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Geomorphological control of fine sedimentation on the northern Portuguese shelf

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ABSTRACT

Six cores sampled at two mud fields located on the northern Portuguese continental shelf have been studied in order to evaluate the control processes of fine sedimentation. The southern mud patch, offshore from the Douro River, is limited on the western side by some Cretaceous and Paleocene outcrops that constitute reliefs of 5-30 m in width; on the contrary, the northern mud patch, offshore from the Minho River, extends along a flat region. Granulometric distribution shows that the sediments from the Minho mud patch are coarser than those from the Douro mud patch, where the grain size diminishes towards the west. Carbonate content is also higher in the Minho mud field. The sediment organisation in fining-up sequences in the Minho mud patch and in the eastern part of the Douro mud patch indicates sediment remobilisation by storms. The Douro mud patch has higher sedimentation rates than the Minho mud patch. The highest values are probably related to the existence of reliefs, which may offer hydrodynamic protection or function as a fine sediment barrier. The elemental distribution for chemical elements was determined in different fractions of these cores. Geochemical patterns are generally quite similar for both mud fields, indicating a common continental origin for the sediments. The major differences in the chemical composition are mainly controlled by the grain-size distribution, either reflecting the presence of coarse quartz particles or a local enrichment in biogenic material.

Key words: Mud patch, continental shelf, sedimentation rate, geomorphological control, chemical composition, sediment remobilisation.

RESUMEN

Control geomorfológico para la sedimentación de fangos en la zona norte de la plataforma continental portuguesa

En este trabajo se han estudiado seis testigos de la zona norte de la plataforma continental portuguesa con el objetivo de evaluar los procesos que controlan la sedimentación de materiales finos en esta región. Los fangos acumulados más al sur, frente a la desembocadura del río Duero, están limitados al oeste por relieves cretácicos y paleocenos de 5 a 30 m de altura. Los fangos septentrionales, frente a la desembocadura del río Miño, se extienden sobre una región plana. La distribución granulométrica muestra que estos últimos son más gruesos que los depositados frente al Duero, en los que el tamaño de grano disminuye hacia el oeste. El contenido en carbonato es más elevado en la zona del Miño. Las secuencias granodecrecientes encontradas en los fangos del Miño y en los del sector oriental del Duero indican retrabajamiento del sedimento por tormentas. La tasa de sedimentación es mayor en los fangos situados frente al Duero, donde los valores más altos están relacionados probablemente con la existencia de relieves, los cuales ofrecerían una protección hidrodinámica o actuarían como una barrera para los sedimentos. La distribución de la concentración de diversos elementos químicos a lo largo de los testigos fue determinada para diferentes fracciones. El patrón geoquímico *es bastante similar en ambas zonas y pone de manifiesto una procedencia continental de los sedimentos. Las principales diferencias en la composición química están fundamentalmente controladas por la distribución granulométrica, bien por la presencia de granos gruesos de cuarzo, bien por un enriquecimiento local en material biogénico.*

Palabras clave: *Fangos, plataforma continental, tasa de sedimentación, control geomorfológico, composición química, resedimentación.*

INTRODUCTION

The location of muddy bottom on the continental shelf depends on different factors, which include the amount of suspended particulate matter, the characteristics of their sources, and the hydrodynamic energy related with the transport and/or deposition of the suspended fine particles (McCave, 1972). The interaction of these parameters leads the existence of variable sites of mud deposits, which can occur as muddy coasts, nearshore, mid-shelf and outer-shelf mud belts and shelf mud blankets (McCave, 1972). A good example of this is the nearshore muddy body in the East China Sea (DeMaster *et al.*, 1985), the mid-shelf muddy body on the Washington shelf (Smith and Hopkins, 1972), or even the mud-blanket on the Valencia (Spain) continental shelf (Maldonado *et al.*, 1983).

The deposition of fine sediment particles is principally dependent on hydrodynamism, which has to be low enough to allow them to settle down. However, the morphological environment may also influence the location or even induce sediment trapping in two ways: by the existence of a depression that may be preferentially filled in relation with other adjacent zones; or by the existence of rock outcrops that may create hydrodynamic protection (contributing to a local lower energy area), functioning as a barrier for the sediments transported by the bottom nepheloid layer, which is intensified during storms.

On the northern Portuguese continental shelf, two mud fields are located offshore from the Douro and Minho Rivers, whose depths vary from 65-35 m, and are north-south oriented (figure 1). The Douro mud patch is limited on the western side by Cretaceous and Paleocene outcrops (respectively, mudstones and detritical mudstones) with a width of 5-30 m (Drago *et al.*, 1994; Drago, 1995). On the other hand, the Minho mud patch extends over a large region of the shelf that is not steep. Sedimentation rates previously determined by the ^{210}Pb technique (Carvalho and Ramos, 1990), in cores collected from both mud fields, revealed higher nourishment in the Douro mud patch. In fact, whereas in the Minho mud patch the sedimentation rate determined for one core was 0.10 cm/year, in the Douro mud patch, the values obtained in the study of two cores were 0.16 cm/year and 0.55 cm/year.

In the present paper, six cores collected at different sites of the two mud patches were submitted to X-ray radiography and subsequently studied by using different methods. The granulometrical distribution, carbonate content, accumulation rates and chemical composition were determined in different defined sections downcore.

The present study is an attempt to contribute to the knowledge of the fine sediment trap processes along the northern Portuguese shelf, in particular at the two mud patches, and to the evaluation of how geomorphological differences may influence fine sediment deposition.

MATERIALS AND METHODS

Six sediment cores with lengths varying from 20-85 cm were collected at the mud fields on the northern Portuguese shelf: two in the Minho mud field (CG11 and CG12) and four in the Douro mud field (CG4, CG6, CG9 and CG15) (figure 1). Samples were collected with a gravity-corer from R/V *Almeida Carvalho* during the cruise GEOMAR 92, in November 1992. After collection, the cores were refrigerated. Later they were longitudinally opened and described. One of the halves of each core was X-rayed in order to analyse the lithological characteristics and sedimentary structures, while the other was sampled along the entire core with a plastic spatula to avoid metal contamination.

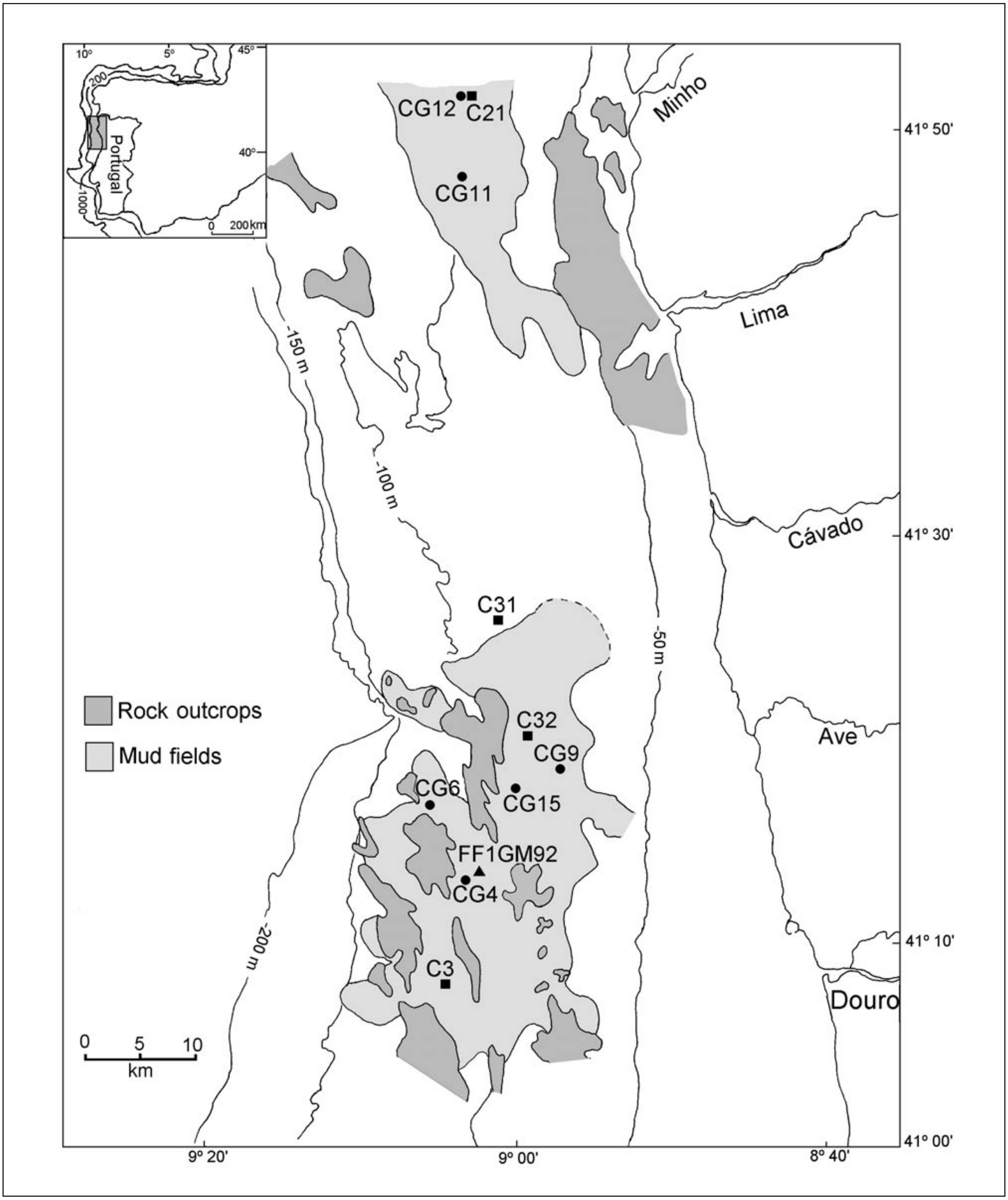

Figure 1. Location of the northern Portuguese continental shelf mud fields and the cores studied. (●): in this work; (■): by Carvalho and Ramos, 1989; (▲): by Drago, 1995

The lithological composition was examined using a MALVERN 3600E laser diffraction particle sizer, and the carbonate content was measured by the volumetric method. The ^{210}Pb radiochronology was performed over 45 levels in the six cores. The boundaries and geometry of the muddy deposits were determined by means of high frequency (72 J) with Sparker equipment. The chemical composition of 45 segments from the six cores were determined by energy-dispersive X-ray fluorescence spectrometry (EDXRF), with a Kevex Delta XRF Analyst System. The bulk sediment samples were prepared and analysed according to a recently described procedure (Araújo, Valério and Jouanneau, 1997) and a total of 15 elements were determined (Al, Si, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Rb, Sr, Zr and Pb).

RESULTS

Sediments of the two mud fields are homogeneous, moderate olive-brown (5y 4/4) and olive-grey (5y 3/2) silty-clayed mud. This homogeneity is also evident in the X-ray analysis, which only revealed some parallel thin horizontal or sub-horizontal regular layers (about 1 mm thick) and plane, low-angle erosional contacts. Sedimentary structures with a biological origin are limited to some gastropods, bivalve shells and bioturbation.

Grain size

Grain-size analysis indicates that the Minho mud patch cores are coarser than the Douro patch samples (figure 2). In the northern mud patch, the sand percentage varies between 20-60 % in the CG11 core, and between 10-40 % in the CG12 core. In the Douro mud patch, the grain-size distribution decreases from east to west: the sand percentage (> 63 µm) varies from 20 % to 60 % in the east (CG9), 10-15 % in the central zone (CG15 et CG4) and 8-12 % in the west (CG6). We noted that all cores collected at the Douro mud patch present an abrupt variation in the grain-size distribution at a depth of around 20 cm, which is visible as an erosion contact in the X-rays.

The mean grain-size distribution is quite constant, varying between 10 µm and 40 µm, except for the CG9

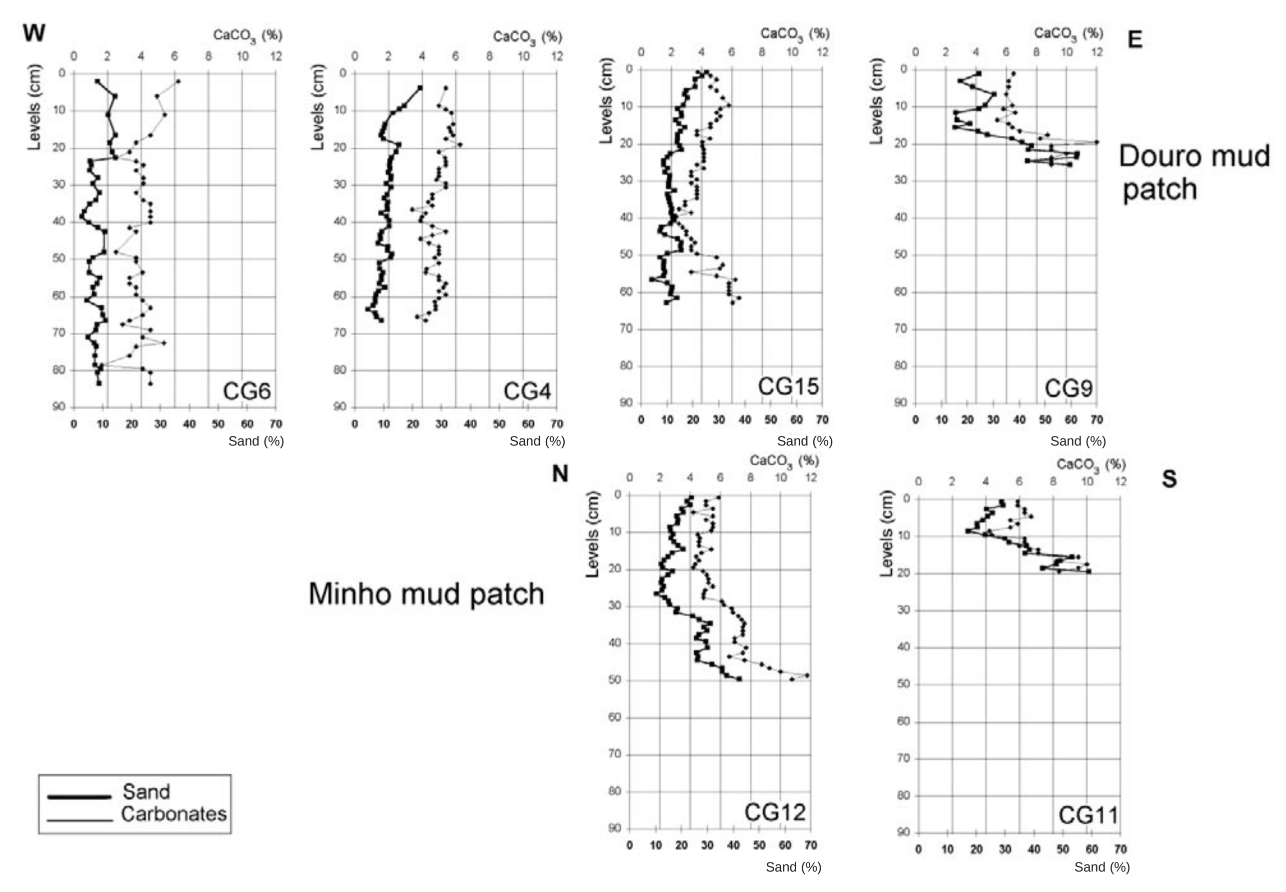

Figure 2. Sand and carbonate contents of sediments from the Douro and Minho mud fields

(Douro mud patch) and CG11 (Minho mud patch) cores, whose mean grain-size may reaches about 70-80 μm. Despite their different location, these two cores present similar lithological characteristics.

Carbonate content

The carbonate content determined varies approximately between 2-12 % (figure 2). In the Minho mud field, the carbonate percentage is higher when compared with the Douro mud complex. In the former, the average is about 7 % (varying between 4-12 %), while for the latter, the mean value is 5 % (ranging from 2-6 %, except the CG9 core, which reaches 12 %).

In some cases, as in the basal part of CG9 (Douro), CG11 and CG12 (Minho) the distribution of $CaCO_3$ is directly correlated with the sand percentage (figure 2) because the carbonate fraction is mainly represented by biogenic coarse particles. When the vertical variation shows a simultaneous decrease of grain size and carbonate content, it corresponds to a fining-up sequence due to a storm event.

On the contrary, we can observe in the upper layer an increase of carbonate content that could correspond to a higher density of benthic fauna at the interface. In that case, no clear correlation between $CaCO_3$ and grain size exists.

Sedimentation rate

The ^{210}Pb excess vertical distribution is represented in figure 3. Profiles mostly show a decrease in the ^{210}Pb activity, to value close to zero. This seems to happen in the upper 20 cm of the Douro mud patch and in the upper 5-10 cm for the Minho mud patch, which means that these sediments have been deposited during the last 100 years (Koide, Bruland and Goldberg, 1973). However, in some ^{210}Pb activity profiles, an increase has been measured in deeper layers, which may be attributed to the reworking of upper sediments caused by bioturbation.

Based on the ^{210}Pb excess values, we have determined the maximum sedimentation rates (we have not taken into account the bioturbation effect),

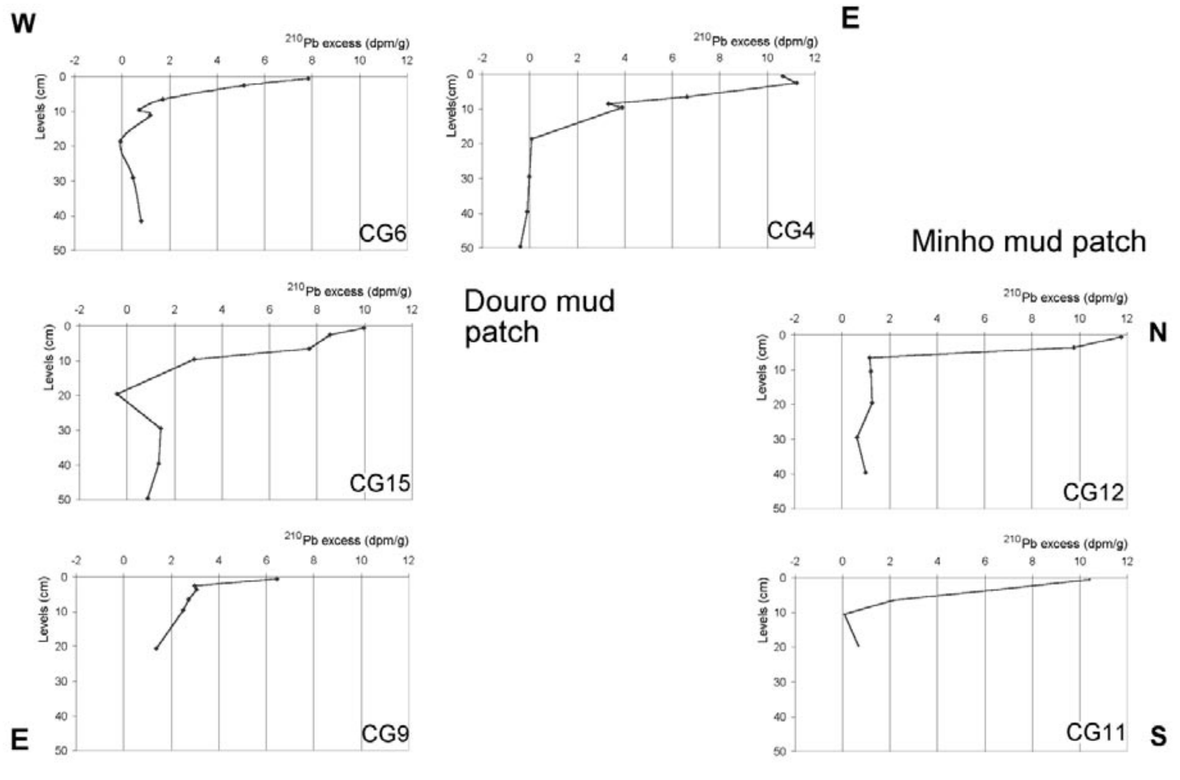

Figure 3. ^{210}Pb excess activity profiles of the mud-field cores

which are shown in table I. We have also compared the results obtained with those reported by Carvalho and Ramos (1990) and Drago (1995).

It is evident that the sedimentation rates in the Douro mud patch are higher than those of Minho mud patch. Whereas in the cores sampled at the Douro patch, values range from 0.17 to 0.58 cm/year, the Minho mud patch presents low and homogeneous values, not exceeding 0.17 cm/year.

On other hand, in the Douro mud patch, the stronger sedimentation rates are located just to the east of the outcrops (0.31-0.58 cm/year), whereas on the borders, values are weaker (around 0.17-0.28 cm/year) (table I and figure 1).

Chemical composition

The chemical composition of the different segments of the cores from the Douro and Minho mud fields are listed, respectively, in tables II and III. Sediment elemental composition revealed higher percentages of Si in the Minho mud patch than in the Douro sedimentary deposit. In fact, in the Minho mud patch, Si percentages vary between 28.5-30.0 % in core CG11 and between 26.5-28.9 % in core CG12. Cores collected at the Douro mud patch show a general decrease in Si towards the west, varying between 27.3-30.1 % near the east mud patch border (core CG9), and between 19.7-27.1 % for core CG6, the westernmost core.

Aluminium distribution shows an opposite behaviour, i.e. a strong negative correlation with Si, since the highest percentages were measured for the samples collected in the Douro mud patch, with a decreasing tendency towards the east. This is related to grain-size distribution, because Si is usually associated with the sand fraction, while Al is enriched in the finer fractions (clay minerals).

The downcore elemental profiles of four cores collected at the Douro deposit (CG6 and CG9) and at the Minho deposit (CG11 and CG12) are represented in figure 4. It is noteworthy that in spite of their different origins, the downcore profiles of both CG6 and CG12 cores show some similar trends. The Al distribution exhibits a minimum value at a depth of approximately 50 cm, which apparently corresponds to an enrichment in the coarser fraction (see figure 2, granulometry and figure 4). However, for CG6, this impoverishment in Al is due to a prevalence of quartz and heavy minerals, since higher Ti and Zr concentrations have also been determined. In core CG12, at the same depth, the low Al value is certainly the result of a dominance of biogenic material, because of the high Ca percentages and carbonate content (figure 2 and figure 4).

In addition, the downcore elemental distribution profiles of cores CG9 (Douro) and CG11 (Minho) show striking similarities. Opposite variations in the Al and Si and Al and Ca content seem to be related to the sediment grain-size distribution. This is because coarser particles are usually enriched with Si or Ca due to a predominance of quartz particles or biogenic materials, respectively. The only exception is the Zr content, higher in CG9, probably due to an enrichment in heavy minerals, which tend to settle faster. Also, in a previous study (Araújo *et al.*,1995) 'anomalously' high contents of Zr (and rare earth elements) were mea-

Table I. Maximum sedimentation rates for the northern Portuguese continental shelf mud fields

Site	Core no.	Latitude N	Longitude W	Depth (m)	Sedimentation rate (cm/year)	Authors
Minho mud patch	C21A	41° 52' 06"	9° 03' 36"	103	0.10	Carvalho and Ramos (1989)
	CG11	41° 48' 11"	9° 04' 03"	107	0.14	This paper
	CG12	41° 52' 19"	9° 04' 01"	113	0.16	This paper
Douro mud patch	C3 (G)	41° 08' 18"	9° 04' 30"	100	0.16	Carvalho and Ramos (1989)
	C32 (B)	41° 20' 06"	8° 59' 24"	75	0.55	Carvalho and Ramos (1989)
	FF1GM92	41° 13' 30"	9° 02' 40"	100	0.57	Drago (1995)
	CG6	41° 16' 51"	9° 06' 15"	124	0.17	This paper
	CG15	41° 17' 41"	9° 00' 31"	89	0.58	This paper
	CG4	41° 13' 14"	9° 03' 29"	104	0.35	This paper
	CG9	41° 18' 41"	8° 57' 34"	81	0.17	This paper
North of Douro patch	C31 (G)	41° 25' 30"	9° 01' 24"	80	0.07	Carvalho and Ramos (1989)

Table II. Elemental composition of CG4, CG6, CG9 and CG15 cores from Douro mud field and the average shale composition (Salomons and Förstner, 1984) in mg/kg unless otherwise indicated

Core	Depth (cm)	Al (%)	Si (%)	K (%)	Ca (%)	Ti (%)	Cr	Mn	Fe (%)	Ni	Cu	Zn	Rb	Sr	Zr	Pb
CG4	0-7	6.58	26.3	2.24	2.20	0.41	41	278	3.06	29	32	83	164	153	229	52
	12-13	7.70	23.9	2.47	2.27	0.42	72	329	3.82	33	25	92	183	156	187	39
	22-23	6.99	24.5	2.36	2.14	0.42	66	310	3.47	34	24	76	173	150	208	23
	32-33	7.41	23.2	2.44	1.95	0.42	62	350	3.87	34	23	92	185	156	183	29
	42-43	7.70	23.7	2.45	1.82	0.43	69	360	3.83	30	22	87	186	150	190	31
	52-53	7.92	25.4	2.50	1.62	0.43	54	350	3.82	34	25	91	195	147	196	25
	62-63	7.98	23.6	2.53	1.88	0.44	77	395	3.92	34	22	90	190	154	200	32
CG6	0-4	7.52	23.3	2.43	2.94	0.41	74	319	3.67	34	25	86	174	174	170	49
	4-8	6.66	21.9	2.80	2.72	0.43	73	353	3.56	38	24	84	184	167	185	33
	10-12	7.65	22.9	2.42	2.44	0.43	80	337	3.53	35	41	85	176	174	203	61
	17-18	7.83	23.3	2.39	1.87	0.42	72	342	3.52	41	23	83	177	175	200	69
	20-22	7.54	23.2	2.29	1.45	0.43	44	359	3.37	32	22	78	165	137	252	34
	27-29	8.33	19.7	2.49	2.14	0.42	72	465	4.43	39	28	102	186	188	143	48
	31-33	8.56	21.7	2.56	2.16	0.44	70	486	4.50	41	29	98	188	179	150	37
	36-38	8.97	21.7	2.66	1.88	0.43	92	503	5.01	37	30	101	193	177	141	34
	45-47	5.85	27.1	1.96	1.32	0.52	43	405	2.58	35	19	66	135	117	415	10
	54-56	7.48	25.4	2.40	1.56	0.49	75	428	3.55	30	22	85	172	137	279	25
	62-64	8.69	21.2	2.52	1.79	0.42	76	533	4.69	40	30	103	195	158	142	31
	68-70	8.78	22.5	2.65	1.79	0.43	65	543	4.51	38	27	102	201	158	150	30
	75-77	9.31	21.7	2.70	1.61	0.43	83	484	4.75	46	30	109	207	152	137	53
	81-82	8.37	21.8	2.56	2.24	0.42	93	454	4.32	37	24	100	188	163	152	41
	87	8.56	21.7	2.64	2.35	0.42	81	415	4.29	42	33	98	192	171	150	30
CG9	0-2	5.12	30.1	2.06	2.28	0.42	64	237	2.33	21	21	70	145	166	462	37
	5-6	5.46	29.3	2.12	2.45	0.39	54	275	2.55	27	19	69	152	179	377	35
	10-12	6.59	27.3	2.25	2.28	0.42	63	292	3.08	30	22	72	163	173	320	29
	18-20	4.22	29.4	1.89	3.68	0.35	19	212	1.87	20	18	46	128	244	433	19
CG15	3-4	6.47	26.5	2.32	2.24	0.42	43	289	3.03	35	23	80	165	153	257	40
	8-9	6.89	25.7	2.41	2.43	0.41	58	296	3.38	33	22	85	171	160	229	40
	12-14	7.39	25.6	2.47	2.19	0.43	78	314	3.57	35	20	84	172	151	221	28
	22-24	7.31	25.3	2.44	1.91	0.43	75	379	3.66	37	23	83	175	153	210	21
	32-34	7.56	24.6	2.52	1.80	0.43	63	350	3.81	36	23	86	176	146	202	25
	42-44	8.03	24.7	2.61	1.35	0.47	73	526	3.99	42	28	91	185	139	227	23
	52-54	8.29	23.6	2.70	1.73	0.44	72	428	4.28	42	24	94	198	148	166	30
	58-60	7.44	24.3	2.57	2.03	0.42	58	382	3.82	37	23	87	187	164	187	34
Average shale		8.0	27.3	2.7	2.2	0.50	90	850	4.7	68	45	95	-	140	160	20

Table III. Elemental composition of CG11 and CG12 cores from Minho mud field and the average shale composition (Salomons and Förstner, 1984), in mg/kg unless otherwise indicated

Core	Depth (cm)	Al (%)	Si (%)	K (%)	Ca (%)	Ti (%)	Cr	Mn	Fe (%)	Ni	Cu	Zn	Rb	Sr	Zr	Pb
CG11	1-3	5.34	30.0	2.32	2.62	0.36	52	254	2.78	24	22	69	145	163	275	32
	8-10	6.19	28.5	2.49	2.52	0.38	57	282	3.20	30	25	69	161	165	266	26
	13-15	4.62	29.6	2.23	3.36	0.32	52	228	2.61	22	19	54	137	186	278	22
	17-18	4.18	29.4	2.10	4.50	0.28	24	185	2.40	20	20	45	120	214	286	20
CG12	1-3	6.09	28.0	2.40	2.29	0.39	54	268	3.00	24	25	84	159	155	258	78
	8-10	6.81	27.8	2.58	2.22	0.41	51	326	3.44	37	26	78	172	159	246	22
	13-15	6.95	26.6	2.59	1.96	0.42	70	329	3.50	33	23	79	177	156	244	32
	17-19	7.05	26.5	2.69	1.76	0.42	55	369	3.84	36	28	86	188	154	222	35
	27-29	7.03	26.9	2.61	2.33	0.40	66	315	3.54	30	25	85	182	166	218	38
	37-39	5.53	28.2	2.36	3.23	0.36	49	251	2.84	25	22	65	156	197	267	22
	47-49	4.66	28.9	2.14	4.62	0.33	53	213	2.53	24	19	56	131	228	275	23
	57-59	6.70	26.8	2.44	2.49	0.37	55	291	3.85	34	29	79	143	176	189	32
Average shale		8.0	27.3	2.7	2.2	0.50	90	850	4.7	68	45	95	-	140	160	20

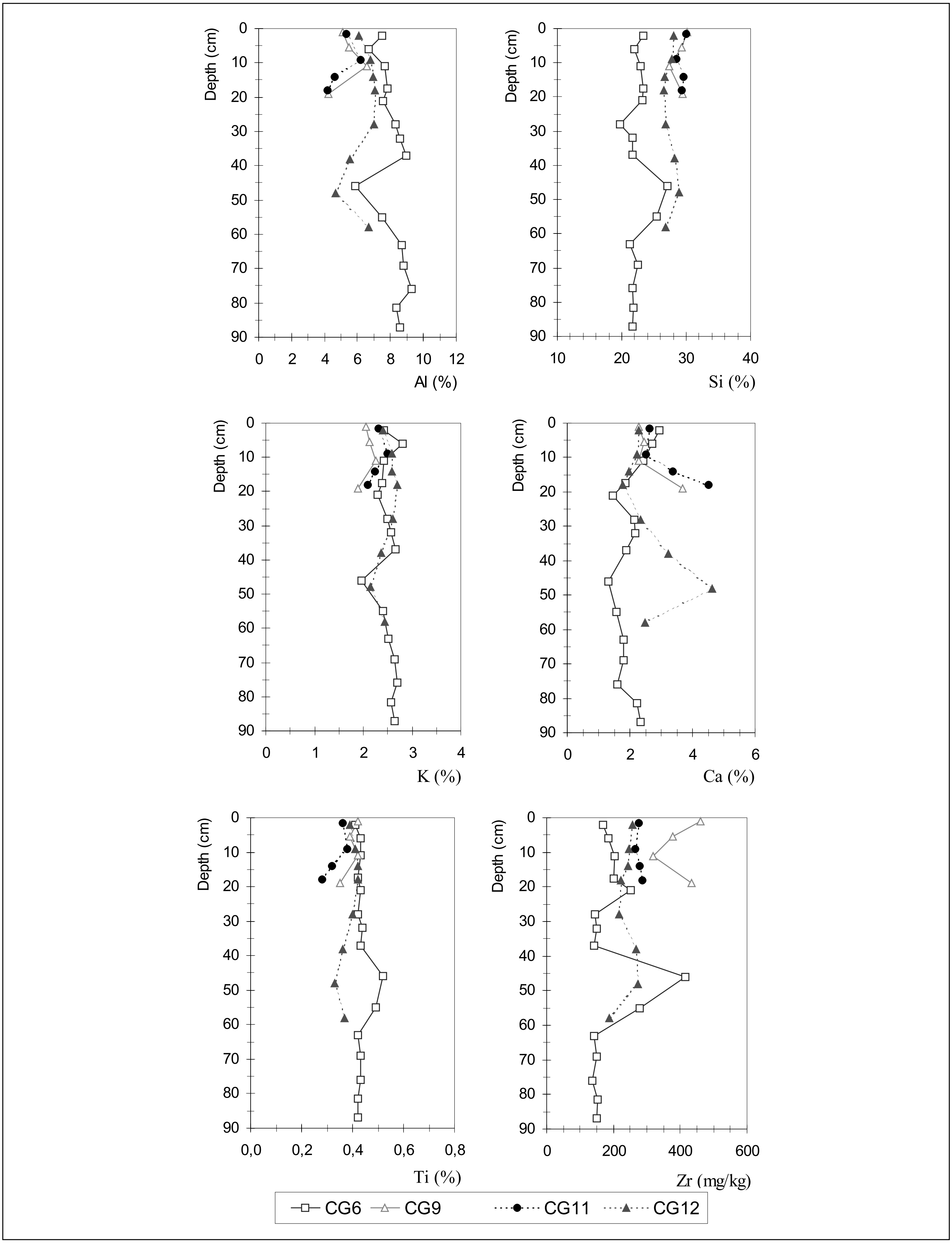

Figure 4. Comparison of the elemental distribution of downcore profiles from Douro (CG6, CG9) and Minho (CG11, CG12) mud fields

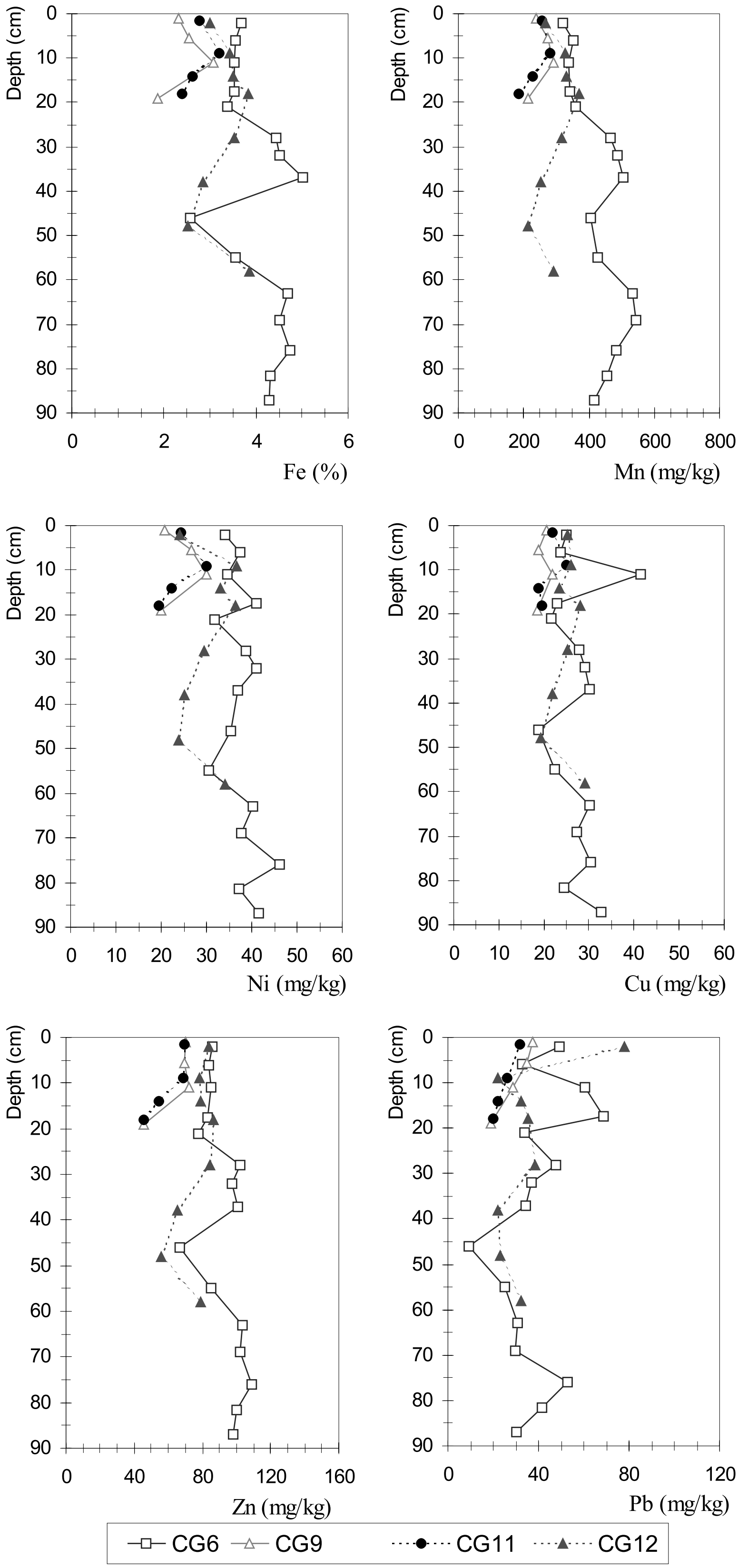

Figure 4 (continued)

sured in samples collected at the inner region of the shelf close to the river mouth.

Trace metals profiles, as well as Mn and Fe content, exhibit a similar trend to the Al downcore distribution, which seems to indicate that the differences in trace metal concentrations can be attributed to particle sorting. In general, trace metal concentrations (tables II and III) are low when compared with published reference values for non-polluted sediments, such as the average shale composition (Salomons and Förstner, 1984).

However, for some of the anthropogenic elements, we found two apparent exceptions: an enrichment in Pb in the top layers of cores CG4 (Douro) and CG12 (Minho), and in Zn (and to a lesser extent in Pb) in some deep layers (figure 4). However, it is difficult to conclude a possible anthropogenic origin for either of these, since their location is rather distant from the coast, or a composition mostly related to grain-size distribution, since these fractions also present the highest Al content. In any case, these ‘enrichments’ are apparently not significant, since they usually do not exceed 10 %.

DISCUSSION

From these results, three processes can be differentiated:

1. Suspension transport of terrigeneous allochtonous material from estuaries

This first process acts on suspended matter coming from different continental sources. This inorganic fine-grained fraction represents 70 % of total sediment over the shelf mud blankets. Since the elemental distribution is rather similar to that of the average shale, the geochemical patterns of the cores collected from fine sedimentary deposits indicate a common continental origin for the sediments. Concentrations in trace metals are rather low; however in marine sediments their distribution is usually determined by inorganic detrital materials whose main constituents (quartz, feldspars and carbonates) are poor in trace elements and serve to dilute other phases richer in these elements (e.g. clay minerals). It is noteworthy that two cores from different sedimentary deposits (CG9 and CG11) exhibit striking similarities (namely, chemical composition, accumulation rates and grain-size distribution).

2. Bedload transport by storm effects and/or wave action of autochtonous biogenic coarse fraction

The marine influence is visible by some higher concentrations in Ca and Sr, associated with an increase in grain size. The widest variations observed in the elements are highly correlated with grain-size distribution. The most noticeable difference is Zr content, highest in core CG9 (Douro), indicating an enrichment in zircon in the inner region.

In some cases, the close relationship between coarse fraction (> 63 µm) and carbonate content indicates that the grain-size variation reflects hydrodynamic evolution occurring during storm events or strong swell periods.

Therefore, the general decrease in sediment particle size westward across the Douro mud blanket leads simultaneously to their removal from sources and the increase in depth, favouring deposition processes with a horizontal sorting.

The sediment organisation in fining-up sequences observed in the Minho mud blanket (CG11, CG12) and in the eastern part of the Douro mud patch (CG9) is a result of the remobilisation of the sediments from the superficial layer by episodic storm events. The sediment must be transported near the bottom, and in this case, the bottom nepheloid layer acquires great importance in the mud patch supply.

3. The role of geomorphological features

A particular distribution of the sequence types and differences in the sedimentation rates have been identified as functions of the location.

Sedimentation rates calculated for the six cores collected at both mud patches are in agreement with those of Carvalho and Ramos (1990). We determined sedimentation rates of around 0.15 cm/year and 0.17 cm/year for the Minho patch, and values ranging from 0.17 cm/year to 0.58 cm/year for the cores collected at the Douro mud patch. In this case, some of the values are significantly higher than those determined for the mid-shelf mud body on the Washington shelf, e.g. 0.3 cm/year (Nittrouer *et al.*, 1979) or even for the Gironde mud patch (0.3-0.4 cm/year) (Lesueur *et al.*, 1989).

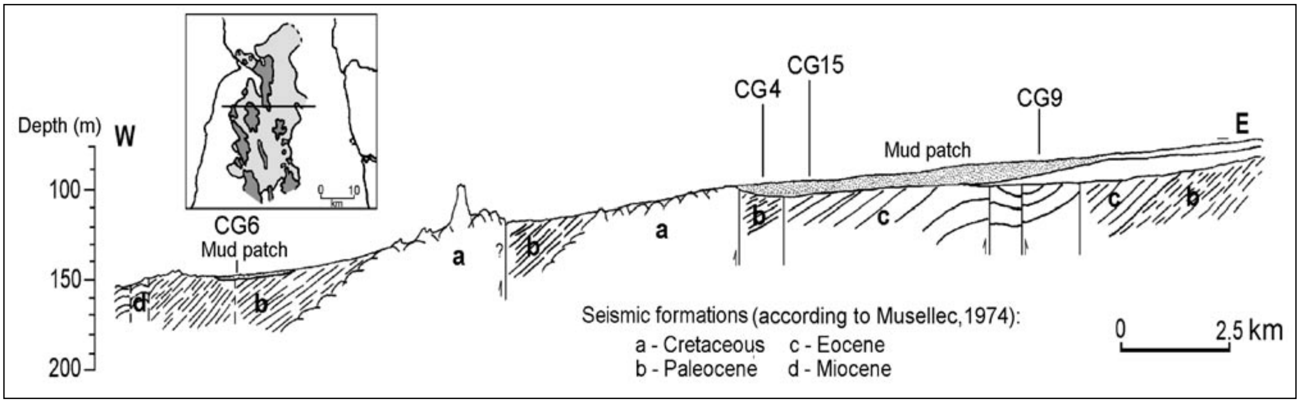

Figure 5. Seismic reflection profile of Douro mud patch and schematic location of the cores

In the Douro mud patch, the higher sedimentation rates are located immediately east of the Cretaceous and Paleocene outcrops. On the other, the lowest sedimentation rates are present in the boundaries of this muddy body. These characteristics are apparently independent of depth, and seem to be closely related to the Cretaceous and Paleocene outcrops (figure 5).

These reliefs may provide a lower hydrodynamic environment with conditions more favourable to fine sediment deposition and/or they may function as a barrier for bottom nepheloid layer, provoking sediment trapping. In this case, the sediments are trapped east of the reliefs and they are hindered to travel for greater depths.

The low sedimentation rate measured for the easternmost core is probably related to a more energetic environment at the lower depth with a weaker fine sedimentation.

In the Minho mud patch, the lower sedimentation rates are also probably the result of a dispersion of the fine sediments into a wide and open area, with no obstacles, and consequently resulting in a greater homogeneity in sediment distribution.

However, the general circulation over the northern Portuguese continental shelf under winter conditions involves a sediment transport towards the northwest (Drago *et al.*, submitted) enhancing the sedimentation close to the outcrops.

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