Some evidences of northward fine sediment transport in the northern Portuguese continental shelf

Teresa DRAGO [a]*, Anabela OLIVEIRA [b], Fernando MAGALHÃES [c], João CASCALHO [c], Jean-Marie JOUANNEAU [d], João VITORINO [e]

[a] FCT/ Instituto Investigação do Mar e das Pescas, Av. Brasília, 1400 Lisbon, Portugal
[b] FCT/ Instituto Hidrográfico, R. das Trinas, 49, 1296 Lisbon codex, Portugal
[c] FCT/ Museu Nacional de História Natural, R. da Escola Politécnica, 58, 1294 Lisbon codex, Portugal
[d] DGO, URA 197 CNRS, Université de Bordeaux I, avenue des Facultés, 33405 Talence cedex, France
[e] Instituto Hidrográfico, R. das Trinas, 49, 1296 Lisbon codex, Portugal

(Revised 13/01/98, accepted 14/01/98)

Abstract – On the basis of sedimentological and oceanographical data, a transport scheme for fine-grained material is proposed in order to explain the location of a muddy deposit present in the northern Portuguese continental shelf, north-west off the Douro River mouth. This mid-shelf deposit is recent, active and its main source is apparently the Douro River. The sediment supply can be related with the oceanographic conditions in winter regime, characterised by a poleward along-shelf current with a bottom westward component, as a consequence of a south-west wind. The resulting fine sediment transport, essentially made in the bottom nepheloid layer, is believed to have a north-west direction. © Elsevier, Paris

Portuguese shelf / fine sediments / biotite / sediment transport / winter regime

Résumé – Quelques arguments en faveur du transport des sédiments fins vers le nord sur le plateau continental au nord du Portugal. Un schéma de circulation des sédiments fins, sur le plateau continental au nord du Portugal, a été établi à partir de données sédimentologiques et océanographiques. Il explique la présence d'une vasière située au nord-ouest de l'embouchure du Douro ; ce dépôt récent et actif proviendrait essentiellement du fleuve. L'apport de sédiment est lié aux conditions hydrologiques hivernales, caractérisées par un courant dirigé vers le nord le long du plateau continental avec, au fond, une composante vers l'ouest due au vent du sud-ouest. Il en résulte que le transport des sédiments fins se fait principalement dans la couche néphéloïde de fond, en direction du nord-ouest. © Elsevier, Paris

plateau continental portugais / sédiment fin / biotite / transport de sédiments / hydrologie hivernale

1. INTRODUCTION

The occurrence and location of mud-grained deposits on continental shelves is deeply affected by the concentration of the suspension and current activity [23]. The characteristics of these deposits (such as sediment composition or accumulation rates) can provide valuable insight into net transport patterns and allow the comparison of processes spanning different time scales to short-term predictions and observations [13, 25]. The transport of suspended sediment usually occurs as strong along-shelf and weak across-shelf flows. For the northern California shelf, Drake and Cacchione [14] and Sherwood et al. [34] have shown that most suspended sediment transport is northward along-shelf during southerly storms, with a significant offshore component (up to 45°). In the

* Correspondence and reprints

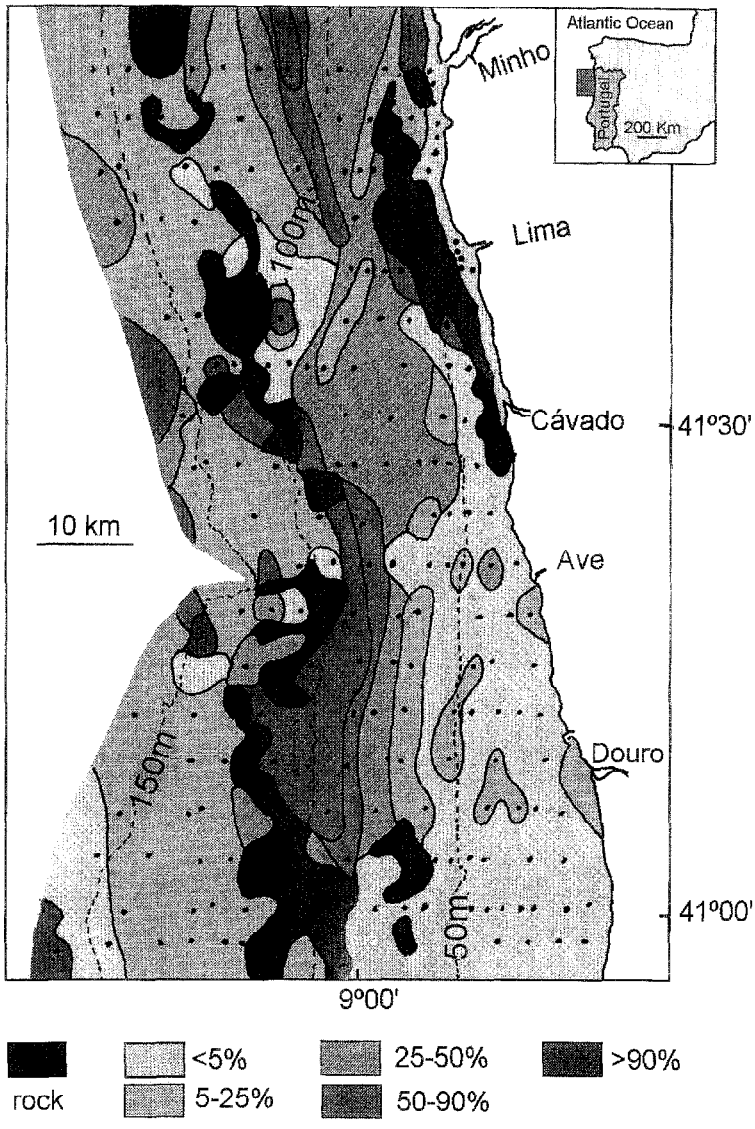

Figure 1. The superficial fine sediment distribution on the northern Portuguese continental shelf (adap. from [2]).

Figure 1. La distribution superficielle de la fraction silto-argileuse sur la plate-forme continentale nord-portugaise (adap. de [2]).

Washington shelf fine-grained material exported by the Columbia River is transported northward, and to a lesser extent westward, only during a few storms each year [37].

The northern Portuguese continental shelf is characterised by a strong fluvial input and by the presence of two important muddy complexes located in the mid-shelf off the Minho and Douro Rivers (*figure 1*). For the objective of the present study, closer attention will be given to the Douro muddy complex (DMC), which is located northwest off of the Douro River mouth. Since this complex was identified by Dias and Nittrouer [9], several authors have studied its sedimentological and geochemical characteristics, e.g. [1, 5, 11, 12, 21, 22] within the framework of several projects aiming at the study of the Portuguese continental shelf.

To understand how fine-grained sediment is supplied to the DMC and which processes determine its preferential orientation, a clear knowledge of the physical oceano-

graphical conditions relevant to sediment transport over the northern Portuguese shelf is required. The circulation pattern is essentially induced by the local wind regime, which is closely linked to the Azores high pressure system, presenting a marked seasonal variation [17, 40, 41]. In summer, when the Azores high is located off Iberia, northerly winds dominate and a well-defined upwelling season exists from June to October [2, 15, 16, 17, 32, 35]. In winter, the Azores high is located further south, off the north-west African coast, and highly variable winds associated with the passage of moving storms characterise the meteorological conditions off Iberia. Winds with a southerly component are frequent, leading to the establishment of downwelling conditions over the western Portuguese shelf [18, 40].

Wind wave regime is dominated by north-west swells which occur during 80 % of the year [29] with significant wave heights between 1 and 2 m and periods between 5 and 7 s [31], resulting in southward along-shore transport [9, 33]. Storms occur 3.2 times each year [30] and, typically, result from south-west winds that generate west swells and south-west waves [29]. These episodes frequently lead to significant wave heights greater than 5 m and periods in excess of 13 s [31]. Every 10 years they reach heights of 10 m [29].

In the present paper, sedimentological and physical oceanographical data are integrated to present a coherent circulation scheme for fine-grained material in this shelf.

2. DATA

This study is based on data presented in previous works, which have been re-analysed and integrated in order to determine preferential transport pathways for fine-grained sediment. Such data are associated with two kinds of studies: 1) sedimentological study, including: a) textural and compositional analysis of surface sediments from the entire shelf [22] and particularly from the DMC [11, 12, 21], b) detailed optical observation of heavy minerals in the 65 –250 μm range [6, 7], c) determinations of grain size (using a laser diffraction technique), concentration and composition of the suspended particulate matter (SPM) from turbid plumes connected with northern rivers [26, 27] and 2) oceanographic data consisting of current measurements over the mid and outer shelf off Oporto [40].

2.1. The silt-clay distribution and the Douro muddy complex

The sedimentary cover of the northern Portuguese continental shelf is dominated by sand [9, 22] with a mean silt + clay (i.e. particles < 63 μm in diameter) content of about 20 % of the entire sediment. However, in the two already mentioned muddy deposits, this content increases significantly, reaching an average value of 78 % and frequently exceeding 90 %, especially in the Douro complex [20] (*figure 1*). The fine-grained fraction is usually dominated by silt. In general, surface sediments become progressively muddier from the coastal zone to depths around 100 m. It is at this mean depth that the two mud-rich areas occur, in association with a low energy deposition environment.

In particular, the DMC, which is located 15 to 25 km away from the coast, develops between 65 and 130 m. Covering an area of approximately 500 km^2, it has a mean thickness of 5 m [12] and an estimated age of 2 000 years BP [11]. Mean grain size is 26 μm at the surface. The comparison of the elemental chemical composition of sediments from the inner shelf (near the Douro and Ave estuaries) and from the DMC suggests that the main sedimentary source is the Douro River [1]. High bulk ^{210}Pb accumulation rates, between 0.16 $cm \cdot yr^{-1}$ [5] and 0.57 $cm \cdot yr^{-1}$ [11] determined in sediment cores indicate that this recent complex is acting as an active trap for fine-grained sediments.

2.2. Biotite distribution

There is a close correlation between the distributions of the sand-sized biotite flakes and muds. The shape of biotite affects its settling characteristics, and, because of the hydraulic equivalence to silts and clays [3, 10], it tends to be winnowed out of high-energy environments such as the inner shelf zone, and carried in suspension into less turbulent deposition environments. Because of its hydraulic behaviour, biotite can be used as a tracer for suspended sediment trajectories in the shelf.

The abundance of biotite in the studied shelf (*figure 2*) is related to the outcrops of igneous rocks, namely granites, which are common in the hydrographic basins of the five major northern rivers (Minho, Lima, Cávado, Ave and Douro). This mineral is clearly related to river supply (as also evident from their immature appearance under the microscope); it bypasses the littoral and inner shelf zones and is deposited together with finer sediments further

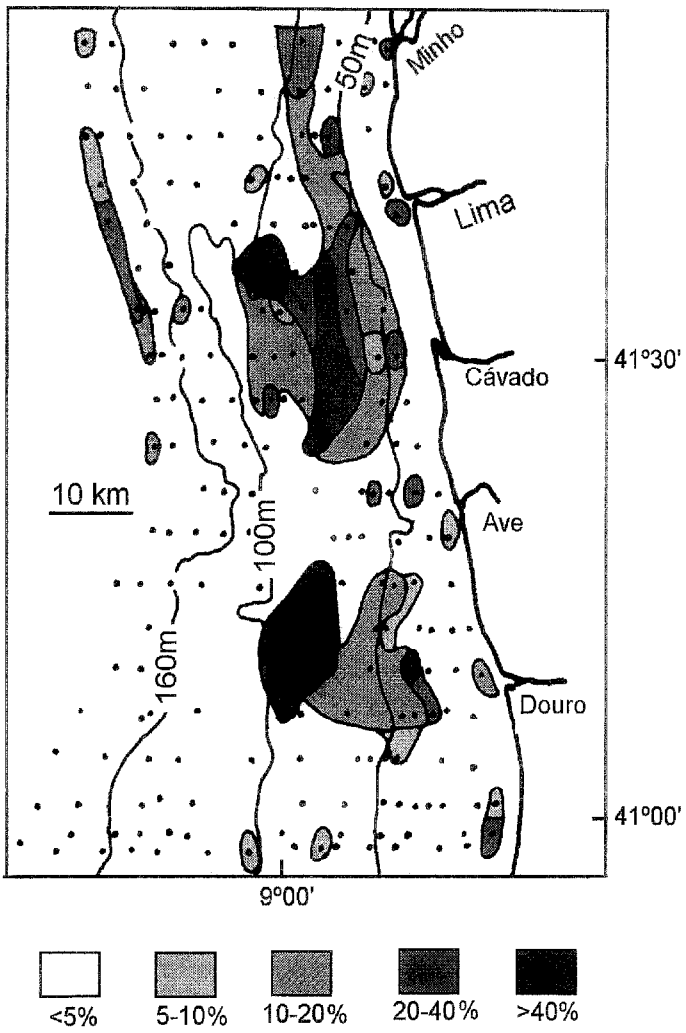

Figure 2. Biotite distribution in sedimentary cover. Values related to the total of heavy minerals (granulometric classes 250–63 μm).

Figure 2. Distribution superficielle de la biotite. Les valeurs sont relationnées avec le total des minéraux lourds (classes granulométriques 250–63 μm).

away, in the mid-shelf, particularly in the two biotite and mud-rich areas [6, 7].

2.3. Input and transport of suspended particulate matter

Measurements of the concentration of SPM in the continental shelf and in different seasons show that the magnitude and area of river plumes are intimately connected with fluvial discharge. In summer (September 1990), fluvial discharge was low and the influence of river plumes in coastal waters was very reduced (*figure 3a*). During this period, the greater importance of the surface nepheloid layer (SNL) (0–20 m thick) was essentially associated with suspended biogenic debris and also with water column stratification, which inhibits particle vertical mixing and settling [26]. In the coast parallel cross section (*figure 3b*), the Ave River had the more developed plume followed by that of the Douro River [28]. In contrast, in winter (March 1991), plumes were much more developed, which is particularly expressed by the stronger nephelometry values of the bottom nepheloid layer (BNL). The Douro River plume presented an extension of about 14 km and showed a north-west displacement

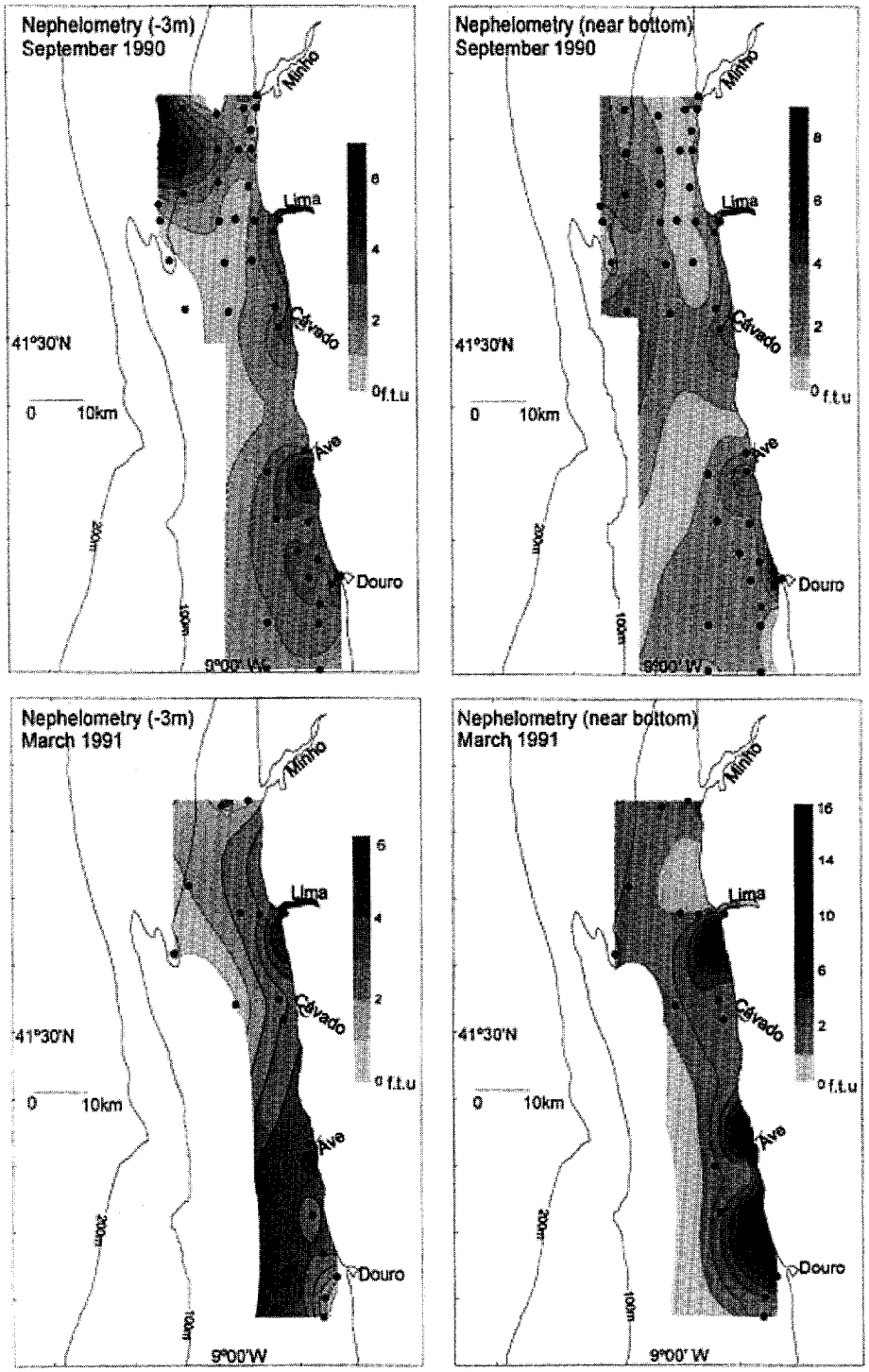

Figure 3a. Surface (3 m) and near-bottom nephelometrical distribution in northern Portuguese continental shelf during cruises in September 1990 (summer conditions) and March 1991 (winter conditions). The dark dots represent the occupied stations.

Figure 3a. La distribution néphélométrique en surface (3 m) et proche du fond dans la plate-forme continentale nord-portuguaise pendant des missions en septembre 1990 (conditions d'été) et mars 1991 (conditions d'hiver). Les points en noir représentent les stations occupées.

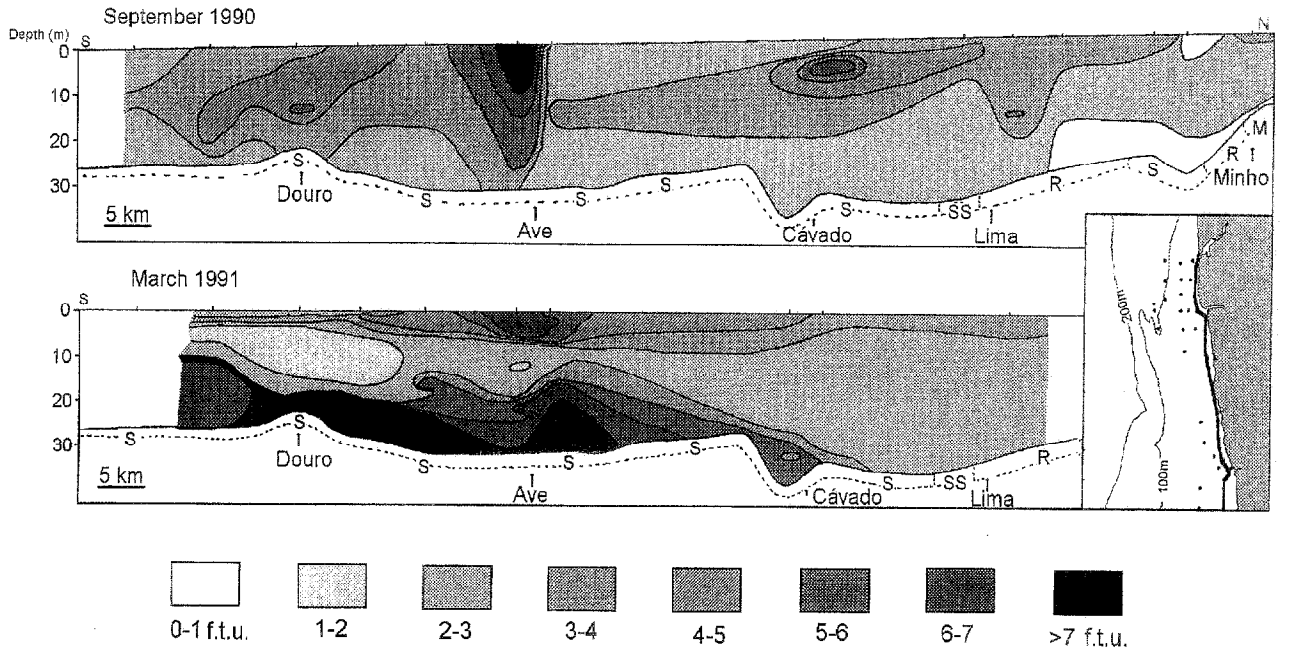

Figure 3b. The turbid plumes of the northern Portuguese rivers (Douro, Ave, Cávado, Lima and Minho) in September 1990 and March 1991 (adap. from [26]). The nepheloid layer associated with the Douro River is shifted northward in relation with the southwest wind action (mg/l = 1.7 f.t.u.). R: rock, S: silt, SS: silty sand, M: mud.

Figure 3b. Les plumes turbides des fleuves du nord du Portugal (Douro, Ave, Cávado, Lima et Minho) en septembre 1990 et mars 1991 (adap. de [26]). La couche néphéloïde associée avec le fleuve du Douro est déplacée vers le nord comme conséquence de l'action du vent de sud ouest (mg/l = 1.7 f.t.u.). R : roche, S : silte, SS : sable vaseux, M : vase.

(*figure 3a*). The highest concentrations of the suspended load of BNL and SNL were 15 and 5 $mg \cdot L^{-1}$, respectively. The suspended load was dominated by silts and clays (> 77 %), with a mean silt content higher than 50 % and a mean grain size between 7 and 22 μm.

2.4. Circulation patterns over the northern Portuguese shelf

Some insight about the processes promoting the transport of fine-grained sediment to the DMC was provided by current observations that were obtained over the northern Portuguese shelf in 1987. Time series of currents were obtained at various depths over the mid-shelf (100 m depth, over the DMC) and upper slope (300 m depth) along a line off Oporto. The observations extended from mid-May to mid-October 1987, covering the upwelling season and the transition to winter conditions.

Mid-shelf residual currents during the upwelling season were essentially variable, responding directly to events of intensification/relaxation of upwelling favourable winds with time scales of 6–12 days [36, 40]. A mean equator-ward current was observed during the period of stronger and more sustained upwelling favourable winds. Over the upper slope a persistent equator-ward flow was observed in the upper 50–100 m, with a poleward undercurrent present in the deeper levels. During periods of stronger upwelling favourable winds the equator-ward flow occupied the total 300 m water column. The across-shelf circulation pattern that emerges from the data reveal offshore transport confined in a surface (Ekman) layer shallower than 40 m depth, with onshore compensation flow occurring immediately below the upper layer [40]. This pattern could favour the offshore transport of suspended sediments present in the SNL.

During winter conditions, strong winds with a southerly component led to the establishment of a downwelling regime over the studied shelf. The along-shelf circulation was characterised by persistent poleward flow at all depths, both over the mid-shelf and upper slope. On shore flow was observed in the upper 50–70 m depth over the mid-shelf with some offshore transport being confined to

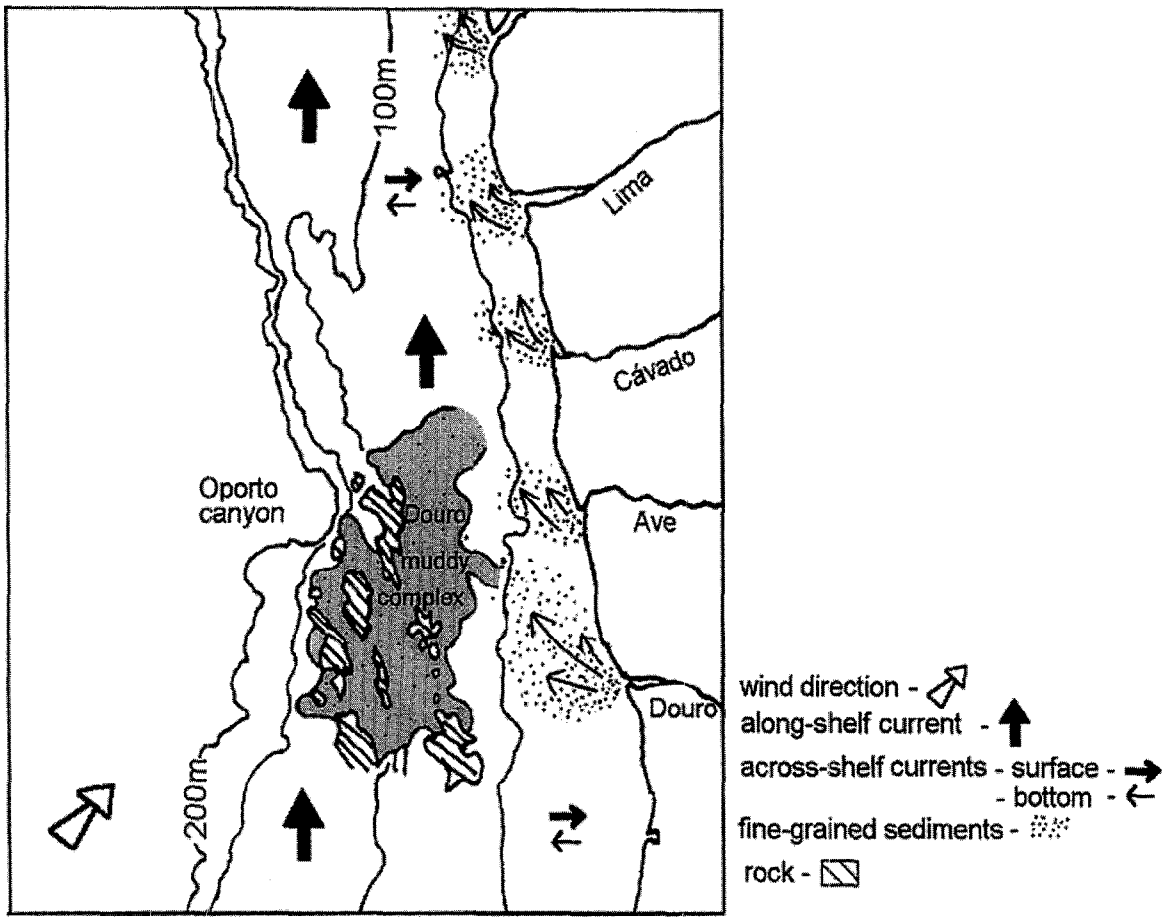

Figure 4. A schematic hypothesis for fine sediments supply to the DMC in winter period (adap. from [11]).

Figure 4. Un schéma hypothétique de l'alimentation en sédiments fins du DMC, dans la période de l'hiver (adap. de [11]).

the bottom layer [40]. The across-shelf circulation pattern favours the offshore transport of fine-grained particles in the BNL.

3. DISCUSSION

The DMC is very recent (2 000 years BP) and actually acts as an efficient trap for fine-grained sediments, as can be seen from the ^{210}Pb accumulation rates (0.16–57 cm·yr^{-1}). The main sediment source appears to be the Douro River [1, 21], which is the most important river of the Iberian Peninsula (with the largest hydrographic basin), transporting around 19×10^6 ton·yr^{-1} of sediment in natural regime [8]. The highest contribution in suspended sediments to the shelf is related to winter conditions when river discharge is maximal. The suspended load of this river is essentially formed by silts and clays, and their hydraulic equivalents, such as fine sand biotite flakes.

These sediments are transported as SNL and BNL, as detected in other continental shelves [19, 24]. In moderate winter conditions, as during the March 1991 cruise (2–3 m wave height), the offshore extension of the BNL was about 14 km. A greater extension can be expected under typical storm conditions (during which wave height is frequently over 5 m), when river discharge and resuspension are more important. However, the material is more likely to undergo several settling and resuspension episodes [39] before reaching the DMC area. In both cases, sediment may be transported by the joint effect of the along-shelf northward current associated with downwelling conditions and the across-shelf circulation which

leads to westward (offshore) transport in the bottom levels. The combination of both effects would lead to a net north-west transport of the fine-grained sediments and could explain the northward orientation of the DMC and the gradual increase of biotite contents from the inner to the mid-shelf (*figure 4*). This circulation scheme is supported by studies on the Washington and northern California shelves, which also correspond to an eastern boundary of an ocean and whose prevailing oceanographic setting is similar to that described for the studied shelf [4, 37, 38]. In these shelves, muddy complexes occur at similar depths as the DMC.

The presented general picture is based on an incomplete set of physical oceanographical data and should be related to actual field measurements in the near future. Further studies are obviously needed for a better understanding of the mechanisms associated with fine-grained sediment transport (in particular, to the DMC). Special attention should be given to understanding the nature of physical processes that favour the existence of preferential mud deposition areas in the mid-shelf, to verifying whether the transport to the DMC patch is limited only to winter conditions or if it can also occur in summer, and to evaluating the relative importance of waves and currents in bottom sediment transport.

Acknowledgement

Contribution Project FCT no. 2248/95.

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