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

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ABSTRACT

As part of the multidisciplinary programme ÉCOMARGE (ÉCOsysteme 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 (advecive transport) mixed with particles produced at the trap site (vertical transport). This particulate material is then transferred to the deep basin.


RÉSUMÉ

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

Dans le cadre du programme pluridisciplinaire ÉCOMARGE (ÉCOSystème des MARGés 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 Lacaize-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
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 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 m² 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
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 Sedi
graph 5000. Qualitative determination of biogenic
constituents and enumeration and measurements of
fecal pellets were made using a stereoscopic micro
scope equipped with a calibrated grid. Only intact
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 H2O2 (30 vol) for metals associated
with organic matter; 2) attack with unbuffered
CH3COOH (35 %) for metals associated with carbonates;
3) attack with NH2OH + CH3COOH for metals associated with oxides. Leaching with
acetic acid and a mixture of acetic acid and hydroxy
xylamine are adapted from the method of Chester and
Hughes (1967). The extracted metals were sub
sequently analyzed by atomic absorption spec
trophotometry.

Natural series thorium radionuclides (228Th, 230Th,
and 232Th) 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 canyon 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 exami
nation revealed the presence at each depth of con
siderable biogenic debris, notably partial or whole
planktonic crustacean molts (principally those of
copepods), phytoplankton remains (diatoms and coc
cololithophores) 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 H2O2 attack and disaggregated by ul
trasonic 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>
<thead>
<tr>
<th>Trap depth (m)</th>
<th>Mass flux (g m⁻² d⁻¹)</th>
<th>Lithogenic fraction (%)</th>
<th>Biogenic fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.99</td>
<td>54.5</td>
<td>45.5</td>
</tr>
<tr>
<td>200</td>
<td>7.68</td>
<td>58.1</td>
<td>41.9</td>
</tr>
<tr>
<td>315</td>
<td>12.96</td>
<td>60.5</td>
<td>39.5</td>
</tr>
</tbody>
</table>
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 (10^7-10^9 m d^{-1}) and thus contribute substantially to the downward mass flux of elements and compounds (Angel, 1984; Fowler, Knaur, 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^{-3} 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^{-3} 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^{-3} 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.

**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 increases in 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 2

Fecal pellet (FP) fluxes and percent contribution of fecal pellet shape classes.

<table>
<thead>
<tr>
<th>Category of shapes of pellets (%)</th>
<th>Cylindrical</th>
<th>Elliptical</th>
<th>Spherical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.3 × 10^4</td>
<td>5.7</td>
<td>35.4</td>
<td>4.3</td>
</tr>
<tr>
<td>200</td>
<td>6.3 × 10^4</td>
<td>21.6</td>
<td>53.4</td>
<td>4.3</td>
</tr>
<tr>
<td>315</td>
<td>7.4 × 10^4</td>
<td>70.1</td>
<td>32.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

### Table 3

Fecal pellet mass fluxes and relative contribution to the total mass fluxes.

<table>
<thead>
<tr>
<th>Trap depth (m)</th>
<th>Cylindrical</th>
<th>Elliptical</th>
<th>Spherical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>20.6</td>
<td>138.0</td>
<td>42.6</td>
<td>201.2</td>
</tr>
<tr>
<td>200</td>
<td>48.2</td>
<td>323.5</td>
<td>89.6</td>
<td>461.3</td>
</tr>
<tr>
<td>315</td>
<td>50.0</td>
<td>523.5</td>
<td>100.4</td>
<td>674.3</td>
</tr>
</tbody>
</table>
The most notable aspect of these results is the proximity to the continent and the relatively 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

### Table 4

Trace metal concentrations (μg 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 (μg m⁻² d⁻¹).

<table>
<thead>
<tr>
<th>Trap depth (m)</th>
<th>Cu</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>315</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 5

Thorium activities (dpm g⁻¹ dry) in trapped particulate material and corresponding fluxes (dpm m⁻² d⁻¹).

<table>
<thead>
<tr>
<th>Trap depth (m)</th>
<th>Activity</th>
<th>Flux</th>
<th>Activity</th>
<th>Flux</th>
<th>Activity</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.8 ± 0.1</td>
<td>7.1 ± 0.4</td>
<td>2.1 ± 0.1</td>
<td>8.4 ± 0.4</td>
<td>3.7 ± 0.1</td>
<td>14.6 ± 0.5</td>
</tr>
<tr>
<td>200</td>
<td>2.1 ± 0.1</td>
<td>16.4 ± 0.8</td>
<td>2.1 ± 0.1</td>
<td>16.0 ± 0.8</td>
<td>3.8 ± 0.1</td>
<td>29.2 ± 1.0</td>
</tr>
<tr>
<td>315</td>
<td>1.9 ± 0.1</td>
<td>25.2 ± 1.3</td>
<td>2.8 ± 0.2</td>
<td>35.9 ± 2.1</td>
<td>4.5 ± 0.3</td>
<td>58.1 ± 3.3</td>
</tr>
</tbody>
</table>
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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