12 Organic Carbon Fluxes and Sediment Biogeochemistry on the French Mediterranean and Atlantic Margins

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12.1 INTRODUCTION

It is now widely accepted that to obtain a better understanding of the oceanic organic carbon cycle special attention must be paid to continental margins. These areas represent some of the highest primary production zones of the ocean and receive important organic inputs from the continents (Jorgensen, 1983; Wollast and MacKenzie, 1989; Wollast, 1990). Organic fluxes to shelf and slope sediments are therefore generally higher than in the open ocean and the subsequent preservation of organic matter confer to margins the role of a preferential sink area for C_{org}.

ECOMARGE (Ecosystèmes de MARGE continentale), part of JGOFS-France, is a multidisciplinary program designed to study the transfer of matter and energy across margins, as well as the response of the benthic ecosystem to such transfers. This paper summarizes results obtained by this program over the last few years on continental margins of the northwestern Mediterranean and northeastern Atlantic. Carbon fluxes through the slope water column and data on the biogeochemistry of surficial sediments are presented and compared with the aim of giving new insights into the overall functioning of these areas and of elucidating the major factors controlling particle transfer processes in these highly contrasted environments.

12.2 SAMPLING SITES AND STRATEGY

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In order to define the respective roles of physical, chemical and biological factors in controlling mass and carbon fluxes on continental margins, identical strategies and methods were used during the ECOMARGE program to investigate two contrasting regions: the northwestern Mediterranean (Gulf of Lions) - a non tidal sea characterized by a fine-grained shelf sedimentation, and the northeastern Atlantic (Bay of Biscay) - a tidal sea with sandy-silty shelf sedimentation. Both regions, however, present the common feature of being subject to large riverine inputs (respectively the Rhône and the Gironde) and to a pronounced alongslope circulation of water masses. Results obtained by DYFAMED, another JGOFS-France program, on two northwestern Mediterranean sites representative of open ocean areas are also given for comparison (Figure 12.1 and Table 12.1).

12.2.1 MEDITERRANEAN SITES

In the Mediterranean experiment, the investigations focused on two sites within the Gulf of Lions: one located at the eastern entrance, off the Rhône River, and the other located at the southwestern end, off the Pyrenean coastline. At this latter site, four time series traps (cylindroconical model PPS3 from Technicap, 0.125 m^2 collection area, 6 receiving cups; Heussner et al., 1990) were moored in the Lacaze-Duthiers Canyon (site LD), in a 645 m deep water column, at depths of 50, 100, 300 and 600m (Monaco et al., 1990b). Three consecutive deployments of five sampling periods were obtained (ECO I, ECO II, ECO III), leading to a total of 15 samples; the sampling interval was 16 days. At the entrance of the Gulf of Lions, the moorings were located in the Grand-Rhône Canyon (site GR) and on the open slope (site IF) between the Grand-Rhône and Petit-Rhône canyons (Monaco et al., in preparation). Four traps were moored in a 965 m water column, at 80, 200, 600 and 900 m depth in the axis of the canyon. A single trap was moored at 900 m, near the bottom of the interfluve site. The sampling interval was set at 15 days.

The two DYFAMED moorings were located in the Ligurian Sea, at 12.8 miles off Corsica (DYFAMED 1) and 28 miles off continental France (DYFAMED 2), in a water column of respectively 2100 and 2300 m (Miquel et al., 1993; 1994). These sites were equipped with PPS3 traps at 80–100 m, 200 m, 500 m and 1000 m. Sampling intervals varied between 9 and 15 days.

12.2.2 ATLANTIC SITES

Traps were deployed on two experimental sites within the Cap-Ferret Canyon, in the southern part of the continental slope of the Bay of Biscay (Heussner et al., 1996). The first mooring site (MS1), equipped with 4 PPS3 traps and associated Aanderaa current meters, was located at the confluence of the northern and southern axes of the upper canyon, in a 2300 m water column. Traps were deployed at nominal depths of 380, 1350, 1900 and 2250 m. The second site (MS2), located at the foot of the slope, in a 3000 m water column, was equipped with two

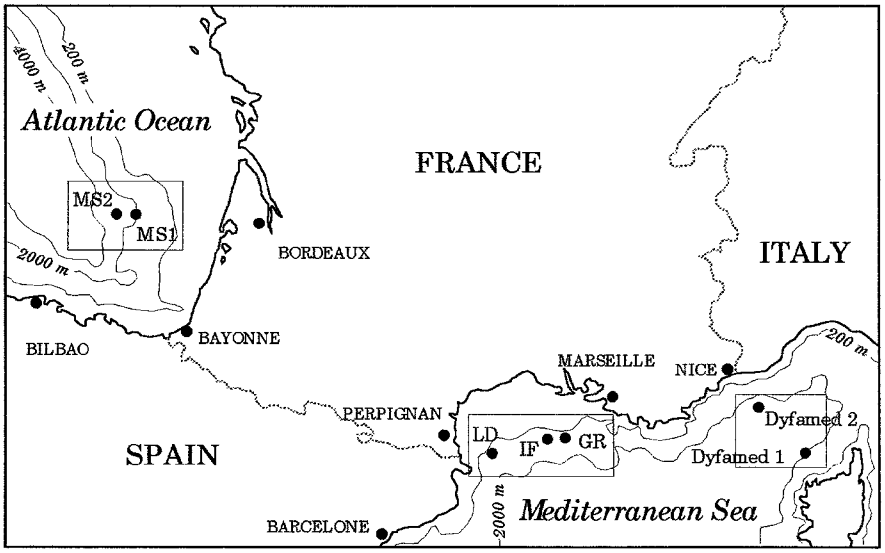

Figure 12.1 Location of the sediment trap mooring sites from the various ECOMARGE experiments on the northwestern Mediterranean (Gulf of Lions) and northeastern Atlantic (Bay of Biscay) continental margins. GR: Grand-Rhône Canyon; IF: Grand-Rhône open slope; LD: Lacaze-Duthiers Canyon; MS1 and MS2: mooring sites of the Cap-Ferret canyon. DYFAMED 1 and 2 are open ocean moorings from the French DYFAMED program in the Ligurian Sea.

Table 12.1 Location and sampling periods of the various moorings deployed during the ECOMARGE and DYFAMED experiments.

	Latitude N	Longitude E	Water depth m	Sampling period
MEDITERRANEAN SITES				
GR: Grand Rhône Canyon	42°50’	04°49’	965	Jan. 1988 - Jan. 1989
IF: Grand Rhône Open Slope	42°45’	04°46’	960	Jan. 1988 - Jan. 1989
LD: Lacaze-Duthier Canyon	42°29’	03°29’	645	Jul. 1985 - Apr. 1986
DYFAMED site 1	42°44’	08°32’	2100	Jan. 1987 - Oct. 1988
DYFAMED site 2	43°25’	07°52’	2300	Dec. 1988 - Nov. 1990
ATLANTIC SITES				
Cap-Ferret Canyon MS 1	44°43’	02°17’	2290	Jun. 1990 - Aug. 1991
Cap-Ferret Canyon MS 2	44°47’	02°38’	3010	Jun. 1990 - Aug. 1991

traps, at 1900 and 2950 m depth. Samples were collected over a period of 14 months, during 3 consecutive deployments. Sampling intervals were respectively 20 (ECOFER II), 27 (ECOFER III) and 16 days (ECOFER IV).

12.3 RESULTS

12.3.1 SPATIAL VARIATIONS IN TOTAL MASS AND ORGANIC CARBON FLUXES

All results from the different sites are reported in Table 12.2.

12.3.1.1 Mediterranean sites

At the GR and LD locations, in the Gulf of Lions, time-weighted mean mass and C_{org} fluxes were quite high. They increased with depth from the surface to the bottom. The comparison of fluxes at the GR and LD sites shows that, at all depths, fluxes increased from the northeast to the southwest (i.e., downstream the general circulation of water masses): 148 to 639 mg m^{-2} d^{-1} in surface traps and 268 to 6025 mg m^{-2} d^{-1} in near-bottom traps for mass fluxes; 27 to 121 mg m^{-2} d^{-1} and 9 to 83 mg m^{-2} d^{-1} for C_{org} fluxes. At the LD station, the most striking feature was the strong reduction in C_{org} fluxes between the two shallowest traps (50 m and 100 m), and the strong increase in total mass fluxes and, to a lesser extent, in C_{org} fluxes at 300 and 600 m. At both stations, the C_{org} content of settling particles strongly decreased from surface to deeper traps: from 182 to 34 mg C_{org} g^{-1} (dry weight) at the GR site and from 189 to 14 mg C_{org} g^{-1} at the LD site. Fluxes obtained at the IF station, on the open slope, were lower than those observed nearby within the GR canyon: 72 and 6 mg m^{-2} d^{-1}, respectively for total mass and C_{org} fluxes. The amount of particulate C_{org} in the trapped material remains, however, important (83 mg C_{org} g^{-1}).

Fluxes recorded at the open ocean stations from the DYFAMED experiment were quite different. Mean mass fluxes were low and decreased drastically with depth from 93 mg m^{-2} d^{-1} in surface waters (100m) down to 33 mg m^{-2} d^{-1} at 1000 m (mid-water). Organic carbon fluxes varied in the same way, from 17 mg m^{-2} d^{-1} in the shallow trap down to 3.3 mg m^{-2} d^{-1} at 1000 m. At all depths, C_{org} concentrations in trapped particulates were high: 183 mg C_{org} g^{-1} at 100 m and still 100 mg C_{org} g^{-1} at 1000 m.

12.3.1.2 Atlantic sites

At MS1, time-weighted mean total mass fluxes for the whole experiment (15 months) increased continuously from 500 mg m^{-2} d^{-1} in the surface trap, down to the near-bottom trap, where a mean flux of 1470 mg m^{-2} d^{-1} was found. The same downward flux increase was observed for MS2 traps, where the values increased from 326 to 457 mg m^{-2} d^{-1}. Fluxes registered by the 1900 m trap of MS2 were always lower than those measured at the same depth on MS1. This general trend of flux increase with depth and seaward decrease was also observed for C_{org}

Table 12.2 Time-weighted annual mean mass fluxes (mg m $^{-2}$ d^{-1}) and organic carbon fluxes (mg m^{-2} d^{-1}) and content (%) on French continental margins. GR: Grand-Rhône Canyon; IF: Grand-Rhône open slope; LD: Lacaze-Duthiers Canyon; MS1 and MS2: mooring sites of the Cap-Ferret Canyon. DYFAMED 1 and 2 are open ocean moorings from the French DYFAMED program in the Ligurian Sea.

Mooring Site		Surface Water		Intermediate Water		Deep Water
MEDITERRANEAN SEA						
	Trap depth	85	200	500		900
GR	*Mass Flux*	148	253	387		268
(1000 m)	C_{org} *Flux*	27	15	18		9
	C_{org} *%*	18.2	5.9	4.7		3.4
	Trap depth					900
IF	*Mass Flux*					72
(1000 m)	C_{org} *Flux*					6
	C_{org} *%*					8.3
	Trap depth	50	100	300		600
LD	*Mass Flux*	639	379	3108		6025
(650 m)	C_{org} *Flux*	121	21	57		83
	C_{org} *%*	18.9	5.5	1.8		1.4
	Trap depth	100	200	500		1000
DYFAMED	*Mass Flux*	93	82	36		33
Site 1 & 2	C_{org} *Flux*	17	11	3.6		3.3
	C_{org} *%*	18.3	13.4	10.0		10.0
ATLANTIC OCEAN						
	Trap depth		380	1350	1900	2250
MS1	*Mass Flux*		498	768	1197	1470
(2300 m)	C_{org} *Flux*		23	28	32	41
	C_{org} *%*		4.6	3.6	2.7	2.8
	Trap depth				1900	2950
MS2	*Mass Flux*				326	457
(3000 m)	C_{org} *Flux*				14	15
	C_{org} *%*				4.3	3.3

fluxes: two-fold increase between the MS1 surface and near-bottom traps (23 to 41 mg m^{-2} d^{-1}) and two-fold decrease between the two at the same depth. Organic carbon content of the trapped particles slightly decreased with depth at both sites. At MS1 for example the flux-weighted mean content decreased from 46 mg C_{org} g^{-1} in the surface trap to 28 mg C_{org} g^{-1} in the near-bottom trap.

12.3.2 SEASONAL VARIATIONS IN TOTAL MASS AND ORGANIC CARBON FLUXES

12.3.2.1 Mediterranean sites

Variations of total mass and C_{org} fluxes with time and depth are given in Figure 12.2. At both mooring sites located at the entrance of the Gulf of Lions (IF and GR), no clear seasonal trend in total mass and C_{org} fluxes were observed: fluxes were quite constant for most part of the experiment, except for a very important flux increase recorded by all traps and which lasted roughly two months (around day 100 of the experiment). On the contrary, at the exit of the Gulf of Lions, within the LD Canyon, total mass and C_{org} fluxes were characterized by a high seasonal variability (Monaco et al., 1990a, b). At 50 m, fluxes varied by one order of magnitude depending on the season (114 to 1500 mg m^{-2} d^{-1}), with the highest values observed during summer. The strong reduction in fluxes between the 50 m and the 100 m traps suggests important recycling processes (degradation and/or consumption) of the organic-rich particles settling through the upper water column. Mass fluxes at 300 and 600 m depth showed a general trend to increase from summer to winter with respective peaks at around 10000 and 20000 mg m^{-2} d^{-1}, which coincided roughly with storm and rainfall events (Monaco et al., 1990b). Secondary peaks were observed in July (both depths) and in mid-September (300 m). It was clear that the highest mass fluxes were characterized by low C_{org} content, suggesting a terrigenous and/or resuspended origin of the trapped particles.

At the DYFAMED sites, fluxes were characterized by a high seasonal variability: they were highest in winter and spring (330–350 mg m^{-2} d^{-1}) and lowest in late summer (5.5 to 8.4 mg m^{-2} d^{-1}). The C_{org} fluxes followed approximately the same pattern as total mass fluxes (Peinert et al., 1992; Miquel et al., 1993; 1994).

12.3.2.2 Atlantic sites

The strongest temporal variations were observed in the surface traps, where mass fluxes varied from a few tens of mg to almost 1.5 g m^{-2} d^{-1} (Figure 12.3). At any depth, there was an important similarity between mass and C_{org} flux variations. The most striking feature is that no clear seasonal trend was detected in the variations of the total mass and organic fluxes (Heussner et al., 1996). Flux changes were rapid and the variation from one sample to the next one was sometimes equivalent to the overall flux range observed at any given depth. C_{org} content of settling particles varied between 30 and 50 mg C_{org} g^{-1} and was quite homogenous over the entire experiment. Only a few peaks were observed on both mooring lines. Based on the study of coccolithophorid fluxes, Beaufort and Heussner (1996) interpreted these peaks, which were also registered by the deepest traps, as primary production signals directly derived from the overlying waters.

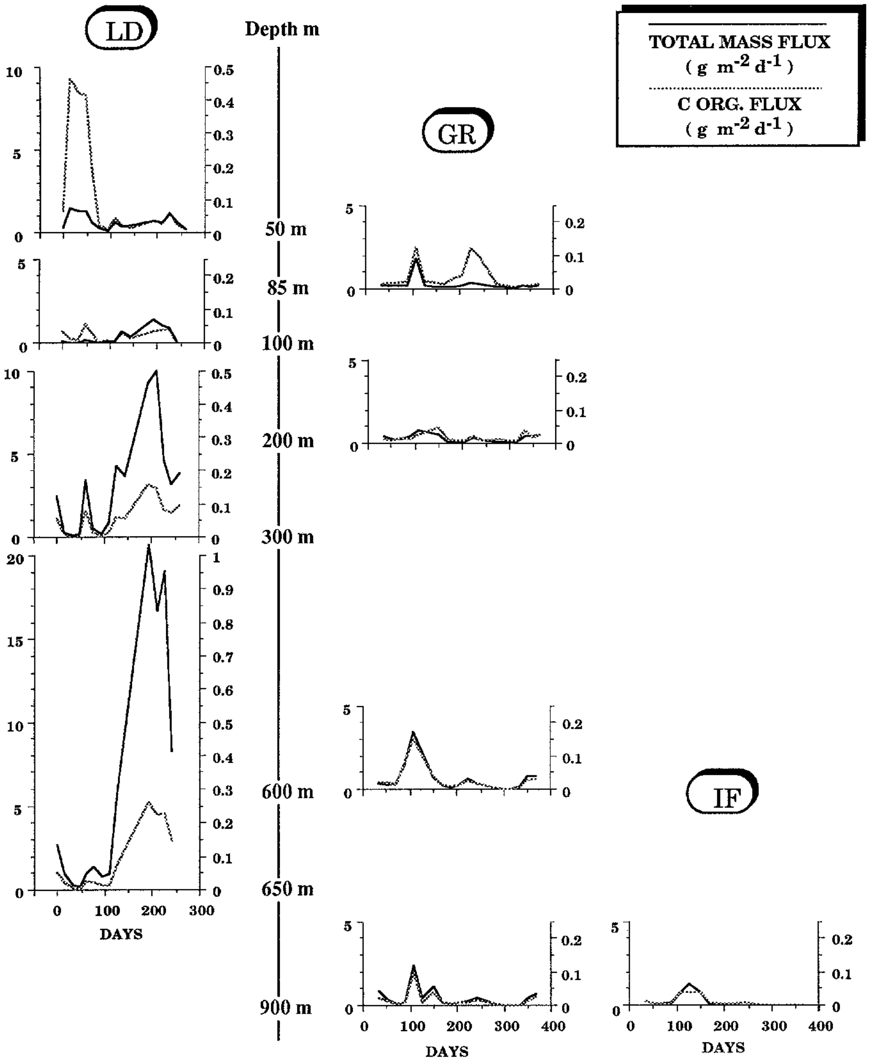

Figure 12.2 Time series plots of total mass (plain lines) and organic carbon (C_{org}) fluxes (dotted lines) at various locations and depths on the Mediterranean margin. LD: Lacaze-Duthiers Canyon; GR: Grand-Rhône Canyon; IF: open slope. See Table 12.1 for more details on mooring position and date of deployment.

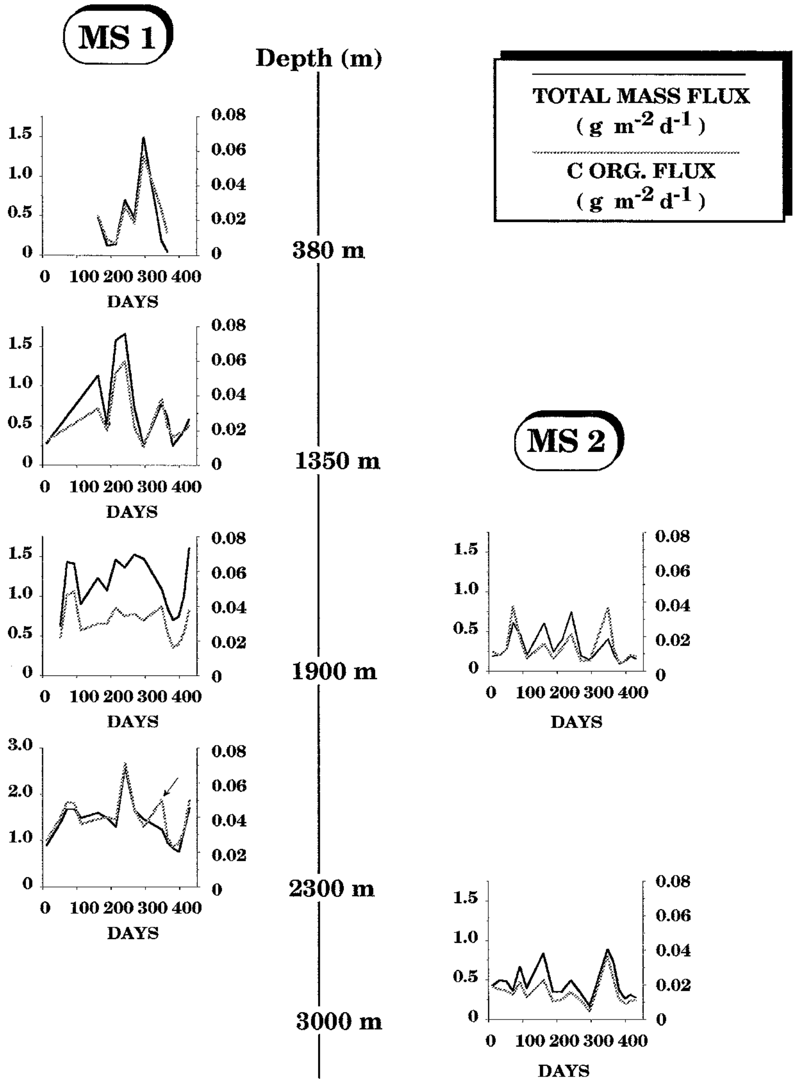

Figure 12.3 Time series plots of total mass (plain lines) and or ganic carbon (C_{org}) fluxes (dotted lines) at the two mooring sites on the Atlantic margin. MS1: Cap-Ferret Canyon, 2300 m; MS2: Cap-Ferret Canyon, 3000 m. See Table 12.1 for more details on mooring position and date of deployment.

12.3.3 BIOGEOCHEMISTRY OF SURFICIAL SLOPE SEDIMENTS

Both the northwestern Mediterranean and northeastern Atlantic margins are characterized by similar C_{org} distributions within the sediments and by high sedimentation rates, which underline the role of margins as preferential accumulation areas for organic matter. Organic content in the slope sediments are, in fact, high in comparison to those observed on the shelf, or in deep-sea fans and deep ocean sediments: on the Mediterranean side, 6–9 mg g^{-1} in the muddy deposits of the canyon, and 2–5 mg g^{-1} in circalittoral muds and silts or deep-sea fan sediments (Buscail et al., 1995); on the Atlantic side, 13–18 mg g^{-1} for muddy material from the Cap-Ferret Canyon, and 1–5 mg g^{-1} for sandy and silty sediments from the continental shelf (Etcheber et al., 1996). On a finer scale, in both margins, the highest C_{org} contents were found within an intermediate zone at the mid-slope depth (600–1300 m in the Mediterranean; 1500–2000 m in the Atlantic). The complex bathymorphology of the slope and the general circulation of water masses can induce the observed gradients in the distribution of high contents in sedimentary C_{org} (Buscail and Germain, 1995; Etcheber et al., 1996): for example, the canyon axes are enriched in comparison to the adjacent open slopes in the Mediterranean Sea.

Another feature common to both margins is the high sedimentation rates calculated from ^{210}Pb activities: 0.19 cm y^{-1} in the NE side of the Lacaze-Duthiers Canyon (Buscail et al., 1996); 0.37 cm y^{-1} at the head of the Cap-Ferret Canyon and 0.20 cm y^{-1} at 2300 m (Radakovitch and Heussner, 1996). These values are probably overestimated, due to bioturbation processes, but they yield, as a first approximation, the same high C_{org} accumulation rate, on the order of 10 g C m^{-2} y^{-1} at 2300 m in Atlantic, and at 650 m in the Mediterranean.

Besides these similarities between the two margins, there are also a some marked differences. On the northwestern Mediterranean margin, a seasonal response of the surface sediment to the near-bottom organic fluxes was observed (Figure 12.4). The amount of C_{org} increased progressively in the first centimeter of sediment during autumn and winter. During spring, one extra milligram of C_{org} was found to be stored per gram of sediment (Buscail et al., 1990). During this period, organic matter became increasingly more labile. The increase of amino acids was five-fold and sugars increased by a factor of 1.2. These values were well correlated with near-bottom C_{org} fluxes, which increased by a factor of 10 during this period (from 21 to 217 mg C_{org} m^{-2} d^{-1}). Between summer and the following winter to early spring period, amino acid and sugar fluxes increased respectively from 5 to 170 mg m^{-2} d^{-1} and from 3 to 28 mg m^{-2} d^{-1}. These inputs of labile material explain the increasing biodegradability of organic matter observed within the surficial sediments. Seasonal variations were also observed at DYFAMED station 2, located much deeper, at 2300 m: an increase of the C_{org} content was found between winter and early spring (from 5.3 to 6.8 mg g^{-1}). During the following periods, a gradual increase of C_{org} content was observed from spring

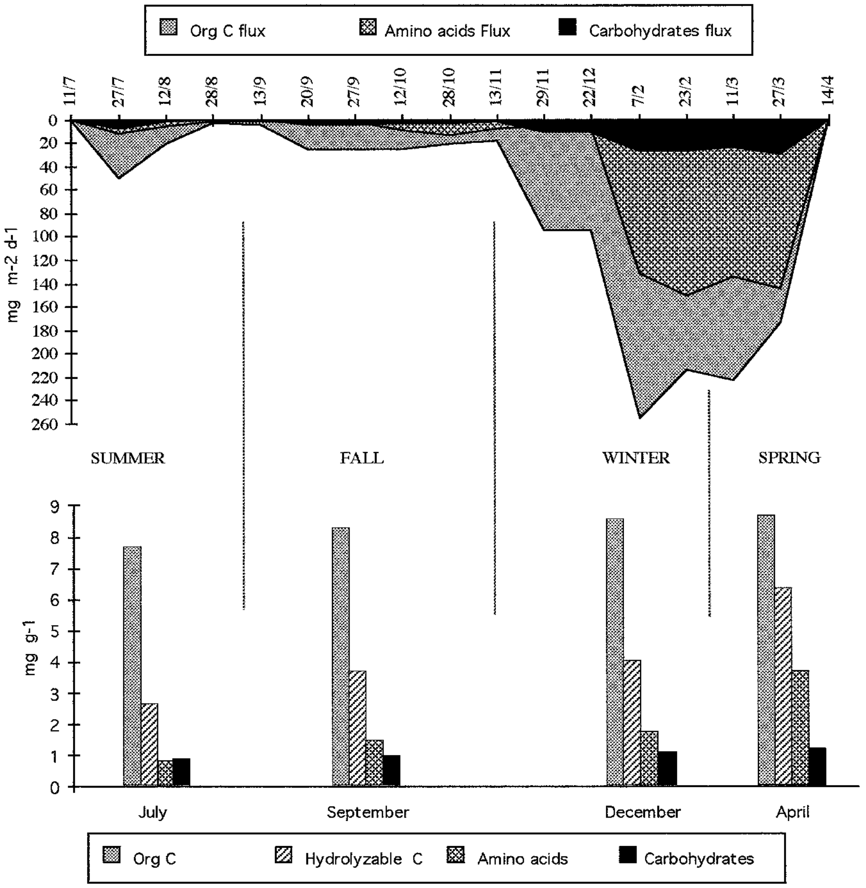

Figure 12.4 Time series plots of organic constituents fluxes in the near-bottom trap (600 m) of the Lacaze-Duthiers site (NW Mediterranean) (upper Figure) and contents of the same in the underlying surficial sediments (lower Figure).

(6.0 mg g^{-1}) to summer (6.6 mg g^{-1}) and autumn (7.3 mg g^{-1}) (Buscail, unpublished data).

On the contrary, the Atlantic margin, presents no marked seasonal variations in the organic fraction of surficial sediments. The biochemical characteristics of surficial sediments in the Cap-Ferret Canyon remained relatively constant over the year: surficial C_{org} contents and even protein concentrations in the first millimeter sediment did not reveal any significant seasonal trend (Etcheber et al., 1996).

Another important difference between both margins concerns the remineralization activity within the surficial sediments, which was less important on the Atlantic side. This is seen in the ratio between C_{org} content in particles of the near-bottom sediment traps (30 mg g $^{-1}$ on average on the Atlantic margin and 18 mg g^{-1} on the Mediterranean margin) and surficial sediments (18 mg g $^{-1}$ in the first millimeter at the Atlantic site and 8 mg g $^{-1}$ at the Mediterranean site) is 1.7 in the Cap-Ferret Canyon (Etcheber et al., 1996) and reaches 2.2 on the Mediterranean margin (Buscail et al., 1990; Buscail, 1991).

The input of natural organic matter at the sediment-water interface was simulated by injection of ^{14}C-labelled diatoms (*Navicula incerta*) in the overlying water of sediment cores. When comparing incubation experiments on the Atlantic and Mediterranean margins, the main differences are the lower quantity of CO $_2$ and the lower proportion of metabolites released in overlying waters of cores from the Cap-Ferret Canyon compared to those sampled within the Rhône Canyon (Figure 12.5) (Buscail, 1992; Buscail and Guidi-Guilvard, 1993). Metabolic processes responsible for the release of dissolved organic matter are clearly less pronounced on the Atlantic side, while the proportion of ^{14}C incorporated into sediments from the Cap-Ferret Canyon is higher than for the Rhône Canyon. This lower degradation activity at the Atlantic sediment-water interface can be related

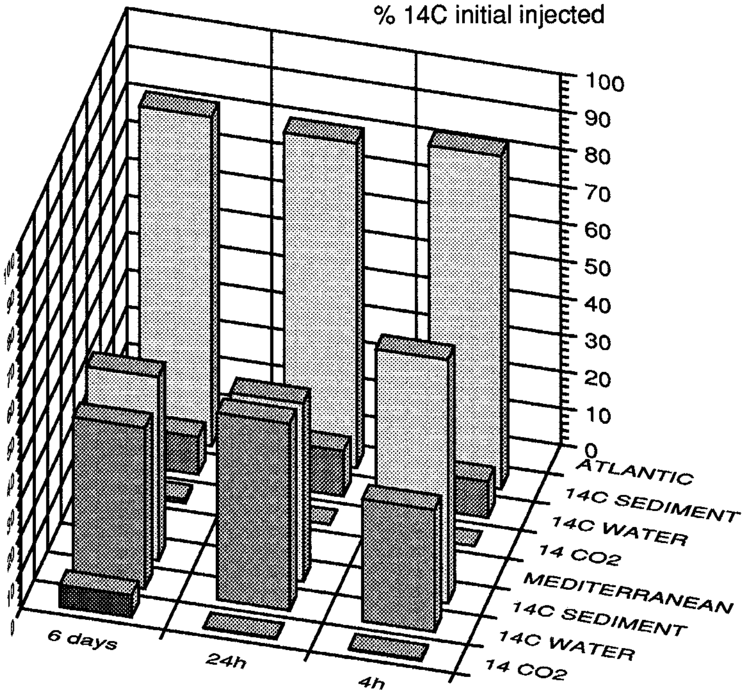

Figure 12.5 Distribution, after various periods of incubation, of ^{14}C-labelled diatoms (*Navicula incerta*), as per cent of the amount of ^{14}C initially injected in the water overlying surficial sediment cores.

to the low temperature of bottom waters (3°C) compared to 13°C in the deep Mediterranean waters and also to a less abundant benthic biomass in the Atlantic compared to the Mediterranean sea (De Bovée et al., 1990; Dinet et al., 1993).

12.4 DISCUSSION

Several features of the overall functioning of these two French margins can be drawn from the data on total mass, organic fluxes and quality of sedimentary organic matter, summarized in Table 12.3.

Table 12.3 Major characteristics of the French northwestern Mediterranean and northeastern Atlantic continental slopes with respect to mesoscale water dynamics, particle flux pattern and sediment response.

Environmental characteristics	Mediterranean Site	Atlantic Site
Alongslope water circulation	persistent unidirectional	fluctuant bidirectional
Flux pattern on the slope	depth increase seaward decrease advection-dominated	
Sources	direct seasonal pulses terrigenous >> marine	delayed periodic, non seasonal pulses terrigenous >> marine
Sedimentary record	strong seasonality stronger biodegradation of organic matter	no seasonality weaker biodegradation of organic matter

12.4.1 IMPORTANCE OF DYNAMICAL FACTORS ON THE TRANSFER OF PARTICLES

The general circulation of water masses is a predominant factor, if not the most important one, controlling the distribution of suspended and settling particles in the margin environments studied during ECOMARGE. Indeed, in the northwestern Mediterranean, some important features observed during our experiments could be linked to the cyclonic Liguro-Provençal Current (L-PC), which follows the continental slope from the coast of Provence to the Catalonian Sea (Millot, 1990). The seaward extension of turbid layers was directly controlled by the position of the L-PC. This current closely follows the shelf break in the northeast (entrance), but moves progressively further offshore in the southwestern part (exit) of the Gulf of Lions. This shift induced an increase of suspended particles (by a factor of 7) between the entrance and the exit of the Gulf of Lions (Durrieu de Madron et al., 1990). Total mass fluxes increased by roughly the same factor between the GR and LD canyons (Monaco et al., 1990b).

The general circulation is quite more complex on the Atlantic side, but several physical processes with different temporal variabilities were recognized as playing a role in particle distribution and fluxes (Castaing et al., 1996a, b; Durrieu de Madron et al., 1996; Heussner et al., 1996). Seasonal thermohaline fronts, located either on mid-shelf during winter or at the shelf break during summer, definitely represent a dynamical barrier reducing seaward transfer of shelf particles, as demonstrated by shelf nepheloid structures (Durrieu de Madron et al., 1996); on the contrary, particle transport towards the slope could be enhanced during the transitional periods of front formation (late spring) and disappearance (fall). Hydrodynamic processes, associated with these fronts (i.e., internal waves, eddies, upwelling), participate in the transfer of particulate matter. On the continental slope, inside the canyon, recorded speeds were linked to cycles of semi-diurnal and lunar tides, and they varied accordingly. Residual speeds were low (< 2 cm s^{-1}) and always directed upslope, a feature which tends to confine particles in the upper canyon, where the quiet environment favors deposition. Above 600 m, the alongslope residual flow was preferentially to the north, but sudden, occasional changes resulted in southward currents. Most of the particle sources are therefore to be sought in areas south of the experimental sites (see below). Below 600 m, residual flow of the different water masses were generally directed northward and residual speeds were low (around 2 cm s^{-1}).

12.4.2 IMPORTANCE OF ADVECTION

Particle flux increase with depth is one of the most characteristic features of continental margins (e.g., Biscaye et al., 1988; Monaco et al., 1990a; Biscaye and Anderson, 1994; Heussner et al., 1996). The phenomenon is more or less marked at the different sites. The intensity of the flux increase with depth depends on the location on the slope; i.e., with the intensity and position of the general alongslope circulation and the position of particle sources. On the Mediterranean margin, the depth effect increases from the GR to LD sites: at similar depths, advection becomes more important in the downstream direction. This effect could not be studied on the Atlantic margin as only one transect was used. On both margins also, the importance of advective inputs decreased seaward (Monaco et al., 1990b; Heussner et al., 1996); such a decrease can be considered as a quite common feature of particle fluxes on continental margins, as it was also observed in other experiments such as SEEP-I and SEEP-II in the Middle Atlantic Bight (Biscaye et al., 1988; Biscaye and Anderson, 1994). According to the intensity of advective processes, margins can be classified into two categories (Heussner et al., 1993): "oceanic" margins, which are characterized by a C_{org} flux decreasing with depth (e.g., the GR site) similar to open ocean systems (e.g., the DYFAMED sites), and "continental" margins, which are characterized by an important C_{org} flux increase at depth (e.g., the LD, MS 1 and MS 2 sites)

By examining the spatial and temporal characteristics of mass and major constituent fluxes in the light of prevailing hydrodynamical conditions, Heussner (1995) and Heussner et al. (1996) proposed a scenario of particle transfer in the Cap-Ferret Canyon, which helps to understand how advection operates. The model takes into account recent considerations about particle transfer and trap measured fluxes (e.g., Heussner and Fowler, 1987; Siegel et al., 1990), the general circulation of slope water masses (Durrieu de Madron et al., 1996), and the main features of the flux pattern, namely a flux increase with depth at each mooring and seaward decrease between the two mooring sites. Particle trajectories are oblique, since they are mainly controlled by the motion of alongslope flowing water masses. All particles arriving at depth on the slope are therefore advected from an "upstream" source. The two mooring sites are working in parallel, which means that there is no direct transfer between MS1 and MS2. Fluxes are higher at MS1 because of a seaward decreasing gradient in the particle concentration within the source. The fact that fluxes increase with depth at each mooring results from a limited horizontal extension of the source and/or from a downstream decreasing gradient in the particle concentration of the source. Progressive discharges of the settling particles through the water column, as the water masses move downstream, leads to more particles reaching the deep traps compared to the shallow ones. This scenario was further improved by Radakovitch and Heussner (1996), who recognized two major sources, on the basis of a mass balance budget for ^{210}Pb, in this region. One is located in shallow waters from the outer shelf and upper slope (<380 m; i.e., the depth of the shallowest trap of MS1) and supplies the entire slope region (i.e.; MS1 and MS2). The second, probably located deeper (at depths between 380 and 1350 m), feeds only the upper and intermediate slope region (i.e.; MS1, but not MS2). The fact that the major constituents (i.e.; organic and inorganic carbon, biogenic silica, lithogenic fraction) of the trapped particles at depth exhibit a relative temporal constancy indicates that both sources represent quite homogenous particle stocks which could be dominated by resuspended material.

12.4.3 SEASONAL VARIABILITY

Seasonal variability of mass fluxes can be linked to climatic and biological factors (Monaco et al., 1990b): at the exit of the Gulf of Lions (LD site), two winter peaks at 300 m and 600 m depth coincided with storms and continental rainfall events registered at the shelf site. Secondary peaks, observed in July (both depths) or in Mid-September (300 m), enriched in C_{org}, were mainly composed of biogenic constituents and related to surface phytoplankton blooms.

On the Atlantic site, at any depth, particle fluxes did not reveal any clear seasonal trend. Direct signals from phytoplanktonic blooms were nevertheless recognized, even in the deep traps, but were not large enough to significantly affect the overall variability of the bulk material (Beaufort and Heussner, 1996). Advection of large amounts of particles, with a strong resuspension and/or continental origin, from the above-mentioned shelf and upper slope sources diluted the primary biogenic signal. Thus, it is less easy to determine the lack of seasonal trend in the lithogenic contribution. One possible explanation lies in the dimensions of the margin: the distance from the main continental sources (the Gironde estuary essentially and other southern sources), which exhibit strong seasonal variations, could prevent direct inputs of material to the slope (Ruch et al., 1993). Continental inputs do not arrive at the slope as directly as in the Gulf of Lions. Sedimentation of particles onto the shelf and upper slope sediments followed by subsequent resuspension and transport by the general alongslope circulation of water masses could level out the original seasonal variations of the continental sources.

12.4.4 BENTHIC RESPONSE TO ORGANIC PARTICLE FLUXES ON MARGINS

Some interesting points can also be derived from the comparison of the distribution of sedimentary organic matter between the two margins, and from the biogeochemical processes observed within the surficial sediments.

First, the combination of high sedimentation rates and high C_{org} contents leads to the conclusion that such environments are preferential C_{org} accumulation areas (Buscail et al., 1990; Etcheber et al., 1996).

Second, the Lacaze-Duthiers Canyon presents some important erosion zones on the flanks, characterized by low C_{org} content, and areas of high sedimentation rates and high C_{org} concentrations within the canyon axis (Buscail and Germain, 1995). Such local differences within the canyon do not exist in the Cap-Ferret Canyon (Etcheber et al., 1996). This feature seems to be related to the general morphology of these canyons: the smaller the size, the greater the spatial and temporal distribution heterogeneities of sedimentary organic matter. Complex interactions of bottom topography with the general circulation could be responsible of these size effects.

Third, the bottom water temperature seems to have a direct influence on the intensity of organic matter degradation processes at the sediment-water interface: the higher benthic activity on the Mediterranean margin, compared to the Atlantic, could be related to the warmer bottom water temperature (13°C vs. 3°C) (Buscail, 1992; Etcheber et al., 1996). C_{org} budgets drawn for both margins nevertheless reveal that important amounts of C_{org} are buried in these areas (Buscail et al., 1990; Etcheber et al , 1996), which can be therefore considered as preferential sinks for organic carbon.

Finally, benthic populations from canyons (especially meiofauna) of both margins are more abundant than on open slope areas. This fact proves the fertile nature of the canyons, where direct response of benthic fauna to changes in particle supply was observed (Monaco et al., 1990a; Dinet et al., 1993).

12.4 CONCLUSIONS

From the comparison of Atlantic and Mediterranean margins presented here, several conclusions can be drawn on particle flux on continental margins and on the organic carbon cycle, in particular. Some of the following conclusions are still quite tentative, or strictly applicable to our study sites and would need to be further refined for general use.

1. The general circulation of water masses (physical factor) represents a major forcing function of the spatial and temporal variability of particle transfer in these two environments. Its effect is modulated by seasonal changes of continental inputs (climatic factor) and marine productivity (biological factor).
2. Particle fluxes through the slope water column exhibit a pattern typical of continental margins, namely a seaward flux decrease and a downward flux increase.
3. Seasonal variability is less pronounced in the case of the Atlantic margin. On the contrary, the Mediterranean margin presents important seasonal changes in fluxes, with minimum values during summer and highest values during winter.
4. Advection plays a prominent role in the transfer of matter and energy on these margins; on the basis of organic carbon flux profiles through the water column a functional distinction can be made between "continental" (strong flux increase with depth) and "oceanic" (constant flux or even decrease with depth) margins.
5. There is an enrichment of sedimentary organic carbon in these margins, which are further characterized by high sedimentation rates and enhanced biological activity.
6. Distance from the continental sources (i.e., rivers) and morphology have a direct influence on spatial and temporal heterogeneity of the biochemical characteristics of sedimentary organic matter; futhermore, water temperature seems to play a direct role on its degradation at the sediment/water interface.

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