Particulate flux
Continental margin
Northwestern Mediterranean
Fecal pellets
Trace elements

Flux particulaire
Marge continentale
Méditerranée nord-occidentale
Pelotes fécales
Éléments traces

ECOMARGE : flux of particulate matter in the Northwestern Mediterranean (golfe du Lion)

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ABSTRACT

As part of the multidisciplinary programme ÉCOMARGE (ÉCOsystème des MARGEs continentales) an experiment to measure vertical flux of particles was carried out in the golfe du Lion off Banyuls-sur-Mer (Lacaze-Duthiers canyon) over a period of 17 days in autumn 1983. Sediment traps were deployed at depths of 100, 200 and 315 m in a water column 350 m deep. The trapped material appeared to consist of fine muddy sediment and numerous biogenic debris. Total mass flux increased linearly with depth from ~ 4 g m^{-2} day^{-1} at 100 m to ~ 13 g m^{-2} day^{-1} at 315 m. The lithogenic fraction was predominant at all depths (55 to 60 % of total mass flux). Trap-collected fecal pellets were categorized by different shape classes and enumerated. Mass calculations showed that intact pellets accounted for only a small proportion (~ 5 %) of the total mass flux at the 3 depths. Sequential leaching of trapped particles showed that Cu was essentially associated with the organic phase, Mn with carbonates and Fe with hydroxides. Measurements of thorium isotopes gave concentrations and ratios typical of suspended terrigenous particles. Based on these results, we suggest that the Lacaze-Duthiers canyon acts as a site of concentration for particles imported into the region by currents (advective transport) mixed with particles produced at the trap site (vertical transport). This particulate material is then transferred to the deep basin.

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RÉSUMÉ

ÉCOMARGE : flux de matière particulaire en Méditerranée (golfe du Lion)

Dans le cadre du programme pluridisciplinaire ÉCOMARGE (ÉCOsystème des MARGEs continentales), une expérience de mesure de flux particulaires a été menée pendant 17 j dans le golfe du Lion, au large de Banyuls-sur-Mer (canyon Lacaze-Duthiers), à l'automne 1983. Des pièges à particules ont été placés à 100, 200 et 315 m au-dessus d'un fond de 350 m. Le matériel particulaire récolté consiste en une vase fine associée à de nombreux débris biogènes. Les flux particulaires présentent une augmentation linéaire avec la profondeur de 4 g m^{-2} j^{-1} environ à 100 m à 13 g m^{-2} j^{-1} environ à 315 m. La fraction lithogène est prédominante aux trois profondeurs (55 à 60 % du flux de masse total). Les pelotes fécales collectées par les pièges, classées par catégories de forme, ont été dénombrées. La contribution

de ces particules biogènes au flux de masse total est estimée à 5 % environ. Une attaque chimique sélective du matériel particulaire a montré que Cu est essentiellement associé à la phase organique, Mn aux carbonates et Fe aux oxyhydroxydes. Les mesures concernant certains isotopes du thorium fournissent des valeurs et des rapports typiques de matériel terrigène en suspension. Le canyon Lacaze-Duthiers paraît, au vu de ces résultats qualitatifs et quantitatifs, fonctionner durant la période d'étude comme un site de concentration des particules amenées par les courants (transfert advectif) et des particules produites dans la zone du site expérimental (transfert vertical). Ce matériel d'origine mixte serait ensuite acheminé vers le bassin profond.

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INTRODUCTION

During the past decade, a major effort in oceanography has focused on studying the question of material and energy transport to the ocean depths. The rapid development of adequate *in situ* sampling techniques (sediment traps, large volume particle pumps, etc.) has made it possible to obtain sufficient particulate material to examine rigorously large particle sedimentation processes in the water column (for review *see* Simpson, 1982 ; Angel, 1984 ; Fowler, Knauer, 1986). For example, research in sedimentology and geochemistry has sought a better understanding of the mechanisms of particle transport and sedimentation processes in deep ocean basins. In the biological context, a principal aim has been to discern the transfer of energy from the ocean surface to depth and its eventual utilization by benthic species.

With the above-mentioned objectives in view, a multidisciplinary research programme was developed to study the ECOsystems of continental MARGins (ECOMARGE). The overall aim of the programme is to understand better the continuity and periodicity of particulate sedimentation processes which occur on the Pyrenees-Catalonia continental margin. This approach includes examining terrigenous inputs from the adjacent land mass, and the processes in the transfer zone (the shelf and its canyons) and the region of ultimate deposition (ocean basin and plains). Most similar studies to date have taken place either in the open ocean or in the nearshore coastal zone. It is therefore essential to study particulate transport processes along the margins in order better to understand material transfer to the open basins. Within ECOMARGE two main objectives have emerged :

1) to determine qualitative and quantitative aspects of the vertical and lateral components of particulate flux, and to examine temporal variability of the fluxes ;

2) to determine the consequences of particulate flux on species diversity and the energetics and dynamics of benthic populations. The preliminary results reported here are from an ECOMARGE pilot experiment during autumn 1983 and pertain only to the first objective.

MATERIAL AND METHODS

Location and sampling methods

The site chosen for the pilot study is situated at the head of the Lacaze-Duthiers canyon (42°35'20" N-3°23'45" E, depth 350 m) roughly 12 miles off Banyuls-sur-Mer (Fig. 1). An anchored mooring

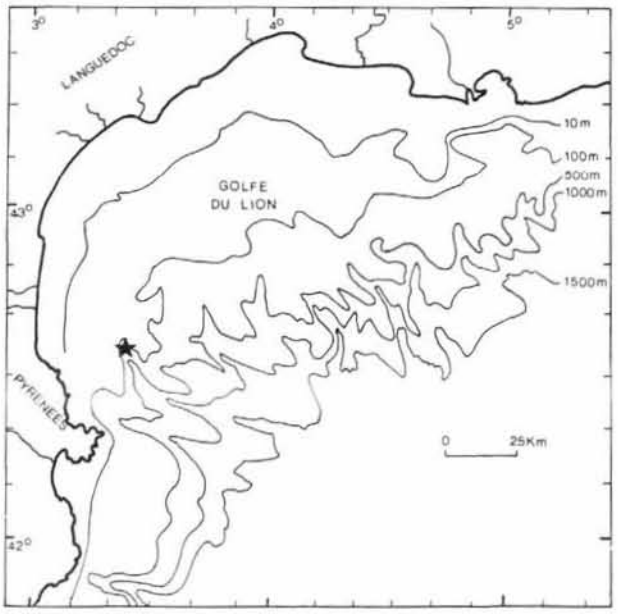

Figure 1
Bathymetric chart of the Gulf of Lion (NW Mediterranean) and location of sediment-trap site in the Lacaze-Duthiers canyon.
Carte bathymétrique du golfe du Lion (Nord-Ouest Méditerranée) et localisation du site des pièges dans le canyon Lacaze-Duthiers.

equipped with an acoustic release and subsurface flotation contained three particle traps at 100, 200 and 315 m as well as an Aanderaa current meter 30 m above the sea floor (Fig. 2). The particle traps are a modified cylindrical type (Model PP3, Technicap) with a surface area of 0.125 m^2 and a height/diameter ratio of 2.5. The body of the trap, a single piece of polyester resin fiber glass on gel-coat, is equipped with a metal support to assure constant alignment with the mooring. A flotation collar of syntactic foam

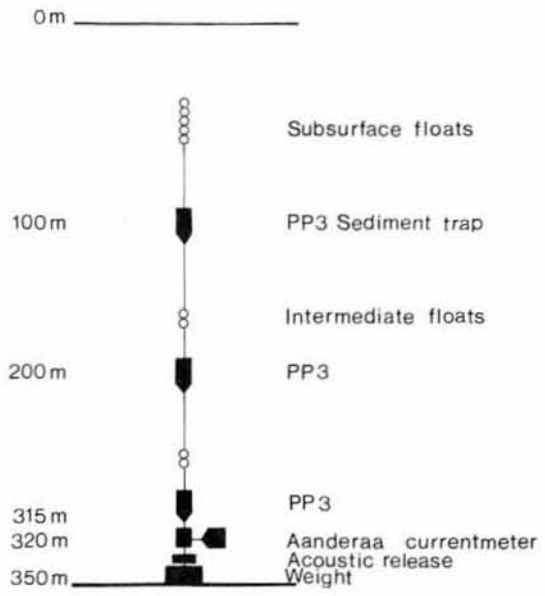

Figure 2
Simplified diagram of sediment-trap mooring configuration.
Schéma simplifié de la ligne de mouillage des pièges à particules.

gives the trap neutral buoyancy in sea water. The teflon collection cup (500 ml) contains a perforated diffuser which slowly releases concentrated (40 %) buffered formalin. The collector is opened and closed manually by nylon cords when the trap is at the surface. The traps were deployed for 17 days between 19 September-6 October 1983.

Laboratory analyses

Particulate material collected at each depth was apportioned with the aid of a Folsom splitter and each aliquot used for various analyses. Weight determinations were made by filtering aliquots through 0.45 μm Millipore filters, rinsing with distilled water and drying for more than 12 h at 60 °C. Biogenic and lithogenic fractions were measured following the method adopted by Honjo *et al.* (1982). Total granulometry was determined by means of a Sedigraph 5000. Qualitative determination of biogenic constituents and enumeration and measurements of fecal pellets were made using a stereoscopic microscope equipped with a calibrated grid. Only intact fecal pellets with a recognizable shape were considered.

The extraction of trace metals (Cu, Mn and Fe) was made by the following sequential and selective leaching techniques :
1) oxidation with H_2O_2 (30 vol) for metals associated with organic matter ; 2) attack with unbuffered CH_3COOH (35 %) for metals associated with carbonates ; 3) attack with $NH_2OH + CH_3COOH$ for metals associated with oxyhydroxides. Leaching with acetic acid and a mixture of acetic acid and hydroxylamine are adapted from the method of Chester and Hughes (1967). The extracted metals were subsequently analyzed by atomic absorption spectrophotometry.

Natural series thorium radionuclides (^{228}Th, ^{230}Th, and ^{232}Th) were extracted by standard techniques and analyzed by alpha spectrometry (Bojanowski *et al.*, 1983).

RESULTS

Hydrodynamics

Current-meter reading 30 m above the bottom indicated the existence of a weak current, oriented along the axis of the caynon towards the southeast, with an average velocity of the order of 1.5 cm s^{-1}. This very low value was just at the limit of resolution for the current meter. However, current measurements also showed the relatively large importance of inertial oscillations (frequency ~ 17.5 h) which resulted in alternating currents with speeds as high as 10 to 15 cm s^{-1}.

Characterization of particulates

The particulate material collected in the three traps was flocculent and appeared visually to consist of a fine, muddy sediment. However, microscopic examination revealed the presence at each depth of considerable biogenic debris, notably partial or whole planktonic crustacean molts (principally those of copepods), phytoplankton remains (diatoms and coccolithophores) and intact zooplankton fecal pellets. The planktonic debris was closely associated with mineral grains and layered silicates which were often in the midst of fecal pellet fragments. The median grain size of the inorganic particles, freed of organic detritus by H_2O_2 attack and disaggregated by ultrasonic treatment, was approximately 1 μm at 100 and 200 m. A slight increase in median grain size (~ 1.2 μm) was noted in material from the deepest trap.

Mass flux

The particulate mass fluxes expressed as grams dry per square metre per day (g m^{-2} d^{-1}) are listed in Table 1. They increase linearly with depth from 3.99 g m^{-2} d^{-1} at 100 m to 12.96 g m^{-2} d^{-1} at 35 m above the bottom. This increase in flux with depth indicates a supplementary input of particulates in the

Table 1
Total mass fluxes and percent contribution of lithogenic and biogenic fractions.
Flux de masse et contributions relatives des fractions lithogène et biogène.

Trap depth (m)	Mass flux (g m^{-2} d^{-1})	Lithogenic fraction (%)	Biogenic fraction (%)
100	3.99	54.5	45.5
200	7.68	58.1	41.9
315	12.96	60.5	39.5

intermediate (100-200 m) and deep (200-315 m) layers with respect to the top 100 m. This could result from a combination of *in situ* production of particulate material in the deeper layers (fecal pellets and other planktonic debris) and lateral advective transport originating from outside the study site.

The major constituents of the particulate material have been grouped into two fractions : lithogenic and biogenic (Tab. 1). The lithogenic fraction (54.5-60.5 %), composed of quartz, feldspars and clays, is predominant at the three depths. The biogenic fraction is comprised of organic material, biogenic silica and carbonates, and its relative importance decreases slightly with depth.

Fecal pellet flux

Discerning the contribution of biogenic particulates, particularly zooplankton fecal pellets, to total mass flux is one of the principal objectives of the ECOMARGE programme. These large particles, varying in size from a few to several hundred μm, sink rapidly (10^2-10^3 m d^{-1}) and thus contribute substantially to the downward mass flux of elements and compounds (Angel, 1984 ; Fowler, Knauer, 1986).

Intact fecal pellets (FP) were counted and grouped into three shape-classes (Tab. 2). Fecal pellet flux was relatively high and increased almost linearly with depth from 2.3×10^6 pellets m^{-2} d^{-1} at 100 m to 7.4×10^6 m^{-2} d^{-1} at 315 m. This increase in numerical flux shows that planktonic organisms produce fecal pellets throughout the entire water column at this site. Cylindrical fecal pellets which originate from euphausiids and large calanoid copepods (Marshall, Orr, 1956 ; Fowler, Small, 1972 ; Paffenhöfer, Knowles, 1979) represented approximately 5 % of the total number of pellets. The mean volume of these pellets, calculated from size measurements ($n = 60$), was 5.65×10^5 μm^3. Smaller elliptical pellets produced mainly by copepods (Marshall, Orr, 1955 ; 1956 ; Sasaki, Nishizawa, 1981) were far more numerous and comprised 60-70 % of the total and the mean volume was 3.65×10^5 μm^3. Spherical pellets, the origin of which at present is unknown, accounted for the remaining 25-35 %, with a mean volume of 1.90×10^5 μm^3.

Using the mean volumes coupled with the relative frequency of each fecal pellet shape category at each depth (Tab. 2), a pellet wet density value of 1.22 g cm^{-3} (Komar *et al.*, 1981) and a wet/dry ratio of 4.4 (Fowler, 1977) the mass fluxes of fecal pellet can be calculated (Tab. 3). These results indicate that intact fecal pellets (*i.e.* identifiable fecal matter) comprised only about 5 % of the total mass flux measured by the traps.

Table 2
Fecal pellet (EP) *fluxes and percent contribution of fecal pellet shape classes.*
Flux de pelotes fécales (PF) et importance relative des différentes catégories de formes.

Trap depth (m)	FP Flux (FP m^{-2} d^{-1})	Categories of shapes of pellets (%)		
		Cylindrical	Elliptical	Spherical
100	2.3×10^6	5.7	59.4	34.9
200	5.2×10^6	5.9	61.6	32.5
315	7.4×10^6	4.3	70.1	25.6

Trace metal flux

To examine further possible sources of the particulate material, aliquots were analysed for selected trace metals and natural series radionuclides. Among the trace metals, Cu, Mn and Fe were chosen because they readily partition between the particulate and soluble phases and are thus useful as geochemical tracers (Bruland, 1983). Furthermore, these metals have been analysed previously in sediment cores from the same region (Monaco *et al.*, 1982 ; Fernandez, 1984).

In general, the results in Table 4 indicate a relatively clear geochemical specificity. Cu is mainly associated with organic material and oxyhydroxides, Mn with carbonates, and Fe with oxyhydroxides and to a lesser degree carbonates. Changes in concentrations of the three elements at different depths, particularly Cu bound to organics and Fe and Mn associated with oxyhydroxides, permit readily distinguishing surface-derived material from that collected at depth. Corresponding leachable metal fluxes for these elements indicate that Cu decreased while Mn and Fe increased substantially at depth (Tab. 4). The increases in Mn and Fe flux with depth resulted from corresponding increased mass flux, since total leachable concentrations of these metals in the particles remained essentially constant with depth. It is also noteworthy that total leachable fluxes for Cu, Mn and Fe through 100 m were approximately 20, 12 and 2.5 times greater, respectively, than average total metal fluxes measured through the same depth at a nearshore

Table 3
Fecal pellet mass fluxes and relative contribution to the total mass fluxes.
Flux de masse des pelotes fécales et contributions relatives aux flux de masse totaux.

Trap depth (m)	Fecal pellet mass flux (mg m^{-2} d^{-1})				FP Contribution to total mass flux (%)
	Cylindrical	Elliptical	Spherical	Total	
100	20.6	138.0	42.6	201.2	5.0
200	48.2	323.5	89.6	461.3	6.0
315	50.0	523.9	100.4	674.3	5.2

Table 4
Trace metal concentrations ($\mu g\ g^{-1}$ dry) *in the different leachable phases of trapped particulate material* (1 : *organic matter* ; 2 : *carbonates* ; 3 : *hydroxides) and corresponding total leachable metal fluxes* ($\mu g\ m^{-2}\ d^{-1}$).
Teneurs en métaux-traces ($\mu g\ g^{-1}$ sec) dans les différentes phases de matériel particulaire collecté (1 : matière organique ; 2 : carbonates ; 3 : oxyhydroxydes) et flux totaux de métaux traces correspondants ($\mu g\ m^{-2}\ j^{-1}$).

Trap depth (m)	Cu				Mn				Fe			
	1	2	3	Flux	1	2	3	Flux	1	2	3	Flux
100	44	29	56	514	178	920	109	4 816	7	2 060	9 410	45 792
200	14	14	44	551	176	847	41	8 172	13	3 810	2 375	47 597
315	2	17	6	323	165	919	25	14 373	10	2 283	3 280	72 226

Table 5
Thorium activities (dpm g^{-1} dry) *in trapped particulate material and corresponding fluxes* (dpm $m^{-2}\ d^{-1}$).
Activités du thorium (dpm g^{-1} sec) dans le matériel particulaire collecté et flux correspondants (dpm $m^{-2}\ j^{-1}$).

Trap depth (m)	^{232}Th		^{230}Th		^{228}Th	
	Activity	Flux	Activity	Flux	Activity	Flux
100	1.8 ± 0.1	7.1 ± 0.4	2.1 ± 0.1	8.4 ± 0.4	3.7 ± 0.1	14.6 ± 0.5
200	2.1 ± 0.1	16.4 ± 0.8	2.1 ± 0.1	16.0 ± 0.8	3.8 ± 0.1	29.2 ± 1.0
315	1.9 ± 0.1	25.2 ± 1.3	2.8 ± 0.2	35.9 ± 2.1	4.5 ± 0.3	58.1 ± 3.3

station in the Ligurian Sea off Monaco (Fowler, 1985). The large difference in metal flux between the two areas is due primarily to much higher mass flux observed in the golfe du Lion during the ECOMARGE experiment.

Activities of thorium isotopes in material collected at the three depths are presented in Table 5. The relatively uniform concentrations at the different depths suggest a similar origin for the majority of the particulate material. ^{232}Th activities, ranging between 1.8 and 2.1 dpm g^{-1} dry, are typical of those found in suspended clays and sediments. Furthermore, the relatively low $^{228}Th/^{232}Th$ ratios (~ 2) are characteristic of those measured in near shore suspended sediments (Spencer *et al.*, 1978). Taken together, these data indicate particulate input of essentially terrigenous origin at the site (Krishnaswami *et al.*, 1976 ; Brewer *et al.*, 1980).

DISCUSSION AND CONCLUSIONS

The particulate fluxes measured at the test site on the Pyrenean continental slope were 10 to 100 times higher than those observed by numerous authors in various oceanic areas (*see* Simpson, 1982). Although to a lesser extent, they were also higher than values measured at comparable depths in different coastal environments including the northwest Mediterranean (Wassmann, 1983 ; Baker, Milburn, 1983 ; Burns *et al.*, 1985). These elevated fluxes are most certainly a combined result of the proximity to the continent (12 miles), the morphology of the trap environment (canyon) and the relatively shallow depth at the site. The most notable aspect of these results is the linearity in the increase of flux with depth, which likely results from a constant large particle concentration over the depth range covered by the traps. This observation coupled with the sedimentological and geochemical characteristics of the particulates (*e.g.* predominance of lithogenic fraction and activities and ratios of thorium isotopes) indicates the presence of a thick nepheloid layer, the effect of which was evident even at the base of the euphotic zone (~ 100 m). The fact that the bottom current along the axis of the canyon was weak strongly suggests that the nepheloid layer was not formed by local resuspension, but rather originated from outside the canyon. The existence of a lateral component in particulate flux dynamics on the continental margin is supported by the work of Aloisi *et al.* (1979) which was carried out on the continental shelf of the golfe du Lion. These authors observed, during the presence of the thermocline, a benthic nepheloid layer which was spread uniformly over the shelf and entered the head of the canyons. Particles in this layer consisted primarily of organo-mineral flocs.

The presence of a substantial biogenic fraction (40 to 45 % of total mass flux), in particular large numbers of zooplankton fecal pellets, attests to the existence of a vertical component of flux. The relative importance of the vertical component can not be quantified in a rigorous manner from the available data. However, as a rough approximation, it is possible to fix a minimum contribution at 5 %, *i.e.* the fraction of total mass flux due to rapidly sinking fecal pellets. Likewise, the remaining lithogenic fraction (55-60 %) which is composed principally of terrigenous material could serve as a minimum estimate of laterally advected particulate material.

Based on the combined results, we can formulate a first hypothesis on particulate transport and flux which attempts to take into account the various

observations made to date. From its morphological characteristics, the area of the canyon studied appears to function as a natural sediment trap in which particles originating from the continental shelf or directly from the adjacent land-mass are transported laterally by advection of water masses and subsequently concentrate in the canyon waters. Added to this lateral input are the large, rapidly sinking biogenic particles whose transport through the water column possesses a large vertical component. The fate of the particles in suspension in the canyon, at least the finest fraction, would then depend upon the prevailing hydrodynamic conditions. At the time of the experiment, due to the presence of alternating near-bottom currents, the particles moved back and forth along the canyon, with a net resultant displacement towards the deep basin.

The present hypothesis is based on a single relatively short-term experiment carried out during the year. Since similar studies have demonstrated that particulate flux shows marked seasonal variability (Deuser *et al.*, 1981 ; Burns *et al.*, 1985), it will be necessary to examine our hypothesis over a longer interval of time. This is to be done by performing repetitive particle trap experiments under similar conditions as in the pilot study. Of equal importance will be an attempt to estimate energy input to the deep areas of the continental margin, its potential utilization by benthic fauna and the biogeochemical processes controlling organic compound transformation at the sediment-water interface.

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