

Drastic changes in deep-sea sediment porewater composition induced by episodic input of organic matter

Abstract—We report the first seasonal time-series observations of porewater composition obtained for deep-sea sediments. We observed considerable temporal variability of O_2 , NO_3^- , and Mn^{2+} profiles at the French JGOFS site DYFAMED (western Mediterranean) in response to a pulsed input of organic matter. A delivery of reactive organic matter representing only 1% of the average organic C content of surface sediments (0.6% wt/wt) was required in order to fuel the observed changes in porewater composition. The perturbation resulted in dramatic changes in integrated reaction rates and sediment–water fluxes. O_2 uptake rates increased from 1.26 to 1.82 $mmol\ m^{-2}\ d^{-1}$, while nitrification rates rose from 0.13 to 0.18 $mmol\ m^{-2}\ d^{-1}$. These changes were paralleled by a decrease in NO_3^- effluxes across the sediment–water interface from 0.07 to 0.01 $mmol\ m^{-2}\ d^{-1}$ and a concomitant rise of denitrification rates from 0.06 to 0.17 $mmol\ m^{-2}\ d^{-1}$. Porewater profiles responded rapidly to the sediment pulse deposition, returning to their steady-state values within a few months. The main driving force appeared not to be the seasonal variability of pelagic production but rather the downslope transport of resuspended upper-shelf sediments.

Numerous studies during the last decade have demonstrated that the deep-sea superficial sediment is an environment of considerable temporal variability. Seasonality of pelagic processes, coupled to rapid delivery of largely unaltered particulate organic matter, and episodic events like benthic storms and turbidity currents generated by downslope transport were identified as potential driving forces of deep-sea temporal variability (Deuser and Ross 1980; Smith and Baldwin 1984; Hollister and McCave 1984; Smith et al. 1992; Pfannkuche 1993; Sayles et al. 1994). Resulting dramatic depositional events have been documented in the past (Lampitt 1985; Gross et al. 1988; Smith et al. 1994), but because of the ephemeral nature of the perturbations and logistical constraints, little is known of the geochemical response of surface sediments.

Pulsed delivery of organic matter to the deep-sea floor may provide an important energy source to deep-sea benthic communities (Lochte and Turley 1988; Graf 1989; Gooday 1988). The benthic response to variations in particulate or-

ganic carbon (POC) flux has been assessed through time-series analyses of sediment community oxygen consumption. These studies have yielded divergent results. While a North Pacific site indicated varying rates of benthic organic carbon mineralization (Smith et al. 1992), only minor temporal variations in metabolic rates in response to variations in POC flux of similar amplitude were documented for an Atlantic site near Bermuda (Sayles et al. 1994). Deep-sea benthic communities have been documented to react within days to fluctuations in food supply (Graf 1989), generating changes in biomass and burying freshly deposited particles down to 9-cm depth. Although such a fast and deep-reaching response should be reflected by changes in porewater composition, the temporal variability of porewater chemistry has not been established. Modelling results suggest that the benthic response will be confined to the sediment–water interface, any temporal variability in porewater O_2 , and nutrient profiles being damped out by the large pool of sedimentary organic carbon (Martin and Bender 1988). This contrasts with estimates of the reactivity of POC in surface sediments (Hammond et al. 1996) and sediment mixing rates (Smith et al. 1993), suggesting that fresh organic particles could be rapidly incorporated in the sediment and influence porewater composition.

We investigated surface sediment porewater composition at the French JGOFS site Dyfamed (43°24.61'N, 7°51.68'E, 2,300-m depth) between July 1994 and June 1995. Surface sediments consisted of fine mud with an average porosity of 78% (0–0.5 cm), decreasing to 55% in a sandy lamina between 4 and 5 cm. Pebbles also occurred erratically. Sediments collected during November 1994 were overlain by a 0.5-cm-thick unconsolidated layer. Numerous animal tracks testified to high biological activity. This distinct layer could be identified during the following months as it was consolidating.

Studying temporal variability requires the assessment of spatial heterogeneity of the sampling area. The latter has to be low to allow identification of a temporal trend. Using GPS navigation, the dimension of the sampling site was restricted to a circle 500 m in diameter. Except for March

Table 1. Detail of sampling scheme indicating date and exact position of individual corer casts. The multicorer allows the recovery of up to eight subcores identified by labels between 1 and 8. The use of subcores for pore water extraction and O₂ profiling is indicated by +. To evaluate the reproducibility of O₂ measurements, two profiles were obtained on several cores. Surface gradients and depth of O₂ penetration were identical for repeated profiles of the same core.

Date of sampling	Corer cast ID	Subcore ID	Latitude	Longitude	Analyses	
					Pore water	O ₂ profile
1994						
5 Jul	KT38	1	43°24.62'N	7°51.67'E	+	–
		2			+	–
		4			–	2
6 Jul	KT40	2	43°24.61'N	7°51.62'E	–	2
30 Aug	KT41	1	43°24.63'N	7°51.66'E	+	–
1 Sep	KT42	3	43°24.63'N	7°51.67'E	–	+
1 Sep	KT43	2	43°24.61'N	7°51.70'E	+	–
		4			–	+
		7			+	–
29 Nov	KT45	2	43°24.58'N	7°51.67'E	+	–
		3			–	+
	KT46	1	43°24.62'N	7°51.68'E	–	2
					+	–
30 Nov	KT47	1	43°24.64'N	7°51.65'E	–	+
1995						
14 Mar	KT51	1	43°24.61'N	7°51.69'E	–	2
		3			+	–
4 Apr	KT52	3	43°24.66'N	7°51.52'E	+	–
5 Apr	KT53	2	43°24.57'N	7°51.59'E	+	+
21 Jun	KT55	8	43°24.70'N	7°51.63'E	+	+
22 Jun	KT56	2	43°24.61'N	7°51.63'E	–	+
		3			+	–
23 Jun	KT57	4	43°24.62'N	7°51.76'E	+	–

1995, two to three multicorers (Maxicorer Bowers & Connelly) were collected during each cruise on up to 3 successive days. Details of the sampling program are summarized in Table 1. Every corer cast allowed the simultaneous recovery of eight sediment cores (i.d. 10 cm) within an area of ~1 m². Only apparently undisturbed cores were selected for processing. Directly after sampling, cores were removed from the coring device and stored or processed at in situ temperature (13°C). Samples were sliced in 0.5-cm slices down to 4 cm and 1-cm slices deeper. Pore waters were extracted by centrifugation at in situ temperature at 4,500 rpm for 15 min. The supernatant was filtered and acidified (1% vol/vol HCl suprapure). Samples were stored at 4°C prior to further analyses. NO₃[–] and Si(OH)₄ were analyzed on an Alpkem rapid flow analyzer following standard procedures outlined in Grasshof et al. (1983). Mn²⁺ levels of pore waters were determined without preconcentration by electrothermal atomic adsorption spectrometry (GFAAS) on a Zeeman 3030 Perkin Elmer spectrometer with an analytical precision of ±3%. Dissolved O₂ profiles were measured using a 10-cm needle Polarographic oxygen sensor (Helder and Bakker 1985). The electrode was polarized at –800 mV against a reference electrode (Diamond General ref. 334) that was inserted in the overlying water. The needle tip of ~0.5-mm diameter allowed for the determination of profiles on a millimeter scale. Bottom-water O₂ concentrations were de-

termined by Winkler titration and served as a reference for calculating the profiles.

The downcore distributions of O₂, NO₃[–], Mn²⁺, and Si(OH)₄ are presented in Fig. 1. Each graph displays porewater data from two to three independently collected sediment cores. They reflect the spatial homogeneity at the sampling site. The low within-cruise variability of porewater profiles is noteworthy: gradients of O₂, NO₃[–], and Si(OH)₄ across the sediment–water interface, depth of O₂ penetration, maximal values of NO₃[–], asymptotic Si(OH)₄ concentrations, and depth of appearance of Mn²⁺ are fairly constant for a single cruise. Comparing individual solute distributions of O₂, NO₃[–], and Mn²⁺ reveals striking modifications between August 1994 and June 1995. The O₂ penetration depth decreased from 5 to 1 cm between August 1994 and November 1994 (Fig. 1a). This change occurs with an upward shift of the NO₃[–] asymptotic level and a strong decrease in NO₃[–] peak concentrations (Fig. 1b). Measurable levels of Mn²⁺ were determined in the upper oxidic centimeter during November 1994 (Fig. 1c). During the following months, the porewater composition relaxed back to its initial composition as evidenced by the June 1995 profiles (i.e. the depth of O₂ penetration deepened, a subsurface NO₃[–] maximum reappeared, and Mn²⁺ disappeared from the uppermost sediment layers). The temporal trend observed for redox-sensitive species contrasts with the low between-cruise variability dis-

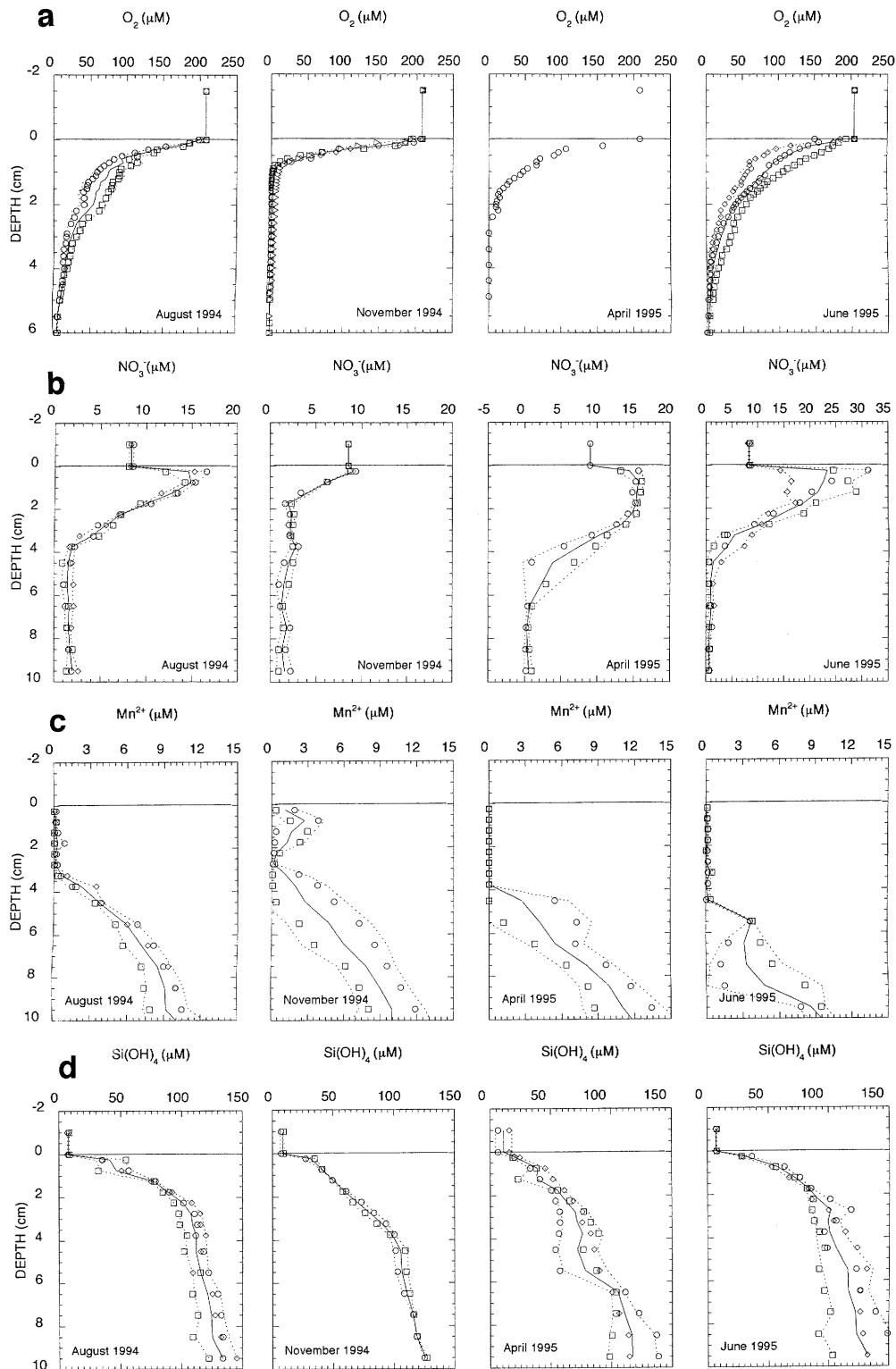


Fig. 1. Depth-dependent distributions of O_2 (a), NO_3^- (b), Mn^{2+} (c), and $Si(OH)_4$ (d) in pore waters. For each profile, data from two to three sediment cores are displayed, indicating the high degree of spatial homogeneity of the sampling site. For each distribution, average concentration (solid line) and standard deviation (dashed line) are indicated. Samples were collected on 5–6 July, 30 August–1 September, 29–30 November 1994, 14 March, 4–5 April, and 21–23 June 1995. The porewater composition is shown for July, August, and November 1994 and for April and June 1995.

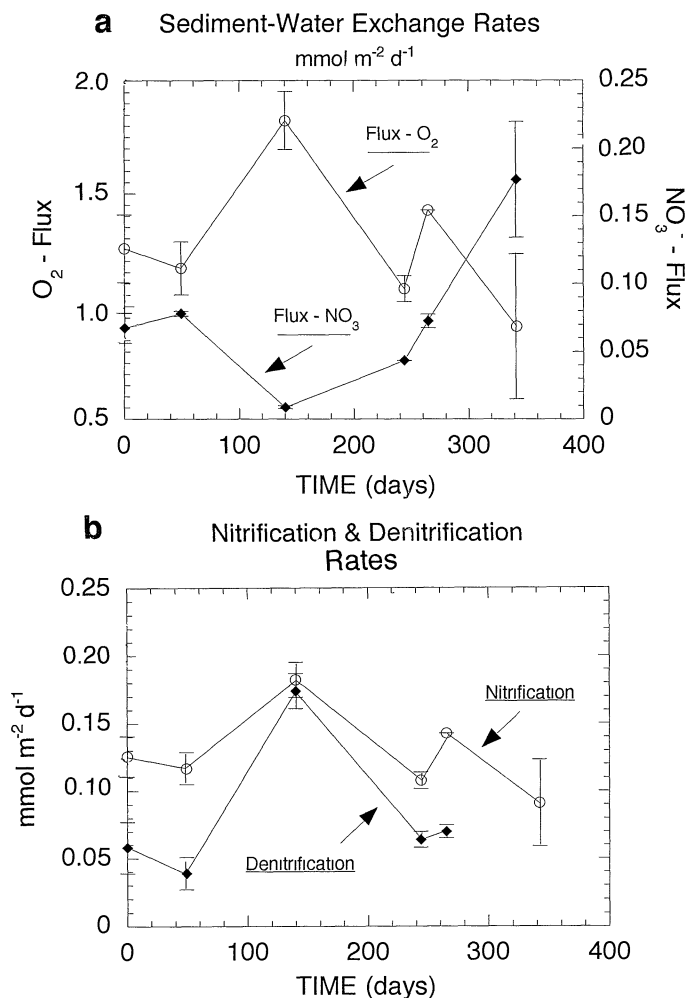


Fig. 2. [a.] Exchange fluxes of oxygen and nitrate and reaction rates for nitrogen plotted vs. time. The time axis starts at our first sampling period (5 July 1994), and the perturbation was recorded after 120 d. Exchange fluxes between the sediment and the water column for O_2 and NO_3^- are in $mmol\ m^{-2}\ d^{-1}$. [b.] Rates of nitrification and denitrification. The error bars in the figure represent the standard deviation ($1\ \sigma$) of the mean values determined for two or three different cores and propagated through the calculations.

played by the dissolved silica distribution. All solute profiles were determined on the same porewater sample. The strong decrease in NO_3^- peak concentrations for example between August 1994 and March 1995 is concomitant to an unchanged $Si(OH)_4$ distribution. It can thus be ruled out that the observed changes of downcore distributions of O_2 , NO_3^- , and Mn^{2+} are merely due to a sampling artifact (e.g. loss of coretop sediments f.i.).

The importance of changes affecting O_2 , NO_3^- , and Mn^{2+} can be estimated by comparing fluxes and depth-integrated reaction rates calculated from the different porewater distributions (Fig. 2). Solute fluxes were estimated according to Fick's first law with a coefficient of diffusion corrected for tortuosity (Ullman and Aller 1982) and temperature (Li and Gregory 1974). Oxygen uptake was evaluated by averaging the gradients determined over 0.5 and 1 cm. The average gradient was multiplied by the porosity (0.75) and the O_2

diffusion coefficient corrected for tortuosity at $13^\circ C$ ($D_{O_2} = 9.6 \times 10^{-5}\ m^{-2}\ d^{-1}$). The NO_3^- gradient was calculated between the overlying water concentration and the mean concentration at 0.5 cm, the latter being an average of two concentrations measured over the first centimeter. The flux of nitrate out of the sediment was estimated using this gradient and a diffusion coefficient ($D_{NO_3^-}$) of $8.1 \times 10^{-5}\ m^{-2}\ d^{-1}$ (Li and Gregory 1974). Nitrification was calculated by multiplying the O_2 demand by a Redfield factor assuming a C:N ratio of 8, thereby implicitly assuming that pore waters are in quasi-steady state and that N is nitrified with the same C:N ratio as the organic substrate. Denitrification was estimated as the difference between nitrification and nitrate effluxes and includes all losses of reduced species (NH_4^+ , NO_2^-) that may occur during the nitrification process. The latter are, however, small in deep-sea environments because of the dominance of oxic diagenesis. Between July 1994 and November 1994, O_2 uptake rates (Fig. 2a) increased from 1.26 to $1.82\ mmol\ m^{-2}\ d^{-1}$, concomitantly with an increase in nitrification rates (Fig. 2b) from 0.13 to $0.18\ mmol\ m^{-2}\ d^{-1}$. During the same period, NO_3^- effluxes (Fig. 2a) showed a large decrease from 0.07 to $0.01\ mmol\ m^{-2}\ d^{-1}$, while denitrification rates (Fig. 2b) rose from 0.06 to $0.17\ mmol\ m^{-2}\ d^{-1}$.

The strong decrease in the depth of O_2 penetration observed in November 1994 induced severe modifications in the distribution of redox-sensitive species, the production and consumption of which are directly affected by the presence of oxygen. Nitrification is a strictly aerobic process (Henriksen and Kemp 1988). The sediment thickness over which nitrification occurs decreases with decreasing O_2 penetration depth, while denitrification, a suboxic process, is favored in the former oxic zone. The shift from aerobic to anaerobic metabolism can be fast, because certain bacterial strains are able to metabolize POC in both redox environments (Lovley and Phillips 1988; Myers and Nealson 1988). But strengthening of denitrification relative to nitrification (Fig. 2b) is not sufficient alone to explain the disappearance of the nitrate peak after perturbation. If nitrification remains large, which is indicated by the oxygen profile, then nitrification and denitrification have to be spatially coupled (i.e. occur in the same layer) if the nitrate peak is to be decreased in concentration (Brandes and Devol 1995). This suggests the presence of microenvironments in which denitrification takes place in a surrounding oxic environment (Jahnke 1985). During relaxation, the build-up of a nitrate peak occurs because of the combined effect of deepening of the oxic zone and suppression of denitrification in the oxic zone due to exhaustion of the microsites. Measurable levels of dissolved manganese in the oxic zone are another clue for the existence of reduced microenvironments in the upper layer. An average inventory of $4\ nmol\ cm^{-3}$ of Mn^{2+} has been determined in the upper 2 cm of the sediments during November 1994. A comparison between the inventory and the flux of Mn^{2+} estimated from the average gradient ($3\ nmol\ cm^{-4}$) indicates that any Mn^{2+} would be lost within <2 weeks by diffusion. Moreover, Mn^{2+} is unstable in the oxic layer and would be oxidized by O_2 within months, the oxidation half-life being 10–20 d in marine oxic environments (Burdige and Gieskes 1983). The presence of a noticeable

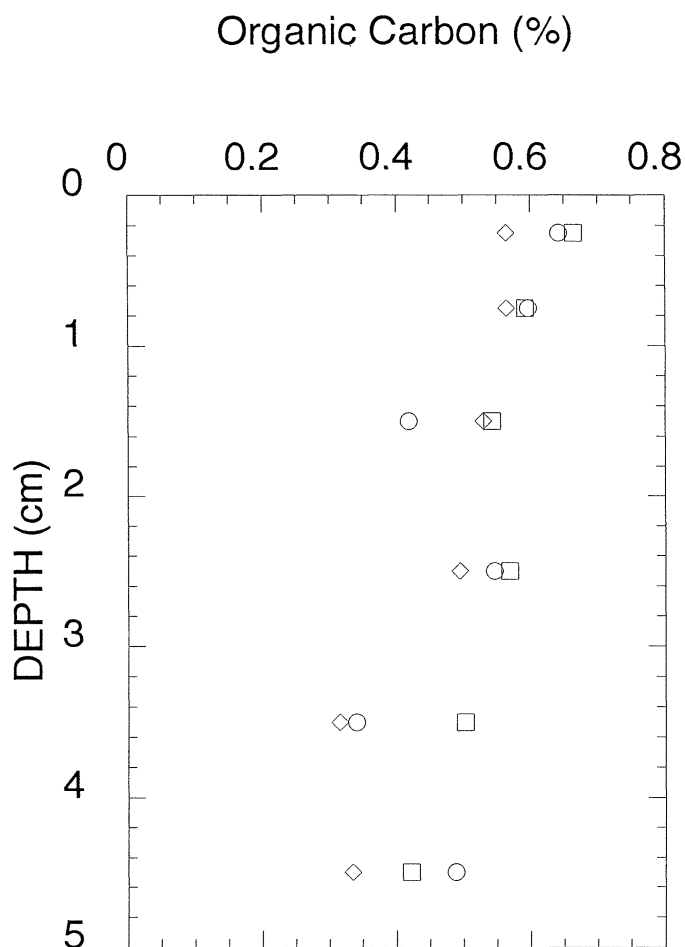


Fig. 3. Organic carbon content of sediments expressed in percent sediment dry weight presented as a function of depth for October 1994 (□), November 1994 (○), and April 1995 (◇). Organic carbon levels decreased from 0.62 ± 0.05 surface sediments to 0.42 ± 0.08 at 4.5-cm depth.

subsurface peak of Mn^{2+} is indicative of its ongoing production at the time of sampling as a result of the perturbation. Consistent with its oxidation half-life, Mn^{2+} found in the first centimeter of the sediment just after the perturbation had completely disappeared by April 1995. Unlike the redox-sensitive species, $Si(OH)_4$ appeared not to be affected by the depositional event. One would expect that deposition of a 0.5-cm-thick new surface layer would modify the concentration gradient across the sediment–water interface. From the coefficient of diffusion of Fanning and Pilson (1974), corrected for in situ temperature and tortuosity ($4 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$), it follows that diffusion would bridge the 0.5 cm of newly deposited sediment within <3 d. By the time of sampling we expect gradients across the sediment–water interface of chemical species not produced within the new layer to be reestablished.

The previous evolution of porewater composition can most easily be explained by an increased delivery of labile POC to the sediment–water interface. Figure 3 compares POC profiles obtained before and after the perturbation with the downcore distribution measured in sediment samples of

November 1994. There is no variation in POC content of surface sediments over that period. This stands in contrast to the increase of O_2 consumption by $1.82 - 1.26 = 0.56 \text{ mmol m}^{-2} \text{ d}^{-1}$, and the strengthening of denitrification by $0.17 - 0.06 = 0.11 \text{ mmol m}^{-2} \text{ d}^{-1}$ observed in November. Using Redfield stoichiometry of C: O_2 of 106:138 and C: NO_3 of 106:94.4, we calculated that an additional $0.6 \text{ mmol C m}^{-2} \text{ d}^{-1}$ was mineralized. Assuming that this enhanced mineralization of C lasted for 3 months and affected a sediment layer of 1-cm thickness (depth of oxic layer), the required increase in POC would be only 0.006% wt/wt. With a mean organic C content of surface sediments of 0.6% wt/wt, this corresponds to 1% of the existing concentration, an undetectable amount. Thus, only a small increase in reactive carbon is needed to support the observed changes in porewater chemistry.

Short-term temporal variation in the reactivity of organic material at deep-sea sites has been documented in the past (Lampitt 1985; Lochte and Turley 1988; Smith et al. 1994) and could be linked to the pulsed delivery of fresh phyto-detritus. Time-series measurements of POC flux at a nearby mooring site ($42^\circ 44' \text{ N}$, $8^\circ 31' \text{ E}$) revealed a well-defined seasonal pattern with maximum fluxes in early summer (May, June) and late autumn (October, November) (Miquel et al. 1994). The amplitude of the late autumn peak, however, is substantially smaller than the spring bloom event. If increased delivery of fresh phytodetritus is the main forcing mechanism of changes in porewater composition, an even stronger response would be expected following the settling of the spring bloom. Our data do not support this hypothesis and although contribution from a settling bloom cannot be completely ruled out, an additional mechanism must have been at work.

Substantial downslope transport of recent sediment has been documented in the Mediterranean Sea (Monaco et al. 1990; Buscail 1991), and pelagic production is not the only source of particles during periods of intense sedimentation (Crassous et al. 1991; Miquel et al. 1994) at our study site. Deep-sea storms have been documented for this area, and resuspension of sediments on the upper part of the shelf slope followed by downslope transport is a likely additional source of particulate matter (Crassous et al. 1991). The importance of lateral transport is suggested by the 0.5-cm-thick layer of unconsolidated sediment observed in core top sediments collected in November 1994. Episodic events of sediment transport may increase the vertical particle flux up to 10 times over the yearly average in this region (Crassous et al. 1991). Heavy storms with rain fall and resulting flash floods occurred 3 weeks before the November cruise and may have produced turbidity currents. Sediments resuspended on the upper shelf are expected to have a higher content of labile organic C than deep-sea sediments. Their downslope delivery will result in a net input of reactive organic C to the deep-sea benthic boundary layer. Along with it, reactive reduced inorganic material resuspended from the suboxic zone is likely to be transferred and would result in the presence of reducing microenvironments in the oxic layer. While the transport of organic matter from the continental shelf to the open ocean represents a globally significant transfer mechanism (Walsh 1991), it is difficult in our study

to obtain an estimation of the amount of organic matter exported from the shelf because the frequency of resuspension and deposition events and the area affected by them are presently unknown.

Previous time-series of deep sea sediments have focused on changes induced by seasonally varying POC fluxes as recorded by total sediment metabolic activity. Past studies emphasized the importance of episodic delivery of POC as a food source for abyssal benthic communities reporting a rapid benthic response in terms of activity and biomass (Lochte and Turley 1988; Graf 1989). While the seasonal variability of pelagic production is widely accepted to be the main driving force of deep-sea benthic boundary temporal variability, we provided evidence for the time-dependent evolution of sediment porewater composition in response to episodic resuspension and downslope transport of upper-shelf sediments. This study demonstrates that the geochemical response of deep-sea sediments to episodic inputs of shelf organic matter and reduced inorganic material, far from being limited to the sediment-water interface, may profoundly modify porewater chemistry down to depths of several centimeters within weeks.

Marion Gehlen¹
Christophe Rabouille
Ullah Ezat

Centre des Faibles Radioactivités
Laboratoire Mixte CNRS-CEA
Avenue de la Terrasse
F-91198 Gif-sur-Yvette, France

Laurence D. Guidi-Guilvard

Laboratoire d'Océanographie
Biochimique et d'Ecologie
Observatoire Océanologique
BP 28, F-06230 Villefranche-sur-Mer, France

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