, 1994; Lampitt et al., 1995; Etcheber et al., 1996; Antia et al., 1999). In a sense, the sediment can be considered as the lowermost trap in the array. This "trap" differs from the trap at 400 mab in the array by (a) its potentially different interaction with the physical circulation, and (b) its susceptibility to the presence of benthic nepheloid layers and their (lateral) transport of material. The patterns of increasing absolute catch with depth in an array are usually explained by the occurrence of lateral fluxes, either cross-slope or along-slope. Apart from quantitative arguments (higher POC and other particulate fluxes in the lower traps), qualitative analysis of the trap material has also suggested the existence of lateral flows. In the OMEX traps the ratios of POC to the more labile phytopigments, as well as the flux of intact diatom frustules, were interpreted as indicative of a rapid and significant transport, in intermediate water layers, of material of similar freshness to the primary flux at 600 m (Antia et al., 2001). Falkowski et al. (1994) showed the occurrence of intact typical shelf diatom species in the lowermost traps on the slope at SEEP sites (Mid-Atlantic Bight), which did not occur in the near-surface traps. Both in the SEEP (Biscaye and Anderson, 1994) and in the OMEX sediment traps (Antia et al., 1999), qualitative traces of shelf or slope

lithogenic material were found in the deeper traps. The relatively small fraction of slowly degrading organic matter at the Goban Spur sites may have had a different origin than the bulk of the fast decaying organic material. It is not necessarily a tracer for all of the sedimenting material. Bauer and Druffel (1998), using organic carbon ages based on ^{14}C dating, also hypothesised that lateral organic matter fluxes between ocean margins and central gyres consist mainly of old refractory carbon.

Differences in time scales between sediment trap catches and the organic matter degradation in the sediment may explain apparent differences in flux. Whereas sediment traps measure the flux over short time intervals (weeks), the organic matter in the sediments accumulates over longer periods. Based on the two degradable fractions of organic matter fitted by our models, we can calculate the average time spent in the sediment by a C-atom from the moment of deposition up to the moment it is mineralised (Table 2). The average time resided in the sediment before mineralisation varies between 0.15 and 3 years. The response time of the model can therefore be expected to be in the order of 1–5 years. This is longer than the response time of the sediment traps, but not long enough to be affected by major changes in the environment at time scales of decades or centuries.

4.5. *Vertical versus lateral organic matter transport at the Goban Spur*

Several hypotheses could be put forward to explain the consistent trends found in sediment trap arrays at ocean margins. We have schematised the hypotheses in Fig. 4.

For the OMEX transect, the benthic data on total mineralisation rates and on degradability constants can be used to constrain the likelihood of these hypotheses. Several observations contradict the *strong lateral transport model* (Fig. 4A), which explains the trend of increasing catch with depth in the arrays by lateral (cross-slope) transport of material produced on the shelf or at the shelf break.

- The observed off-slope water currents (Antia et al., 1999) are not strong or consistent enough to transport the organic matter as passive suspended matter at the speeds required by the lateral input hypothesis. At the OMEX II station, virtually no net off-slope currents were observed. At OMEX III, off-slope currents were observed in mid-water (where they may be responsible for material transport), but almost no net currents at all have been observed near the deepest trap. Near-bottom material transport, therefore, should depend on material being deposited and resuspended on the bottom (Antia et al., 1999).
- The depth profile of the OMEX transect is much less steep than conventional cartoons suggest. A 150-m depth increase corresponds with a horizontal step of 3–6 km. *Net* horizontal velocities of the organic matter in the order of 3–6 km d^{-1} therefore are required. Near-bottom transport can only lead to net off-slope transport under conditions of tidal asymmetry, with much stronger down-slope than up-slope currents. Thomsen and van Weering (1998) present a calculation of potential down-slope transport (3–4 km d^{-1}), but these calculations were based on an absolute tidal asymmetry (no up-slope currents higher than the erosion threshold, a condition that was not observed) and on the high current velocities only observed in autumn. Most importantly, the freshness of the deposited organic matter, even at the deepest station, precludes the large number of deposition–erosion cycles needed to arrive in place by this

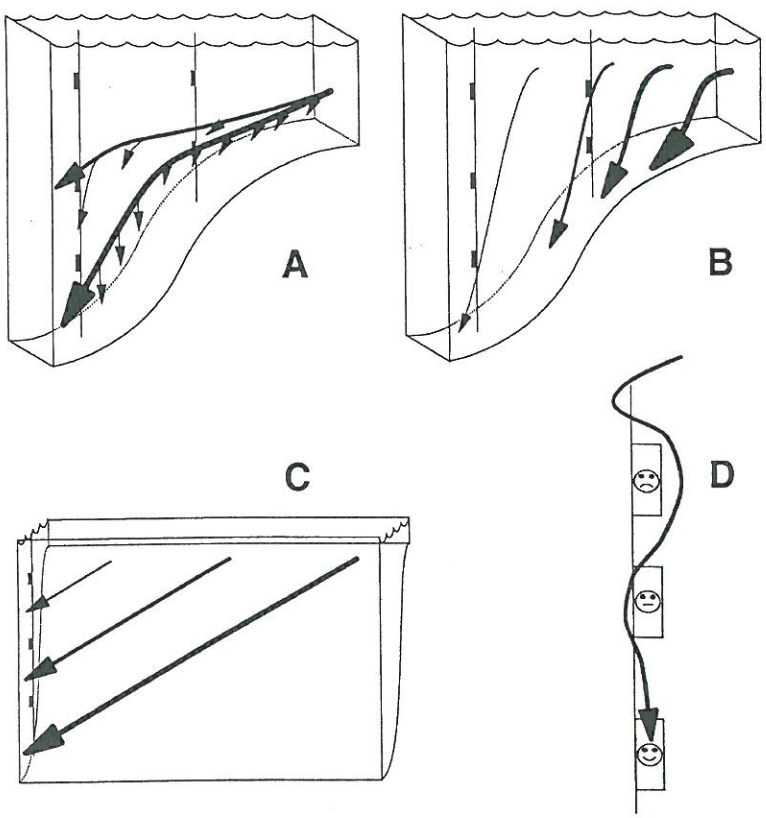


Fig. 4. Schematic representation of the different hypotheses discussed to explain trends in moored trap arrays along continental margins. The hypotheses are (A) strong lateral transport, (B) weak lateral transport, (C) along-slope gradient and (D) trap (in)efficiency. See text for details.

mechanism. It also precludes a mechanism only operating in autumn because the material would then be much older at arrival since the major peak of deposition is in early summer.

- The deposition area has a cross-slope length of at least 150 km. The production area cannot be much inshore of the shelf break because of the freshness of the material. Consequently, the material deposited over a 150-km stretch, *plus* the material that is degraded during the transport to the deposition area, should all be produced in the shelf break area, which is probably 5–10 times narrower. With these numbers, one arrives easily at an export production needed (around the shelf break) that is an order of magnitude higher than in the slope region. Although there are indications from remote sensing that chlorophyll content is higher at the shelf break region (around the 200-m isopleth) than elsewhere (Groom et al., 1995), the gradients are not of the order-of-magnitude difference needed to fuel the benthos on the slope. Joint et al. (2001) do not describe any clear off-slope trend in export production, although this could partly be due to scarcity of data.

The "*weak lateral transport model*" (Fig. 4B), assuming that (a) there is a cross-slope gradient in export production, and (b) there is a general off-slope transport of organic matter while it is

sinking, should be considered as a realistic possibility to explain part of the observed patterns in the OMEX area. We concluded above that quality and quantity of the arriving flux at the different stations are consistent with a model assuming no cross-slope gradient in export production, and a uniform vertical sinking rate of $132\,m\,d^{-1}$. However, they could equally well be fitted by a model assuming a cross-slope gradient in export production (by a factor of 1.5) and a vertical sinking rate of $200\,m\,d^{-1}$ (which is at the highest end of the range $80–200\,m\,d^{-1}$ given by Honjo, 1980). Such a cross-slope gradient in export production could explain that for each trap depth there was a decreasing trend with distance from the shelf, a pattern also observed at other continental margins (Biscaye and Anderson, 1994; Etcheber et al., 1996). However, it is too small to explain the increasing trend in trap catch with depth, or the difference between the lowest traps and the benthos, unless the net offshore currents near the bottom would be extremely strong.

The "*along slope gradient model*" (Fig. 4C) hypothesises that, since dominant currents in slope regions tend to be along slope (e.g., Pingree and LeCann, 1990), the catch of a deeper trap is produced further upstream than the catch in a shallower trap of the same array. It is difficult to evaluate this for the OMEX area, because the data needed for this evaluation are not available. Except for one station with a very pronounced bloom, Wollast et al. (1995) did not find consistent trends in primary production on a transect between La Chapelle Bank and the Goban Spur. The along slope gradient model is also inconsistent with the generality of the observed patterns in sediment trap arrays along continental margins: it would be a remarkable coincidence that all such moorings would have been deployed at the downstream end of slope regions with a strong decreasing trend in productivity.

The *trap (in)efficiency model* (Fig. 4D) hypothesises that shallower traps in continental margin arrays suffer more hydrodynamic or other interferences than deeper ones, leading to a more efficient catch by the deeper traps. It is clearly insufficient to consider it as a default hypothesis to be accepted only because of the objections against the other hypotheses. However, data on radionuclide activities (^{230}Th, ^{210}Pb, ^{231} Pa) in the OMEX traps show the importance of this factor (Antia et al., 2001). Undertrapping may have been a severe problem, at least in the upper traps of the OMEX arrays. Antia et al. (2001) conclude that it was rather unlikely that the lowest trap at OMEX III had a low trapping efficiency. Therefore this trap should compare well with the benthic flux, and the actual discrepancy with the benthic flux, at least for organic matter, remains unexplained.

It is possible that a combination of factors is responsible for the observed patterns. We discussed earlier that our results cannot exclude a limited transport of relatively refractory material from the shelf or shelf break to slope sites via benthic boundary layer transport mechanisms. This transport, surely able to leave qualitative traces, however, cannot be responsible for most of the discrepancies. However, as we discussed, the "*weak lateral transport*" hypothesis (Fig. 4B) could also explain part of the off-slope gradient in the catch of sediment traps. Along slope differences in shelf-slope exchange could be influenced by the presence of canyons upstream of the Goban Spur. Interactions between traps and hydrodynamics could be responsible for some of the vertical increase in catch within the same array. These factors taken together would at least partly explain the observed patterns, although it is difficult to quantify any of them precisely and therefore to judge whether these mechanisms taken together offer a complete explanation.

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