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# Suspended particulate matter distribution and composition on the northern Portuguese margin

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**ABSTRACT**

On the North Atlantic continental margins, the Portuguese continental shelf has a singular morphology and hydrology. These characteristics are reflected in the sedimentary processes that occur on the continental shelf and in deeper areas. The main objective of the present paper is to review the nature, spatial distribution and dynamics of suspended particulate matter (SPM) on the continental shelf north of 41° N, in winter conditions. The data were collected during the Corrente da Vertente (CORVET) cruise sponsored by the Portuguese Hydrographic Institute in November 1996. During the cruise, hydrographic data (conductivity, temperature, and nephelometry) were obtained along transepts perpendicular to bathymetric contours. At most of these stations, suspended sediment samples were also collected from near-bottom turbid water (the bottom nepheloid layer, BNL) and from the surface turbid water (–5 m). SPM over the shelf consists of inorganic particles, skeletal biogenic particles and organic debris. Inorganic matter is dominated (> 60 %) by fine silt particles (< 15 μm) in the inner shelf near river mouths, although in the middle-to-outer shelf biogenic debris prevails in coarser particles (greater than 28 μm).

Currents and waves induce resuspension events, which are clearly shown by concentration fluctuations in the BNL. These events are greatly intensified during storms. The nephelometrical distribution near the bottom can reflect this events with a rise of the values in the middle shelf far away from the river inputs. Near the continental slope, the BNL nourish the intermediate nepheloid layer (INL). The nourishment increases during storm events, showing the importance of these events to the transport of particles to deeper areas.

**Key words:** Suspended matter, nepheloid layers, continental shelf, Portuguese margin.

***RESUMEN***

***Distribución y composición de la materia particulada en suspensión del margen portugués norte***

*La plataforma continental portuguesa, situada en el ámbito más vasto del margen continental del Atlántico norte, puede ser considerada como única a causa de sus características morfológicas e hidrológicas. Estas características se reflejan en los procesos sedimentarios que ocurren tanto en la plataforma continental como en las áreas más profundas. El objetivo principal de este trabajo es caracterizar el tipo, la distribución espacial y la dinámica de la materia particulada en suspensión de la plataforma continental situada al norte de 41° N, en condiciones invernales. Los datos fueron obtenidos en el mes de noviembre de 1996 durante la misión CORVET (Corrente da Vertente) promovida por el Instituto Hidrográfico de la Marina Portuguesa, según secciones perpendiculares a la costa. Las muestras de materia en suspensión fueron obtenidas a 5 m de la superficie y en cercanía del fondo.*

*El análisis de las muestras indica que la materia particulada en suspensión de la plataforma continental está constituida esencialmente por partículas terrígenas, bioclastos siliciosos y calcáreos, así como de otros detritos orgánicos. Cerca de la desembocadura de los ríos, más del 60 % de la materia terrígena está compuesta de partículas finas (< 15 μm); en cambio, en el resto de la plataforma los bioclastos son dominantes y presentan, generalmente, dimensiones superiores (> 28 μm).*

*Las corrientes y las olas inducen periodos de resuspensión de las partículas sedimentarias más finas localizadas en la plataforma media. Este fenómeno, ilustrado por las variaciones de concentración de la capa nefeloide de fondo, es particularmente intenso durante las tormentas, alimentando entonces una capa nefeloide intermediaria que circula cerca del borde de la plataforma.*

*Los valores observados muestran la importancia de los periodos energéticos en el traslado de las partículas de la plataforma continental hacia los sectores más profundos.*

***Palabras clave:*** *Materia en suspensión, capas nefeloides, plataforma continental, margen portugués.*

## INTRODUCTION

On the North Atlantic continental margins, the Portuguese continental shelf is characterised by complex hydrological processes, including: upwelling (Bôto, 1945; Wooster, Bakun and Mclain, 1976; Fiúza, Macedo and Guerreiro, 1982; Silva, 1987, 1992), formation of eddies and filaments (Pingree and Cann, 1992), major river inputs (Oliveira,Valle and Miranda, 1982; Dias, 1987; Oliveira, 1994), frontal areas (Silva, 1992), northward intrusion of Mediterranean water (Ramalho and Dentinho, 1928; Ambar and Howe, 1979; Ambar, 1983, 1984), persistant poleward current along the slope (Vitorino, 1989, Frouin *et al.*, 1990; Haynes and Barton, 1990) and important morphological features, such as canyons, seamounts and tectonic depressions (Vanney and Mougenot, 1981, 1990; Rodrigues, Magãlhaes and Dias, 1991, 1993; Rodrigues, Dias and Riveiro, 1992). These characteristics are reflected in the spatial and temporal distribution of suspended particulate matter, which plays a major role in the sedimentary processes that occur on the continental shelf and in deeper areas.

The present paper describes the results of research concerning the nature, spatial distribution and dynamics of suspended particulate matter (SPM) collected on the continental shelf north of 41° N, under winter conditions.

This area is characterised by a very narrow shelf (35 km wide) and a steep slope. An average volume of $10.7 \times 10^6$ ton of river-borne particles is exported to the shelf every year through the discharge of 5 major rivers. The sedimentary cover (Magalhães and Dias, 1992) of the inner continental shelf is essentially sandy with irregular patches of coarser relict sediments. Rocky outcrops are also found. Two main muddy deposits (silty sediments with smaller amounts of fine sand and clay) occur on the middle shelf, developing parallel to the coastline, between depths of 70-120 m; the largest one is located off the mouth of the Douro River, and the smaller one is located in front of the Minho River having its major extension on the Spanish continental shelf. The Douro muddy deposit is cut by rocky outcrops and irregular patches of outer shelf sandy deposits; the continental slope is covered by silty and muddy deposits with rocky outcrops in the canyon head (figure 1).

## MATERIALS AND METHODS

### Field work

The samples were collected during the Corrente da Vertente (CORVET) cruise, sponsored by Portugal's Hydrographic Institute, aboard the N.R.P. *A. Carvalho* (1-22 November 1996), mainly for oceanographic and SPM studies. During the cruise, hydrographic data (conductivity, temperature, depth) and nephelometry were obtained along transepts perpendicular to bathymetric contours (figure1). At most of these stations, suspended sediment samples were also collected from surface turbid water (–5 m) and from the near-bottom turbid water (the bottom nepheloid layer, or BNL). On the continental slope (water column deeper than 2 800 m) the lower sample was collected, after the nephelometric profile, at the maximum nepheloid layer that usually corresponds to an intermediate nepheloid layer (INL). At the surface, SPM was sampled by direct filtration with 142 mm filters (for large volumes of water) and 47 mm filters

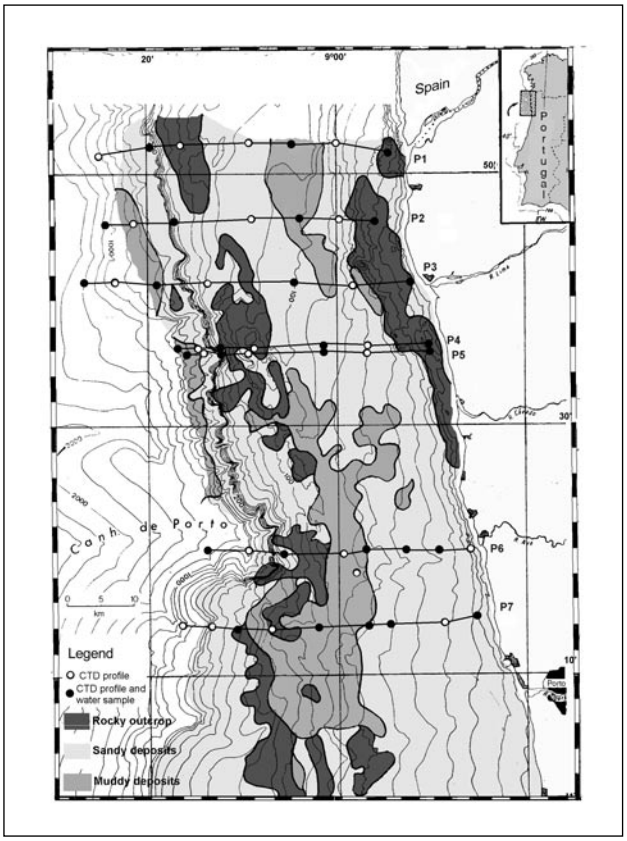


Figure 1. Bottom sedimentary cover (adapted from Rodrigues, Magalhães and Dias, 1991) and CORVET cruise stations

(Millipore and Whatman GF/F), using a pressurised pumping system. Intermediate and bottom water were sampled with Niskin bottles (12 bottles in the CTD rosette of 1.75 l each) and filtered on board with the classic vaccum system using the same 47 mm filters. All samples were dried after collection (40 °C) and weighted.

Since the cruise was performed under typical winter conditions, with highly variable winds associated with the passing of lows and frontal systems, two of the sections (4 and 5) were repeated after a storm event (19 November), in order to detect changes in the water masses structure and SPM distribution.

### Laboratory work

Laboratory analyses included particle grain-size analysis (laser), organic carbon content, and optical analysis of SPM (microscope and SEM). The grain-size analyses, performed only on surface samples, involved the previous elimination of the organic fraction of SPM, with $H_2O_2$ (20V), and subsequent analyses in a diffractometer laser (Malvern 3600E equipment), which makes it possible to perform grain-size analysis with small amounts of material. The particulate organic carbon (POC) was determined in the Whatman GF/F filters. These filters were impregnated with HCl (2N) to eliminate all traces of carbonates in refractory cups; afterwards they were dried at 50 °C (12 h). They were then reduced to ashes in a high- temperature induction oven (1 200 °C) and the $CO_2$ produced was analysed with an infrared detector (LECO CS 125).

The general composition of the SPM was determined by the aid of a petrographic microscope (amp. ×1 250) with subsequent observation of selected samples by SEM. The estimate of phytoplankton abundance, principally coccosphere and coccoliths can be used as tracers of particular water masses off the Iberian Peninsula (Cachão *et al.,* in preparation).

## RESULTS

### Environmental conditions

As reported by several authors (e.g. Fiúza, Macedo and Guerreiro, 1992) on the northern Portuguese margin the hydrological and biogeochemical conditions are controlled by atmospheric forcing, especially the prevailing winds from the west and northwest, which can establish upwelling conditions or perturb the euphotic layer.

During the cruise, there were northwesterly prevailing winds, with the passage of severe storms from the west. Wind monitoring shows that velocity was frequently higher than 10 m/s.

Another important factor, in SPM distribution, is the debit of the five major rivers, principally the Douro River; indeed, whether under flood or dried conditions, the quantity and the quality of SPM on the continental shelf is affected (Oliveira, 1994). In figure 2, the importance of the discharge of the Douro River, compared with the other two, is evident. Due to meteorological conditions, the Douro River presented its maximum debit values at the end of the cruise (756 $m^3/s$), contrasting with the minimum values observed at the beginning of the cruise (99 $m^3/s$).

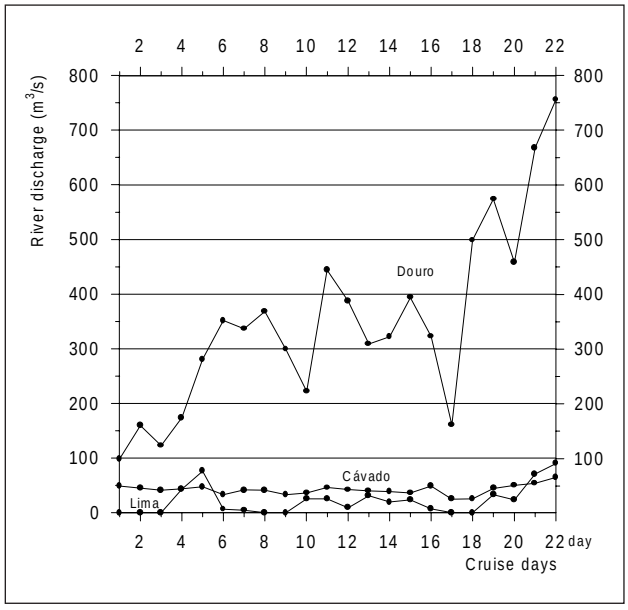


Figure 2. River discharge (Douro, Lima, Cávado), during the CORVET cruise

During the storm event on 19 November, the wave regime showed significant wave heights of 6 m (maximal heights of 10 m) within periods of 12 s. This regime induced near-bottom velocities higher than 20 cm/s, with maximum values over 40 cm/s (Vitorino *et al.*, 1997).

## Nephelometry

As expected for a continental shelf strongly affected by fluvial inputs, on the inner shelf the nephelometry values increase from the surface to the bottom, but when the water column is higher than ≈ 30 m, the turbid waters differentiate into a surface and a bottom nepheloid layers (SNL and BNL, respectively), which can be clearly identified in the nephelometrical profiles (figure 3). They are separated by a less turbid water mass, with values under 0.1 ftu (profiles 1, 2, 3, 4). After the storm event (profiles 5, 6, 7), at mid-shelf the surface layer tends to disappear as a result of mixing by wave action, and the water column above the thermocline tends to be homogenised.

The BNL shows a wide variability in its concentration values, until 8 ftu in thickness (from 5-50 m), and it is always more important than the surface one. Locally (80 m), resuspension events (stations 47, 85, 92), related with the finer bottom sediments can enlarge the nephelometrical values of the BNL.

The effect of the storm event is also shown in BNL thickness (> 20 m) and in turbidity values. Near the continental slope, the presence of an incipient INL associated with the BNL was intensified (figure 4).

## SPM concentration - POC contents

Data on SPM concentrations is shown in figure 5. The SPM concentration is higher in proximity to the bottom, and at the stations near the rivers. In surface waters (5 m) the SPM concentration are quite constant throughout the middle and outer shelf (from 0.13 to 1.4 mg/l, average: 0.5 mg/l) with an increase to the inner shelf, up to 3 mg/l. Near bottom the observed SPM concentration became much higher, up to 13 mg/l (inner shelf), due to the considerable terrigenous input via the Lima and Douro Rivers and resuspension. Values range between 0.3-18.5 mg/l (average: 3.7 mg/l). The SPM concentration values also reflect the storm event, especially in the BNL.

POC content (expressed as % of SPM) shows values lower than 6 % in areas where the SPM concentration is higher (especially at bottom and in the inner shelf adjacent to the river mouths). As shown in figure 6, the POC content is quite low, ranging from 3.4 % to 5.9 %, related to the high mineral content of suspended material. At the surface, concurrently with deepening that attenuates resuspension and distance to river input influence, POC percentage increases, from east to west, with values ranging from 6 % to 32 %. This suggests an organic, plankton-rich SPM, with a decrease or a quasi-absence of terrigenous component. Section 7 (near the Douro River) presents lower surface values of POC, which is clear evidence of the importance of this river for the transport of terrigenous material to the shelf.

## Composition

The direct count of cells in filters makes it possible to estimate the population of phytoplankton, and acquire a good idea of the SPM composition. Phytoplankton are dominated by coccolithophorids (coccosphere and coccoliths), chiefly *Gephyrocapsa oceanica* (Kamptner, 1943); *Gephyrocapsa muellerae*

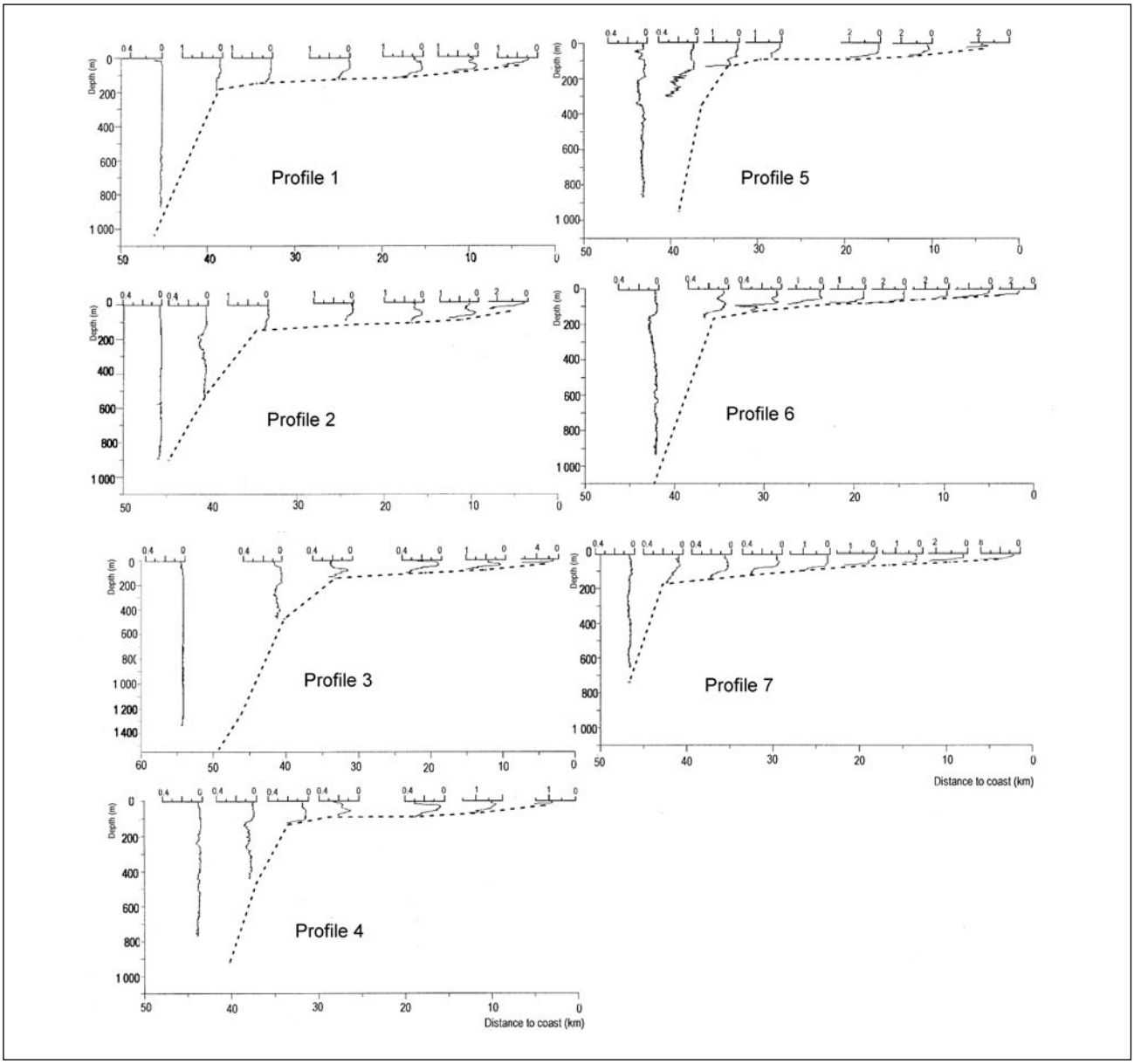


Figure 3. Cross-shelf nephelometric profiles (for location see figure 1). Nephelometric units in ftu (ftu = 1.6 mg/l)

(Bréhéret, 1978); *Gephyrocapsa ericsonni* (McIntyre and Bé, 1967); *Emiliania huxleyi* (Lohmann, Hay and Mohler, 1967); *Coccolithus pelagicus* (Wallich and Schiller, 1930); *Syracosphaeras* sp. (Lohmann, 1902) and *Helicosphaera carteri* (Kamptner, 1954). Total surface coccolith concentration values ranged from $1.4 \times 10^7$ liths/l to zero, with the highest concentrations near the coast. However, the species diversity is low, when compared with samples collected southward and in the open ocean (Cachão, Oliveira and Vitorino, in preparation). Near the bottom, the concentration and assemblage was similar to the surface, approximately $1.6 \times 10^7$ liths/l, but with no significant decrease towards deeper water (650 m), where the minimum value was $1.3 \times 10^6$ liths/l.

Less abundant were diatoms, dinoflagellates and silicoflagellates. Foraminifers were absent or rare.

Terrigenous debris with a fluvial origin forms the bulk of the SPM in the remainder of the samples. Much of the terrigenous material consists of platelike clay minerals, with other mineral grains present in small amount (quartz, mica, and feldspar). Some of the clay grains form aggregates that were formed either during the filtering process or as natural floc-

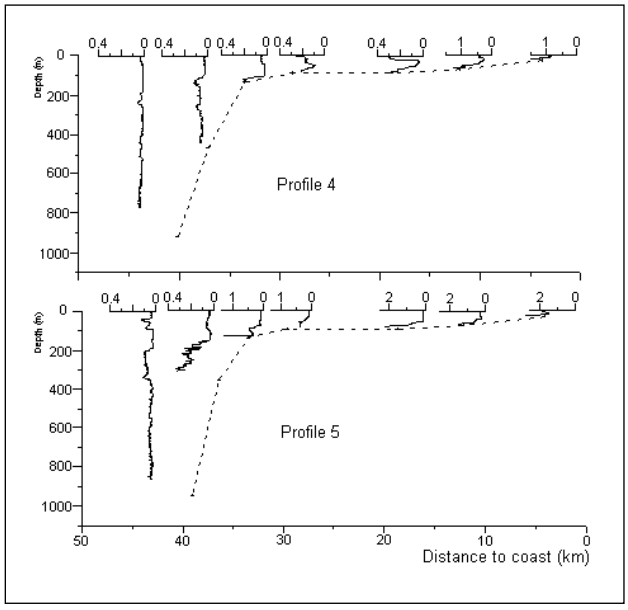


Figure 4. Comparative nephelometric profiles before and after the 19 November storm event (for location see figure 1)

culates. The organic material can also occur as aggregates that commonly enclose minute coccoliths.

## Grain-size distribution

The mean diameter of suspended particles reveals a general oceanic increase from less than 9 µm to more than 14 µm offshore. The coarser mean diameters occur over the outer shelf and deeper waters beyond the continental shelf, where the major terrigenous river input is minimal and the macrozooplankton debris prevails (essentially siliceous and carbonated skeletal).

Grain-size distribution (figure 7) into the five classes chosen (>125, 125-63, 63-30, 30-15, <15 µm), reveals the same tendency.

In the inner-to-middle shelf, the higher percentage occurs in the < 15µm class (> 75 %), but in

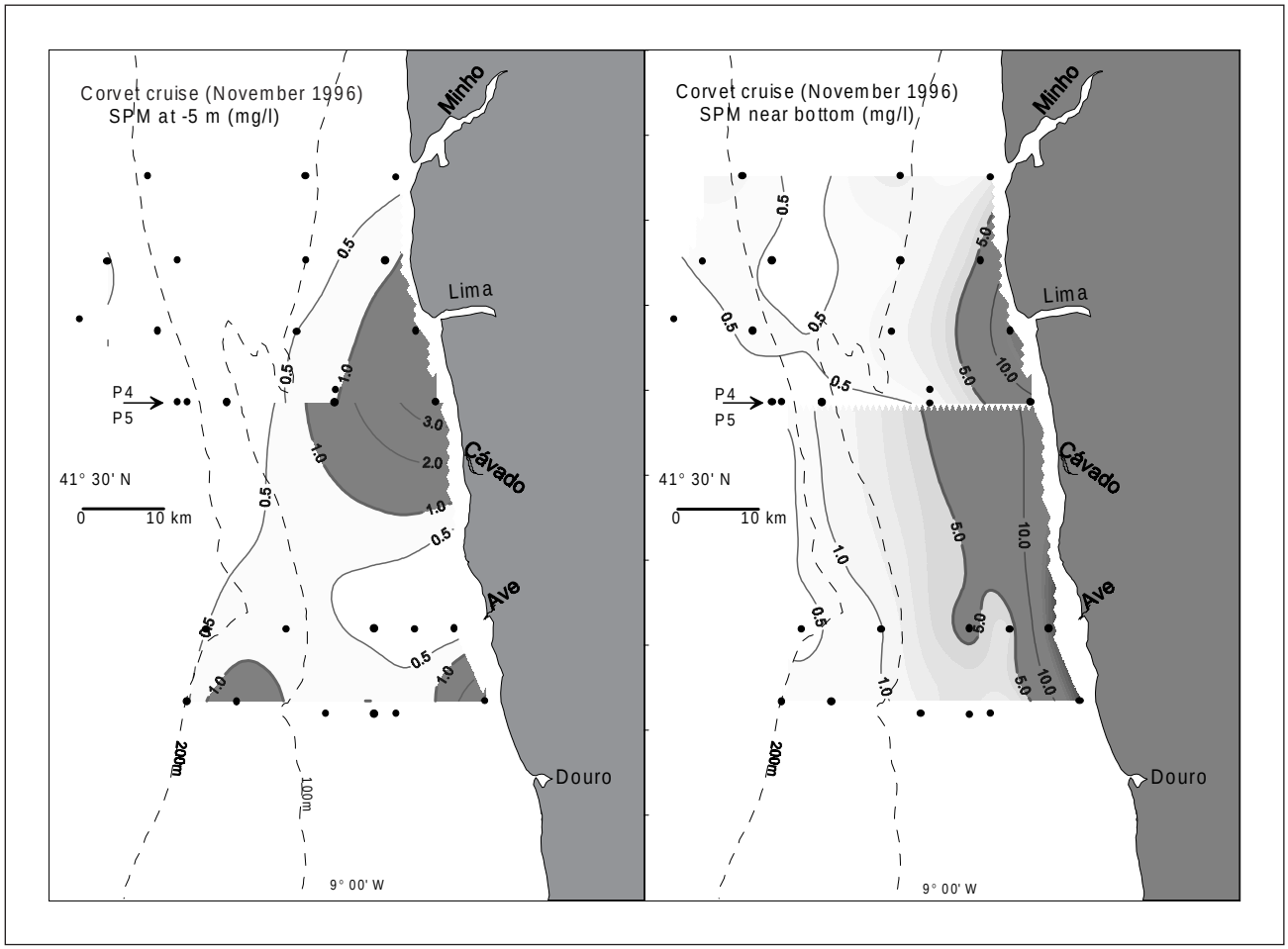


Figure 5. SPM distribution at surface (5 m) and near bottom, in mg/l, obtained during the CORVET cruise. SPM distribution reflects the two distinct oceanographic regimes, before and after the 19 November storm event (P4 and P5)

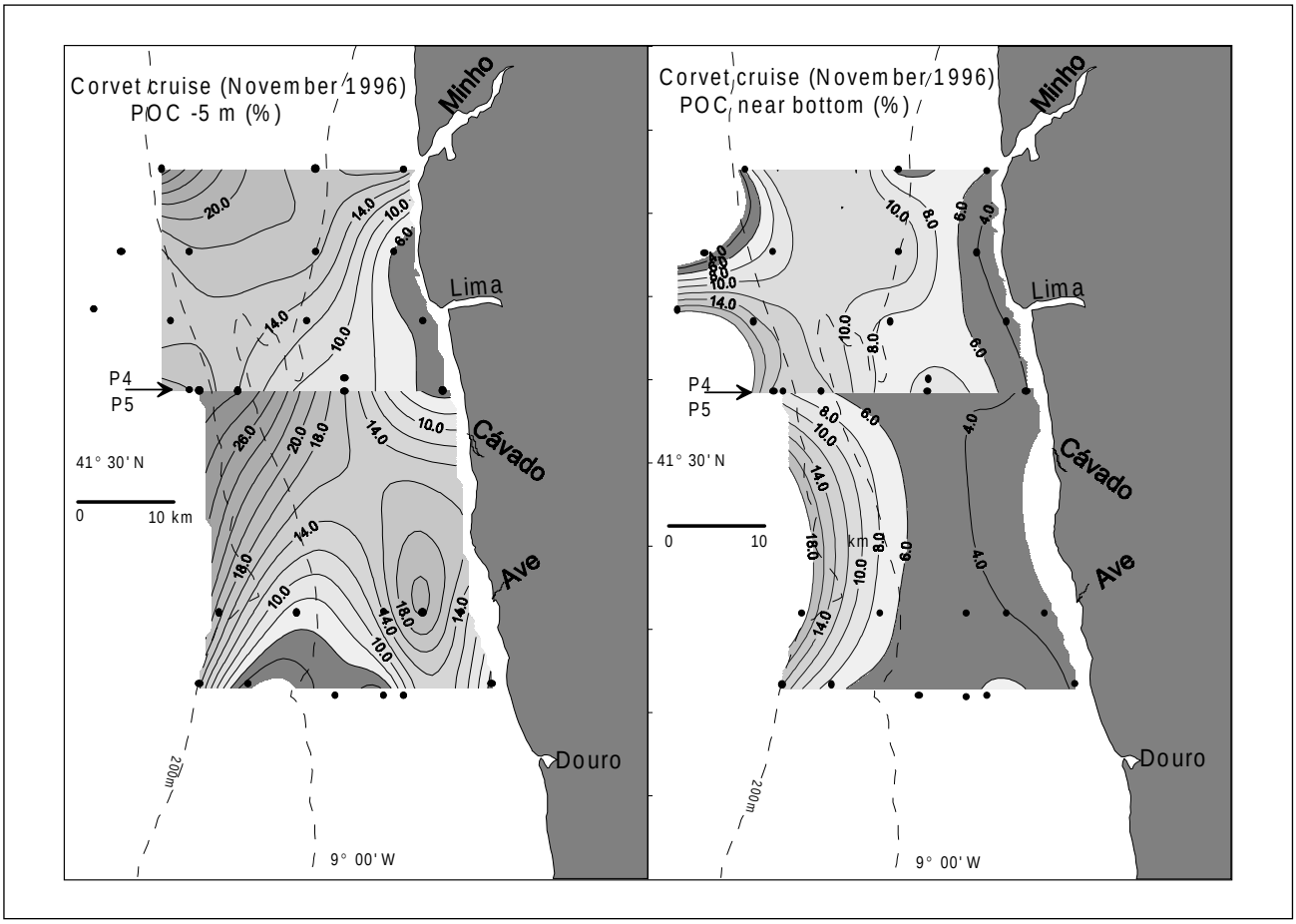


Figure 6. POC content (%) distribution at surface (5 m) and near bottom, obtained during the CORVET cruise. As in figure 5, the impact of a storm event is evident

deeper waters there is an enrichment in coarser particles, i.e. class 63-30 μm.

At the surface, distance to the origin is the principal factor that affects the terrigenous particle distribution, being more important than depth, because resuspension events have little or no influence in deeper waters. In fact, these particles are well represented until 35 km off the coast (particles less than 15 μm accounted for more than 60 %), where the coarser biogenic particles became more important.

## DISCUSSION

River discharge is responsible for most of the nearshore concentrations of the SPM in this region. Suspended particulate matter shows a consistent distribution along the northern Portuguese shelf, the pattern of which is similar to the one detected in previous research carried out in this area (Oliveira, 1994). On the inner shelf (< 50 m), higher concentrations, more than 13 mg/l, are found near the bottom, progressively decreasing to 1 mg/l near the surface, in relation to river input. On the middle shelf, clear waters separate a SNL and a BNL. As expected, the BNL is more significant than the SNL.

Sediment concentration in both layers shows a seaward decrease, reflecting settling of inorganic particles. Consequently, fine terrigenous particles are preferentially removed, and the SPM becomes increasingly coarse-grained seaward, as the biogenic component increases. Particulate organic carbon percentage is higher on the middle-to-outer shelf, reflecting this increase.

Currents and waves induce resuspension events, which are clearly shown by concentration fluctuations in the BNL. These events are greatly intensified during storms. During the CORVET cruise, near-bot-

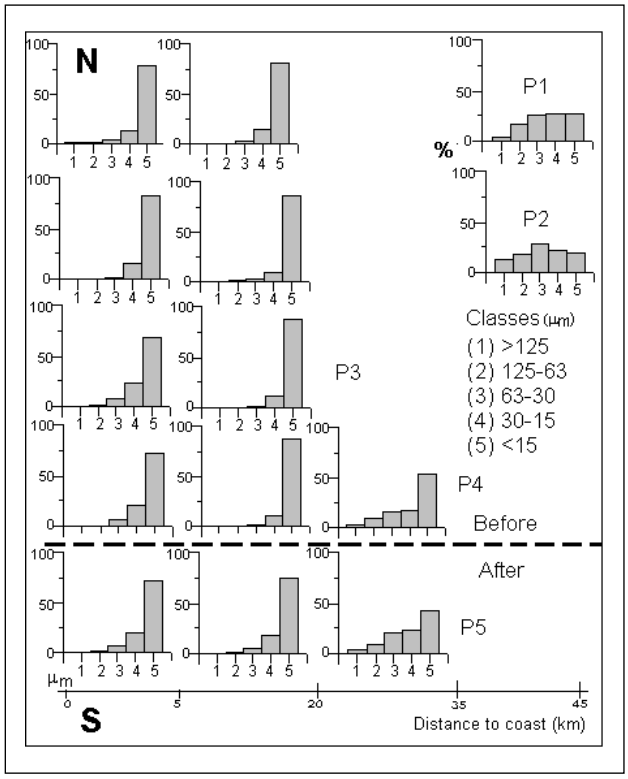


Figure 7. Inorganic matter grain-size distribution at the surface (%). Histograms show the importance class 5 (silt and clay) up to 35 km from the coast (this distance is the average length of the continental shelf north of the Ave River). Towards deeper waters, this class is not so representative, indicating the increase of coarser biogenic debris (opal and carbonated skeletals) in the SPM

tom velocities (depth of 80 m) induced by wave conditions were higher than 20 cm/s. This is sufficient to promote resuspension of bottom sediments, especially the silty and fine sand particles of the Douro and Minho muddy deposits. Particles are integrated into the BNL and transported offshore over the mid-shelf to the upper slope region and nourish the INL.

The present study confirms the importance of energetic events, such as the 19 November storm event, in transferring particles to deeper domains.

The general composition of SPM on the shelf under winter conditions consists of inorganic particles, skeletal biogenic particles and organic debris. Inorganic matter is dominated (> 60 %) by fine silt particles (< 15 µm), mostly concentrated off the mouths of rivers, but the largest median diameters occur in offshore regions, where biogenic debris prevails in coarser particles (greater than 14 µm). The most numerous biogenic fragments and cells are coccolithophorids, followed by marine diatoms and silicoflagellates.

Coccolithophorids are indicators of marginal seas versus open ocean through greater number or concentration, lower diversity and greater percentage of malformations in the marginal seas (Honjo, Emery and Yamamoto, 1974). In the study area, the limit between the marginal sea and the open sea seems to be at approximately 30-35 km off the coast, with the same distribution of terrigenous particles. Optical observation shows that these carbonated particles are very important in this margin, principally on the inner shelf, but the terrigenous particles were also important. Future work will focus on the balance between these two types of particles in order to evaluate the true terrigenous river input.

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