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# Assessing organic matter mineralization, degradability and mixing rate in an ocean margin sediment (Northeast Atlantic) by diagenetic modeling

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## ABSTRACT

We test whether organic matter degradability, mixing activity, and total sediment mineralization can be estimated by inversion of a coupled nonlinear numerical steady-state diagenetic model. We use a single data set comprising oxygen, nitrate, ammonium and organic carbon versus depth profiles from a slope station in the Goban Spur area (1034 m, Northeast Atlantic).

Based on an extensive sensitivity analysis, it appears that (1) when using all data, the total mineralization rates can be determined with reasonable precision; bioturbation and degradability are less well constrained and (2) total mineralization rates can be determined based on nitrate and oxygen profiles only; estimates of organic matter mixing rates and degradability are refined when including the solid phase organic carbon profile.

The bulk mixing rates obtained for organic carbon are one order of magnitude higher than mixing rates previously estimated from <sup>210</sup>Pb profiles, lending validity to the hypothesis that organic particles are mixed faster than inert particles. The degradability of the organic carbon prior to its incorporation in the sediment is in the order of 10–30 yr<sup>-1</sup>, indicating that mineralization in this slope station of the Goban Spur area is fueled mainly by freshly deposited organic matter.

## 1. Introduction

It is now common knowledge that primary produced organic matter may settle rapidly through the water column (Lampitt, 1985) and arrive at the deep-sea floor in a very fresh state (Lochte and Turley, 1988). In addition to this vertical deposition, lateral advection may be a significant mode of organic matter transport (Biscaye *et al.*, 1994; Wollast, 1991; Walsh, 1991) and much of the organic matter raining on the continental slope sediments can originate from old deposits on the continental shelf (Anderson *et al.*, 1994). The quality of organic matter that becomes incorporated in the sediments is an important characteristic of a benthic system, because of its presumed impact on the magnitude and timing of various benthic fluxes (Martin and Bender, 1988; Soetaert *et al.*, 1996a), on the relative contribution of the various pathways in organic carbon mineralization (Aller, 1990), and on

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the composition and life strategies of the benthic fauna (Graf, 1992; Pfannkuche, 1993). However, it is very difficult to actually measure the degradability or quality of the organic matter entering the sediment. The characteristics of organic matter in the sediment matrix are considerably different compared to what originally settled on the surface because of the increasing dominance of recalcitrant matter with age and hence depth into the sediment (Middelburg, 1989). Also, not all of the organic matter caught in deeply-moored sediment traps may end up incorporated in the sediment, or the traps may contain some resuspended material (Walsh *et al.*, 1988). Consequently, measurements performed on material in the sediment or obtained from traps may be biased. It may be possible to estimate organic matter quality by dynamic models, linking carbon deposition with sediment oxygen consumption rate measurements (Martin and Bender, 1988; Sayles *et al.*, 1994; Soetaert *et al.*, 1996a), but this requires the availability of a data set which is hard to obtain for the deep sea.

The activity of sediment-inhabiting organisms can be expressed, amongst others, as the degree to which they mix particles, the so-called sediment bioturbation activity (Wheatcroft and Martin, 1996). This mixing activity has important consequences for the geochemical properties of the sediment (Aller, 1990), as it tends to favor suboxic and/or anoxic mineralization pathways. Traditional approaches have estimated bioturbation by modeling radioactive tracers, with known decay rates, that are strongly associated with particulate matter. As it has been demonstrated that the mixing coefficient thus obtained depends on the tracer used, due to age-dependent or particle-size dependent mixing (Wheatcroft, 1992; Smith *et al.*, 1993), it is important to estimate bioturbation rates by means of a tracer whose mean half-life and mixing history matches the one of the substance one wants to study. As such, bioturbation rates estimated with  $^{210}\text{Pb}$ , the most commonly used tracer, may not accurately reflect mixing activity with respect to food particles (Smith *et al.*, 1993). Ideally, to be useful for diagenetic models, the mixing coefficient should be estimated based on a tracer that is mixed in the same way as the organic matter.

Recently a series of coupled, nonlinear numerical diagenetic models has been developed independently by a number of authors (Boudreau, 1996a; Van Cappellen and Wang, 1996; Dhakar and Burdige, 1996; Soetaert *et al.*, 1996b). In general, these models are used to estimate total sediment mineralization rates and the importance of the various mineralization pathways in marine sediments. Since they are highly coupled, such models could potentially be used to obtain more geochemical information. In this paper, we use a single data set obtained from the Northeast Atlantic margin, and perform an extensive sensitivity analysis to test if and how far the simplest of these diagenetic models (Soetaert *et al.*, 1996b) can be used to characterize sediments geochemically. We try to estimate total mineralization of organic matter, the degradability of the organic matter prior to its incorporation into the sediment and its rate of mixing. The obtained mixing rate is then compared to bulk sediment mixing rates obtained from  $^{210}\text{Pb}$  profiles from the same station (Soetaert *et al.*, 1996c).

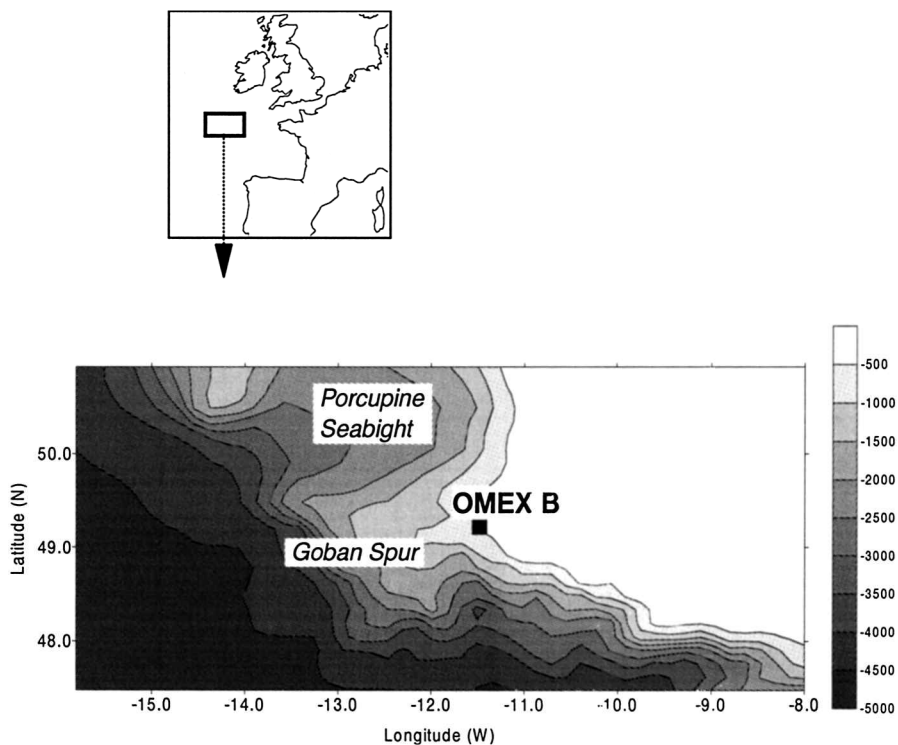


Figure 1. Position of the Goban Spur area and OMEX station B.

## 2. Material and methods

### a. Sampling and processing

The data were kindly provided by Willem Helder and Eric Epping (NIOZ, the Netherlands). The sediment cores were collected in the Goban Spur area (NE Atlantic) in October 1993 with R. V. *Pelagia* from OMEX station B at 1034 m depth (49°22'N, 011°48'W; Fig. 1). Sediments were obtained by a modified boxcorer with a closing lid on top, retrieving cylindrical (50 cm), relatively undisturbed surface sediments. The sediment was sliced as follows: the upper cm into slices of 0.25 cm; from 1 to 3 cm depth into slices of 0.5 cm, from 3 to 7 cm depth into slices of 1 cm, the remainder up till 15 cm depth into slices of 2 cm thick. All slices were squeezed and analyzed for solutes (nitrate, ammonium) using a Technicon TRAACS auto-analyzer (Slomp *et al.*, 1996). The residues of the sliced cores were used for organic carbon determination on a Carlo-Erba elemental analyzer after removal of carbonate by acidification. Oxygen profiles were made with oxygen micro-electrodes (Diamond General Corporation; type 737) in subcores in a thermostated laboratory at the *in-situ* bottom water temperature. Resistivity profiles were made with a resistivity probe according to Andrews and Bennett (1981).

### b. The diagenetic model

The model used was extensively described in Soetaert *et al.* (1996a,b) and further explored in Middelburg *et al.* (1996). It is a numerical, nonlinear, coupled model based on the diagenetic equations outlined in Berner (1980) and Boudreau (1996b). Solids are moved by advection, compaction (related to porosity gradients) and bioturbation; the latter is described as a diffusion-like process, with a constant mixing coefficient in the upper 5 cm of the sediment below which the bioturbation coefficient decreases exponentially with depth. In the model runs discussed here, dissolved substances are moved by molecular diffusion only, as similarity between chamber- and profile-based oxygen fluxes suggested that biologically-mediated irrigation was unimportant. The model explicitly describes oxic mineralization, denitrification and nitrification whereas all anoxic processes are lumped. It generates profiles of oxygen, nitrate, ammonium, ODU (Oxygen Demand Units) and two fractions of carbon with different degradabilities and C:N ratios (Westrich and Berner, 1984). Reduced manganese, iron and sulphur, which are formed upon anoxic mineralization, are lumped into so-called 'oxygen demand units' (ODU) that are re-oxidized when in contact with oxygen. Part of these reduced substances is permanently buried below the zone of bioturbation. As the parameter values entering the sensitivity analysis performed in this manuscript relate to the two organic carbon fractions, the differential equations that describe the dynamics of carbon are repeated in Table 1. Their finite difference equivalents can be found in Soetaert *et al.* (1996b). We used the steady-state version of the model, as there was no information on the temporal variation of organic matter flux at this station. Soetaert *et al.* (1996a) showed that steady-state of dissolved substances to organic carbon profiles is a reasonable assumption for deep-sea sediments. The steady-state set of nonlinear equations (including those for oxygen, nitrate, ammonium and ODU) were solved using the Newton-Raphson method (Press *et al.*, 1994).

The sediment is subdivided into 50 unequally spaced slices, that are 1 mm thick near the sediment-water interface, and increase in thickness, with 5% steps, downward. All parameter values as described in Soetaert *et al.* (1996b) were used, except for two constants that relate to the onset of denitrification with respect to the oxic and anoxic mineralization. This was necessary as initial runs demonstrated that the pronounced nitrate peak that was observed in these sediments could not be generated with the original parameter settings as these allowed too strong an overlap between oxic mineralization and denitrification. The inhibition coefficient of oxygen on denitrification was set to  $1 \mu\text{mol l}^{-1}$  (instead of 10), while the inhibition constant of nitrate on anoxic mineralization was set to  $10 \mu\text{mol l}^{-1}$  instead of 5. Other characteristics of OMEX station B, used as input to the model, are given in Table 2.

### c. Model strategy

We used an indirect inversion technique based on a Monte Carlo method to estimate the range of 'good' parameter values that describe the profiles of oxygen, nitrate, ammonium and organic carbon in the sediment. An extensive sensitivity analysis, consisting of more

Table 1. Equations used for the two fractions of organic carbon ( $C_0$  and  $C_1$ ). For a description of the equations describing oxygen, nitrate, ammonium and other reduced substances, we refer to Soetaert *et al.* (1996b).

$$\frac{\partial(1-\phi)C_i}{\partial t} = 0 = \frac{\partial}{\partial x} \left[ -(1-\phi) \cdot Db_x \frac{\partial C_i}{\partial x} + w_\infty \cdot (1-\phi_\infty) \cdot C_i \right] - k_i \cdot (1-\phi) \cdot C_i$$

for  $i = 0, 1$ .

$(1-\phi)C_i$  is the carbon concentration per volume of bulk sediment,  $C_i$  is the concentration per volume solid,  $x$  = depth into the sediment, positive downward (cm),  $w_\infty$  = advection rate at depth (cm yr<sup>-1</sup>);  $Db_x$  = bioturbation coefficient, (cm<sup>2</sup> yr<sup>-1</sup>);  $k_i$  = first-order consumption rate of the carbon fraction (yr<sup>-1</sup>). The value of the bioturbation coefficient is constant in the upper 5 cm, below which it declines exponentially:

for  $x <= 5$  cm

$$Db_x = Db_0$$

for  $x > 5$  cm:

$$Db_x = Db_0 \cdot \exp\left(-\frac{x-5}{coeff_{Db}}\right)$$

where  $coeff_{Db} = 1$

At the lower boundary ( $x = x_\infty$ ), there is no diffusive flux of material:

$$\left. \frac{\partial C_i}{\partial x} \right|_{x=x_\infty} = 0$$

The upper boundary condition is an imposed flux  $F_{C_i}$  ( $\mu\text{mol cm}^{-2} \text{yr}^{-1}$ ),

$$F_{C_i} = p_i \cdot F_C = -(1-\phi_0)Db_0 \left. \frac{\partial C_i}{\partial x} \right|_{x=0} + (1-\phi_\infty)w_\infty C_i \Big|_{x=0}$$

where  $p_i$  is the relative contribution of fraction ( $i$ ) in the total flux,  $C_i \Big|_{x=0}$  is the concentration of the carbon fractions at the sediment-water interface.

than 10<sup>6</sup> runs, was performed starting with broad ranges of the model parameters relating to total mineralization, the degradability of the sedimenting organic matter and organic carbon mixing intensity. The degradability of the settling organic matter in the model is determined by three parameters (Table 1): the relative contribution of both degradable fractions to total flux ( $p_0, 1-p_0$ ) and their first-order decay rate ( $k_0, k_1$ ). The original ranges of these parameter values can be found in Table 3.

The goodness of fit of the model with respect to the oxygen, nitrate, ammonium and organic carbon profile was appraised as the sum of the absolute value of deviations between modeled and observed data (i.e. the so-called L1 norm). The absolute values of residuals were preferred to the squared residuals (L2 norm), as they are less sensitive to the presence of outliers and do not require the errors to be normally distributed (Press *et al.*, 1994). The merit of a model run in relation to a certain profile was then assessed by comparing its goodness of fit with the best goodness of fit obtained for that variable during the entire sensitivity analysis. This was chosen in analogy to maximum likelihood

Table 2. Station characteristics.

	OMEX B
Latitude	049° 22'N
Longitude	011° 48'W
Depth	1034 m
Bottom water temperature	8.7°C
Bottom water oxygen	208 $\mu\text{mol l}^{-1}$
Bottom water nitrate	17.9 $\mu\text{mol l}^{-1}$
Bottom water ammonium	3.3 $\mu\text{mol l}^{-1}$
Bottom water ODU	0 $\mu\text{mol l}^{-1}$
Refractory C concentration	0.32%
Sedimentation rate $w_{\infty}$ (*)	0.003 $\text{cm yr}^{-1}$
Porosity (**)	$\phi_x = 0.734 + (0.947 - 0.734) \cdot e^{-\frac{x}{0.518}}$
Sediment dry density	2.5 $\text{g cm}^{-3}$

(\*) Van Weering, pers. comm.

(\*\*) Calculated based on the formation factor based on the relationship  $1/F = \phi^3$  (Ullman and Aller, 1982).

estimates of simple nonlinear models, where the goodness of fit of a model run relative to the best goodness of fit, is used to estimate confidence intervals of the parameters. A 'good run' was then defined as one for which the goodnesses of fit for each variable fell within 45% of its 'best' goodness of fit. The 45% range was chosen on a pragmatic basis, because it resulted in a workable number of good runs.

### 3. Results

There are some features in the data which the model cannot represent and which merit attention (Fig. 2). Near the sediment-water interface, there is a sharp rise in both nitrate and ammonium concentrations, which the model could not reproduce with reasonable organic C/N ratios. High concentrations of dissolved inorganic nitrogen in the upper centimeter have been observed before in studies that used sectioning followed by centrifugation or squeezing to obtain porewater, like in this study, but not in studies that applied *in situ* sampling devices (e.g. Martin and Sayles, 1996) or whole core squeezing techniques (e.g. Berelson *et al.*, 1990). These high concentrations of dissolved nitrogen near the sediment-water interface have been considered to be an artifact due to decompression and warming during recovery (Aller, 1990; Berelson *et al.*, 1990; Hammond *et al.*, 1996). Similarly, in OMEX station B they were considered suspect. Ammonium was most difficult to fit, not only in the upper part of the sediment, but also in the lower part, where concentrations increased further, whereas the model estimates tended to level off sooner. Because of this problem, including ammonium profiles did not provide additional constraints to the model outcome; whenever the nitrate profile was well fitted, ammonium proved to be reasonably represented as well. The ammonium increase at depth was probably due to mineralization

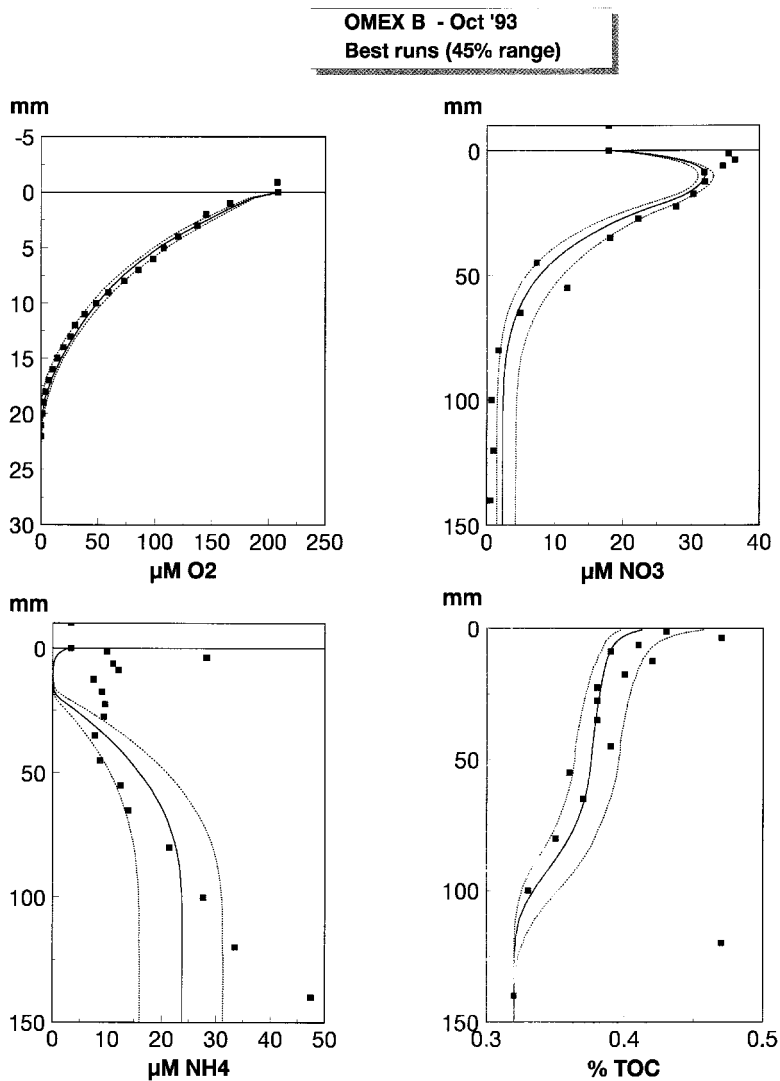


Figure 2. Observed data and the range of 'best' model runs retained after the sensitivity analysis.

of relict labile organic matter in sediments from the last glacial (Wallace *et al.*, 1988; Jahnke *et al.*, 1989).

Of the one million runs performed using the original ranges, only 200 were retained because they reproduced the observed data of all constituents within acceptable limits (here—arbitrarily—defined as the 45% norm, see above). In practice all runs were in the 35%–45% range. The observed range of modeled profiles withheld is represented in Figure 2.



Table 3. Original ranges of model parameters and reduced ranges resulting from the sensitivity analysis.

	Original range		Reduced range		
	Minimum	Maximum	Minimum	Maximum	Average
$Db_0$ ( $\text{cm}^2 \text{yr}^{-1}$ )	0.4	11	2.2	8.2	4.6
$F_C$ ( $\mu\text{mol cm}^{-2} \text{yr}^{-1}$ )	30	100	57	73	64
$p_0$ (-)	0.6	0.95	0.81	0.90	0.85
$k_0$ ( $\text{yr}^{-1}$ )	2	42	10.7	41.7	28.5
$k_1$ ( $\text{yr}^{-1}$ )	0.01	0.2	0.02	0.06	0.03

The resulting range of total mineralization, organic matter mixing rate and degradability was significantly reduced compared to the initial range (Table 3). The range of total mineralization rates was most narrowly constrained (Maximal/Minimal rate = 1.3); organic matter mixing rates and degradability could only be determined in much broader intervals (Maximum/Minimum = 3.7).

Of all possible combinations of mineralization, mixing and degradability that produced a reasonable fit, there was a significant and positive relationship between bioturbation and degradability (correlation coefficient,  $r = 0.72$ ; Fig. 3). Model runs with relatively refractory organic matter ( $10 \text{ yr}^{-1}$ ) under low mixing regimes produced comparable fits as runs

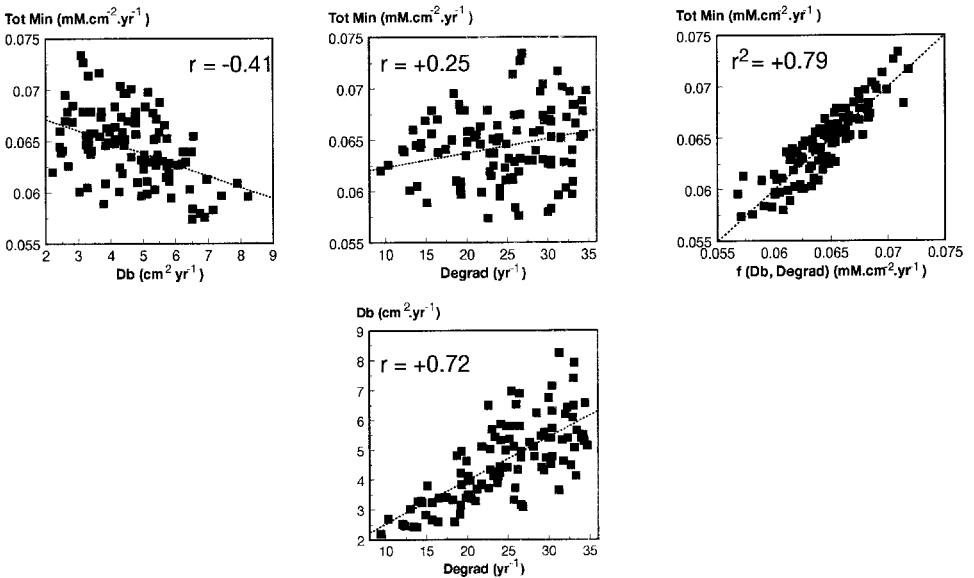


Figure 3. Relationship between total mineralization rates (Tot Min), mixing coefficient (Db) and decay rates (Degrad) in the 200 model runs retained after the sensitivity analysis (i.e. resulting in ranges depicted in Fig. 2), with their correlation coefficient ( $r$ -value). The rightmost graph depicts the goodness of fit of total mineralization rates and the best predictor, consisting of a linear combination of mixing rate and degradability.

Table 4. Original ranges of derived variables and reduced ranges from the sensitivity analysis.

	Original range		Reduced range		
	Minimum	Maximum	Minimum	Maximum	Average
Total degradability ( $\text{yr}^{-1}$ ) (*)	2	38	9.4	34.7	24
$\text{O}_2$ flux ( $\mu\text{mol cm}^{-2} \text{yr}^{-1}$ )	44	132	79	99	88
$\text{NO}_3$ flux ( $\mu\text{mol cm}^{-2} \text{yr}^{-1}$ )	-16	-6	-12	-10	-11
$\text{NH}_3$ flux ( $\mu\text{mol cm}^{-2} \text{yr}^{-1}$ )	3.8	3.9	3.9	3.9	3.9
% oxic	62	91	81	88	84.9
% anoxic	7	28	7.6	13.8	10.5
% denitrified	3	10	4.3	5.3	4.5

in which highly reactive organic matter ( $35 \text{ yr}^{-1}$ ) is more vigorously mixed. There was no relationship between total mineralization and either bioturbation or organic matter degradability alone ( $r = -0.41, 0.25$ ). Nevertheless, a linear combination of both mixing and degradability proved to be a strong predictor of total mineralization rates (multiple linear regression;  $r^2 = 0.79$ ). This suggests that it is not possible to derive unique and independent estimates of all three parameters based on a single data set. Given accurate estimates of the total mineralization rates (which can be best constrained), a multitude of combinations of bioturbation and degradability rates can produce equally acceptable fits. However, the range of possible values of mixing and degradability can be narrowed considerably compared to the original range. Also, there is a shift toward a larger contribution of the oxic processes (Table 4; 81–88%, average 85%) compared to the original range (62–91%). Some 4 to 5% of all organic carbon mineralization occurs by denitrification; anoxic mineralization accounts for 8–14% (Table 4).

In an attempt to test which combination of data sets is minimally required to constrain the model, the same analysis was done for any combination of data sets. Results are depicted in Figure (4). In order to constrain total mineralization rates, a combination of oxygen and nitrate data appears to be sufficient; inclusion of organic carbon only slightly narrows the interval of best mineralization rates. Oxygen profiles alone already narrow the possible range of total mineralization considerably, but occasionally some parameter combinations with high total mineralization rates fit the oxygen profiles well, resulting in a long tail toward high mineralization rates (Fig. 4a, 4th distribution from the right). These high rates are, however, not retained when including the nitrate data into the analysis. Also, nitrate alone narrows the allowable range of total mineralization considerably, although the results are conspicuously higher than the ultimately obtained range. Based on nitrate profiles alone, the originally large ranges in the organic matter mixing coefficient (Fig. 4b) and degradability (Fig. 4c) are strongly reduced, but estimates are much improved when including oxygen and carbon profiles into the analysis.

There is a certain degree of subjectivity in the model approach used. First of all, we chose to use absolute values of residuals rather than squared residuals, because of the

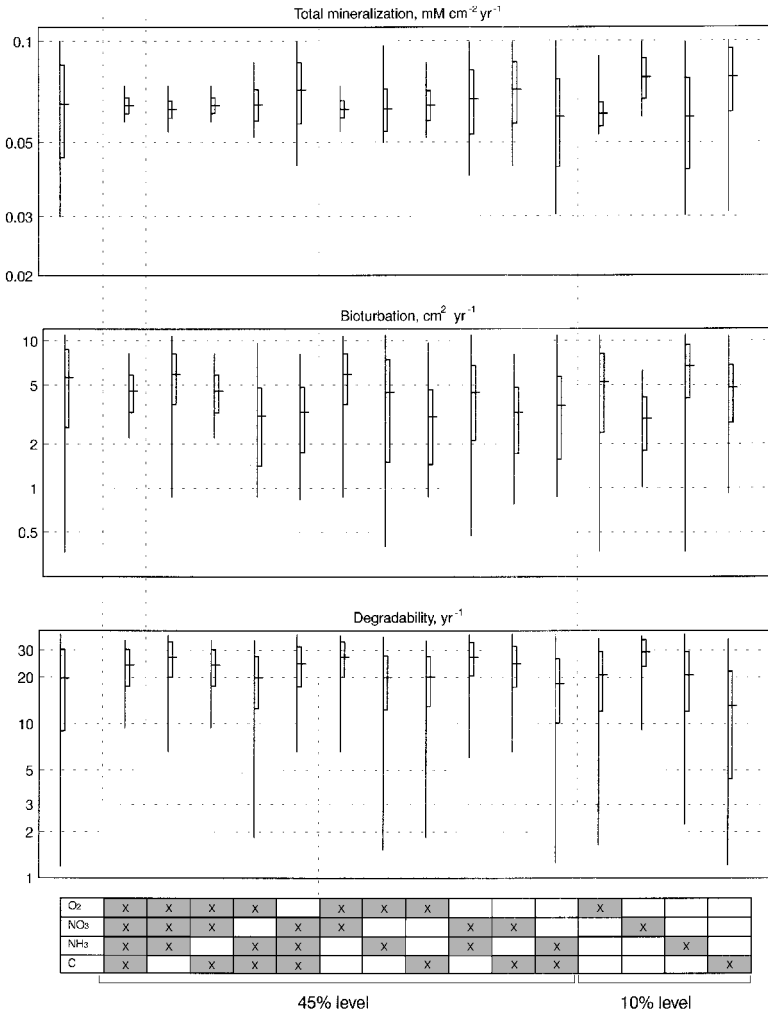


Figure 4. Results of the sensitivity analysis. Depicted is the distribution of obtained total mineralization (above), bioturbation (middle) and degradability (below), performed on variable combinations of observed data. The data sets used to constrain the ranges are represented in the bottom part of the figure as dark boxes. The distribution of a certain variable is represented by the total range (vertical line), the mean value (short horizontal dash), and the mean  $\pm$  the standard deviation (light boxes). The original distribution used in the sensitivity analysis is the leftmost one. Obtained distributions retained after fitting all data sets are immediately on the right of the original distribution. For analyses based on only one data set, a 10% range was used; when based on more than one data set, a 45% deviation was used.

presence of a prominent outlier in the organic carbon profile (Fig. 2) that otherwise dominated the analysis, and because the assumption of a normal distribution of errors, required for using the L2 norm (Press *et al.*, 1994), may not be valid. Because we are dealing with distinct species with different spatial resolution (oxygen versus the other

constituents) and different (unknown) associated errors, the definition of a 'model' performance criterion is nontrivial and also subjective.

Also, more stringent model constraints produce more compressed ranges, however, without affecting the main conclusions. For instance, reducing the allowable range to the 35% norm produced 46 good runs out of  $10^6$ , the maximal/minimal ratio of obtained ranges was 1.2, 2.4 and 2.6 for total mineralization, mixing and degradability, respectively.

#### 4. Discussion

Sediment organic carbon profiles are mainly shaped by the total carbon flux, the rate of mixing and the organic matter degradability. As various combinations of these processes may affect the organic profiles in a similar way, interpretations based on carbon alone may be hopelessly equivocal. For instance, a steep decrease in carbon concentrations near the surface may indicate a low mixing regime, transferring organic matter slowly to deeper layers, but it could also be due to a high reactivity of the organic matter. Because of this ambiguity, interpretation of organic matter profiles has always been performed in conjunction with independent estimates of at least one of the three unknown parameters (Billen, 1982; Emerson *et al.*, 1985; Heggie *et al.*, 1987; Anderson *et al.*, 1994).

In contrast to organic carbon, the rate at which dissolved constituents (oxygen, nitrate) are mixed into the sediment is usually well known (molecular diffusion, corrected for the tortuosity, Ullman and Aller, 1982; Boudreau, 1996b). This is mainly true for deep-sea conditions where enhancement by animals is restricted (Archer and Devol, 1992; Sayles and Martin, 1995). The gradient of these dissolved constituents at the sediment-water interface may then be used to estimate the net in- or efflux, which, assuming steady state, equals the net integrated consumption or production rate. This is in essence why modeling of oxygen or nitrate profiles has been so successful in deriving total mineralization (and related) rates (e.g. Billen, 1982; Goloway and Bender, 1982; Jahnke *et al.*, 1982; Bouldin, 1968).

In some of these modeling studies, subtleties in the profiles of oxygen or nitrate were better described when including depth-dependent mineralization rates (e.g. Murray and Kuivila, 1990; Martin *et al.*, 1991; Hammond *et al.*, 1996; Epping and Helder, 1998). Assuming that the bioturbation rate is known, this depth-dependency may then be translated into first-order degradation rates of the organic matter at the sediment-water interface (Hammond *et al.*, 1996).

In the sediment, the cycles of carbon, oxygen, nitrate and ammonium are intimately linked, but it is unclear to what extent the information intrinsic in the shape of the various profiles is redundant. If some of the information were to be complementary, it could be possible to better describe the geochemistry of the sediment using all profiles concurrently than when focusing on one single profile. It was one of the aims of this study to investigate how far we can estimate mineralization, bioturbation and degradation rates of the organic matter based on such a set of data.

The results of the sensitivity analysis performed in this study suggest that more is to be

obtained from modeling the profiles of oxygen, nitrate and carbon concurrently than from fitting one profile at a time (Fig. 4). Total mineralization rates were well constrained based on oxygen alone, but the range of likely values narrowed distinctly when nitrate profiles were fitted as well (Fig. 4a). Results were not as straightforward for bioturbation and degradability estimates. Whereas total mineralization rates were constrained in a narrow interval (Maximum/minimum value = 1.3), the likely range encompassing estimates of the latter variables was much larger (Maximum/minimum = 3.7). Nevertheless, there was a notable shift of both the mixing rates and the degradability toward higher values, compared to the original ranges. Also, amongst the parameter estimates that reasonably reproduced the observations there was a significant and positive relationship between the mixing coefficient and organic matter degradability. Such indeterminacy between bioturbation and degradability estimates is not surprising as profiles of various reactive constituents in the sediment scale with  $e^{-\sqrt{kDb}x}$  where  $k$  is the apparent first-order decay rate,  $Db$  the mixing coefficient and  $x$  the depth into the sediment (Berner, 1980; Boudreau, 1996b). A similar indeterminacy between mixing intensity and sedimentation rate was observed by Lynch and Officer (1984) when modeling steady-state and time-dependent flux inputs for a radioactive tracer.

Results of the sensitivity analysis suggest that 80 to 90% of the material on the sediment surface has a reactivity higher than  $11 \text{ yr}^{-1}$ , whereas the remaining fraction has a degradability 2 to 3 orders of magnitude lower (Table 3). All this indicates that OMEX station B, on the slope along the Goban Spur, is fueled mainly by fresh organic matter, with only a minor contribution of recycled material. Furthermore, the organic carbon burial rate is only about 1% of the estimated carbon mineralized in the sediment (van Weering, pers. comm.) precluding this site as an important depocenter of organic carbon.

There are many relationships in the literature describing the dependency of the rate constant of organic matter mineralization on sedimentation rate or organic carbon flux (reviewed in Boudreau, 1996b). Most of these equations focus on the decay constant of the less degradable organic matter fraction ( $k_1$ ), ignoring the highly reactive component that decomposes on a seasonal time scale (with first-order decay rate  $k_0$ ). From a biological point of view however, the latter component is the most interesting, as it is the main contributor to seasonal variability of the sediment (Martin and Bender, 1988) and as it fuels benthic metabolism. Also, our results suggest that it constitutes the most important fraction of the settling detritus at the Goban Spur station (>80%). Similarly, in a North Pacific station at 4100 m depth, the most readily degradable fraction was estimated to contribute about 70% to the total flux to the sediment (Soetaert *et al.*, 1996a), while in some sites studied in the central Pacific (3300–5000 m), more than 70% of the organic matter was estimated to have degradabilities of  $2\text{--}40 \text{ yr}^{-1}$  (Hammond *et al.*, 1996). In sediments fueled with such a reactive pool of organic matter, the estimate of the total mineralization rates and benthic fluxes obtained from one sample period may not be an adequate predictor of yearly averaged fluxes. The estimated variability of benthic response under sinusoidally varying rain rates can easily be quantified using the analytical solution given in Martin and

Bender (1988). Using mean parameter values as derived in this study for OMEX station B (Table 3) and imposing a rain rate of organic matter varying tenfold (both fractions), the expected response of total mineralization in the sediment (and oxygen flux) is very fast (it lags only about 2 weeks to deposition) and varies about 5-fold. If true, this puts serious constraints on the number of samples needed to adequately evaluate yearly-averaged mineralization rates at this slope station. This finding is somewhat in contrast to the apparent lack of seasonality in oxygen consumption rates, observed by Lampitt *et al.* (1995) in samples taken in April, June and August from the nearby slope of the Porcupine Seabight. Degradation rates obtained for OMEX station B fall nevertheless in the same range as rates obtained by Lochte and Turley (1988) in the Northeast Atlantic.

The bulk bioturbation coefficient obtained ( $2.2\text{--}8.2\text{ cm}^2\text{ yr}^{-1}$ ) is one order of magnitude larger than mixing rates derived by modeling  $^{210}\text{Pb}$  profiles ( $0.4\text{ cm}^2\text{ yr}^{-1}$ ), suggesting that organic particles are moved about at a higher rate compared to the solid fraction to which  $^{210}\text{Pb}$  is adsorbed. This is in agreement with the concept of age-dependency of mixing rates (Smith *et al.*, 1993). We have derived the bioturbation rate directly based on sediment-versus-depth profiles of constituents that are shaped by the process of early diagenesis. As such we do not rely on the assumption that radioactive tracers with decay rates approximately similar to the organic particles are mixed in a similar way. In one sense, our approach is more down-to-earth, because we do not need to match tracers whose half-lives are presumed to be comparable to the substance whose half-life we want to estimate (as in Hammond *et al.*, 1996). On the other hand, the organic matter in the sediment consists of a mixture of quality classes (in our model represented by two classes), and it is unlikely that these are handled in a similar way by the organisms. However, deriving two bioturbation coefficients, one for each degradability class cannot be achieved by the modeling strategy proposed here.

In conclusion, we have shown that it is possible by inverse modeling based on a Monte Carlo method, to constrain estimates of total mineralization, organic matter degradability and mixing rate within reasonable ranges using a single set of depth profiles of oxygen, nitrate and organic carbon concurrently. We are well aware that there are many drawbacks associated with the method and there remains a large uncertainty interval around some of the estimated values. Nevertheless, as it is based on a single set of profiles, it provides a relatively inexpensive assessment of expected seasonal variability and may therefore serve as a first guideline to the number of samples required to obtain reasonable estimates of yearly integrated mineralization rates.

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