Calcareous nannoplankton as a tracer of the marine influence on the NW coast of Portugal over the last 14 000 years

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Abstract A calcareous nannoplankton taphonomic and palaeoecological study was performed on cores from the Minho and Douro Estuaries (NW Portugal) and from the NW Portuguese middle continental shelf. Because certain nannoplankton species are taphonomically resistant to the highly energetic and aggressive conditions between the estuaries and the shelf, their sedimentary record acts as an oceanic tracer in such coastal domains. For the Late Quaternary, this allows interpretation of eustatic variation from the induced sequence of palaeoenvironmental changes. Palaeogeographically, the time-series pattern of nannofossil abundances in these coastal sediments is interpreted as follows: (1) persistently high amounts of nannofossils (2×10^7 nannofossils/g) are related to marine environmental conditions, produced by post-glacial flooding of pre-existing valleys; (2) the gradual increase in intermittency of nannofossil abundances through time indicates a regressive trend, first due to recovery of the estuarine conditions, followed by a total absence of nannofossils, indicating evolution towards complete emersion either by fluvial (Core CPF1) or barrier-beach sediments (Cores M1, M2, D1A and D1B). During the Late Holocene, the nannoplankton assemblages were similar to those found in Present Day neritic conditions. The main taxa comprise *Gephyrocapsa* spp., *Helicosphaera carteri*, *Emiliania huxleyi* and *Coccolithus pelagicus sensu lato*. An unexpected and extremely high percentage of *H. carteri* in the Douro Estuary's mouth was likely related to local confinement, which probably provided adequate and particular nutrient concentrations that prompted opportunistic behaviour in this species.

Keywords Calcareous nannoplankton, taphonomy, Quaternary eustatic variations, NW Iberia, Minho Estuary, Douro Estuary, coastal palaeogeography

1. Introduction

The littoral zone is a region of great instability, in which marine and terrestrial domains interplay, both characterised as being particularly sensitive to a variety of climatic, oceanographic and geological processes. Their ecosystems are highly productive, constantly changing their interface, and controlled by global (*e.g.* glacio-eustacy and climate), as well as local, factors (such as sedimentary discharge and antropism) (Drago *et al.*, 2002).

Estuaries represent the main channels for supply of nutrients and terrigenous material to the ocean. Most Present Day Portuguese estuaries have lost their typical 'v'-shaped profiles and acquired flat-bottomed valleys, as a result of sedimentary infilling induced by Holocene base-level elevation (Andrade, 1998). Consequently, they tend to exhibit extensive sedimentation in distal alluvial plains, forming estuarine flats and marshes, and frequently have undergone intense infill of the valley's interior sections. This infill represents high-resolution sedimentary sequences that allow documentation of marine/fluvial interactions during the Upper Quaternary (Freitas, 2003). Chemically, estuaries are characterised by a high spatial and temporal variability of environmental conditions, particularly as far as salinity is concerned (Ortega *et al.*, 1994). The transformation of certain elements from a solution state into a particulate phase, and their subsequent stock-piling in the sediments, turns estuaries into sources of nutrients and a number of metals that are commonly transported by rivers (Ortega *et al.*, 1994).

River discharge into the ocean frequently produces temperature, salinity and turbidity plumes along the coastline, due to the different physical parameters that distinguish fresh from marine water (Oliveira *et al.*, 1994). According to Baumann *et al.* (2002), nutrients transported by upwelling promote high biological productivity along coasts, such as the Portuguese west coast, mainly in the proximity of capes. In such an upwelling coastal region as that of the study area, phytoplankton assemblages may be controlled by certain trophic axes, related to turbulence degree and nutrient availability (Margalef,

1997). Therefore, regions located in proximity to continental margins, which are characteristically turbid, are associated with situations where spatial confinement of nutrient-rich conditions may occur (Cachão & Moita, 2000). On the other hand, understanding of the physical, geological and biological processes that occur above the middle continental shelf is also important to allow tracking and quantification of the nutrient flux that is being introduced into the shelf-break zone (Oliveira *et al*., 2002), as well as the possible influence of the nannoplankton, as recorded in both the water-column and the sedimentary record.

Considered as an oligotrophic group, some calcareous nannoplankton species seem to have developed delicate and highly elaborate morphologies, possibly to favour buoyancy (*e.g. Discosphaera tubifera*, *Umbellosphaera* spp., *Rhabdosphaera* spp.; see Siesser & Winter, 1994; Young, 1994). This may have allowed them to dwell in stratified, nutrient-poor oceanic water-masses and, consequently, to be globally represented in oceanic oozes. Other taxa evolved large coccoliths/spheres (*e.g. Coccolithus pelagicus*: Cachão & Moita, 2000) or developed as r-type opportunists (*e.g. Emiliania huxleyi*: Brand, 1994), possibly allowing them to compete for nutrients in more turbulent water-conditions, such as coastal environments. Their sedimentary record, however, is modified by the hydrodynamics of bottom conditions (Roth & Berger, 1975) that can cause resuspension and dispersion of the nannofossils, and that may prevent them from being deposited with coarser sediments on the inner shelf. Diluted by high sedimentation rates, their deposition occurs both on the middle and outer sectors of the shelf, and on paralic low-energy inlets of the estuaries and lagoon coastal systems (Ferreira & Cachão, 2005; Ribeiro *et al*., in prep.).

Previous studies have already shown the usefulness of nannofossils in multi-proxy studies, tracking marine sedimentation within paralic systems, such as estuaries and lagoons, and contributing valuable information to palaeoenvironmental and palaeogeographic reconstructions (Freitas *et al*., 1999; Drago *et al*., 2003). Using data from the NW Portuguese coast and shelf, the present study aims to add additional support to the use of calcareous nannoplankton to this type of study.

2. Environmental setting of the study area
2.1 General oceanography of the Portuguese middle continental shelf

The Portuguese middle continental shelf presents a generally gentle and regular morphology, with four deep incisions: the submarine canyons of Nazaré, Lisboa, Setúbal and São Vicente. The Oporto Canyon is also one of the important morphological characteristics of the Portuguese shelf (Dias, 1987; Figure 1).

The Atlantic coast of Iberia represents the northern limit of the upwelling zone associated with the North
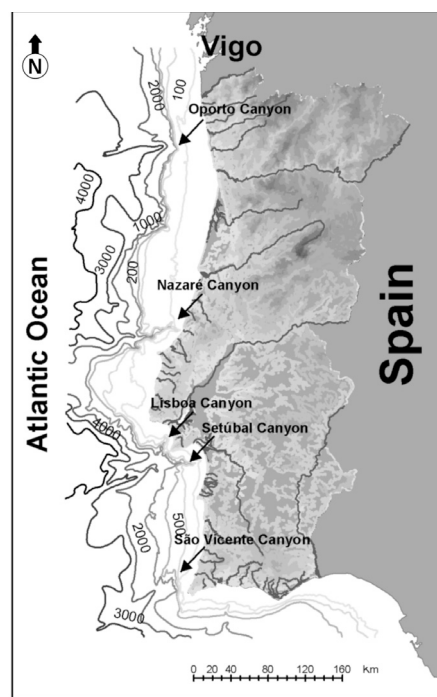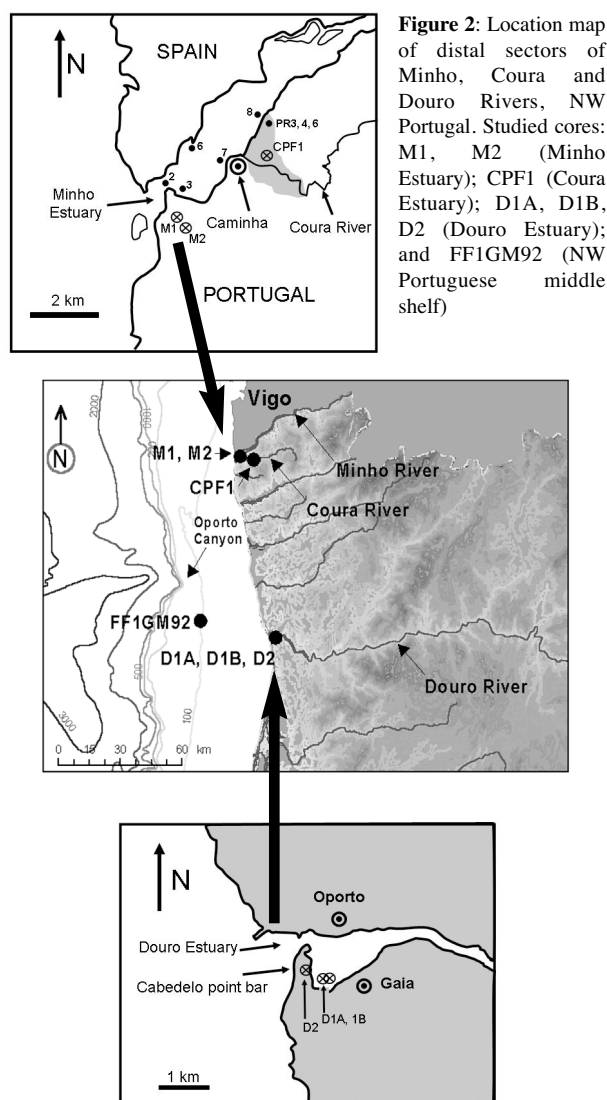

Figure 1: Location map showing NW Portugal submarine canyons and continental shelf

Atlantic Anticyclone Gyre (Woster *et al*., 1976). This is a hydrographically complex region, characterised by the confluence of different water-masses (Fiúza, 1984; Rios *et al*., 1992; Fiúza *et al*., 1998) and currents (Frouin *et al*., 1990; Haynes & Barton, 1990; Dias *et al*., 1996; Fiúza *et al*., 1998). Consequently, Portugal's location on the eastern margin of the North Atlantic Ocean somewhat determines the climatic and oceanographic characteristics of the adjacent oceanic region (Dias, 1987; Oliveira *et al*., 2002), while meteorological conditions are controlled by the Azores High Pressure System.

Summer over the Iberian middle continental shelf is characterised by an equator-ward superficial current, which is controlled by northerly to north-westerly winds that are favourable to upwelling (Fiúza, 1983; Vitorino, 1989; Silva, 1992). Immediately below this southward-flowing current, a polar-ward current was detected. The flux pattern made by both currents is called the Iberian Mid-Shelf Water-Cross Summer Circulation. In the winter, southerly to south-westerly strong winds are favourable to the establishment of a downwelling regime over the shelf, induced by a polar current that persists at all depths (Vitorino, 1989). These patterns are also controlled by the coastal morphology, the upper shelf bathymetry and by local winds (Fiúza, 1983).

2.2 The Minho Estuary

The Minho River (Figure 2) reaches the ocean through a softly contoured estuary, oriented approximately NNE–SSW. Its width is <500m for the lower 25km, gradually increasing in the upper 15km, to reach its maximum width (about 2km) at the confluence with the Coura River,

Figure 2: Location map of distal sectors of Minho, Coura and Douro Rivers, NW Portugal. Studied cores: M1, M2 (Minho Estuary); CPF1 (Coura Estuary); D1A, D1B, D2 (Douro Estuary); and FF1GM92 (NW Portuguese middle shelf)

at Caminha. The River Minho's mouth is narrow, controlled by underwater outcrops, and exhibits a submersed bar with two shallow (~1m) channels, one trending south, the other north. These outcrop ridges reach the water's surface in certain locations near the northern channel (Fatela *et al*., 2003).

The Minho Estuary is affected by a meso- to microtidal system, showing amplitudes of approximately 4m. This value may be significantly amplified during storm-surge episodes. As a result of the tidal regime and the estuary's flatness, tides reach up to 40km upstream, causing intense silt-up, which is reflected in immersion of 70-80% of the estuary's bottom during spring low-tides (Alves, 1996).

High sea-water penetration into the estuary is shown by temperature/salinity (T/S) profiles performed during spring high-tides (summer 2002: Moreno *et al*., 2003). These measurements reveal weak estuarine/strong marine characteristics (salinity = 35–30‰: Moreno *et al*., 2003). The estuary water remains vertically homogeneous until 4km upstream, after which it becomes partially mixed for the next 10km. At low tide, however, almost null salinity

conditions may reach the river's mouth.

The main marsh comprises the area where the tributary issues from the Coura River's mouth, associated with a few small islands and a small marshy area (Figure 2). The Coura River is vertically homogeneous during spring high-tide, losing the marine signature 4km upstream of the confluence with the Minho Estuary. According to Moreno *et al*. (2003), this extreme salinity gradient, which characterises the lower estuary during each tide-cycle, may be causing a strong ecological pressure on the environment, which controls microfaunal (benthic foraminiferal) distributions.

2.3 The Douro Estuary

The Douro River (Figure 2) is one of the most important of Iberia's rivers, being the third longest (927km) and the first in hydrographic basin area. It has very irregular flows, which, in its lower section, may reach 17 000m³/s, during winter, decreasing to <100m³/s during summer. It has the highest rate of sedimentary discharge, representing the NW Iberian margin's main source of fine sediment. Near the river's mouth, >80% of the total terrigenous input is transported in suspension (Dias, 1987).

The Douro Estuary is narrow and funneled, partly barred by a sand-barrier (Cabedelo). The estuary has a minimum width of 135m near Dom Luis Bridge (about 6km upstream of the river's mouth) and a maximum width of 1300m near Arrabida's Bridge. In the presence of large water-volumes (>10 000m³/s), the sand-barrier is destroyed by drainage; this is gradually rebuilt, during decreased flow regimes.

3. Material and methodology

A total of 362 samples were analysed for this study: (1) 23 surface-sediment samples from the Minho Estuary; (2) 201 samples selected from Cores CPF1 (11.5m thick), M1 (28.7m thick) and M2 (21m thick) from the Minho Estuary; (3) 108 samples from D1A (0–7.9m depth), D1B (10.1–19.7m depth) and D2 (20-40m depth), all recovered from the Douro Estuary; and (4) 35 samples selected from Core FF1MG92 (3m thick), recovered from the Portuguese middle shelf, off Oporto, at 100m depth (Figure 2). Sample interval varied from 10 to 20cm, depending on lithology and the texture of the sediments. Since conditions favourable to the settling of calcareous nannoplankton are characterised by low hydrodynamics, silty-clay-richer intervals were sampled in more detail.

As a first stage, a coccolith abundance index (CAI) was determined on randomly selected 30mm traverses of the smear-slide, based on the methodology described in Cachão & Moita (2000). Since the CAI tends to optimise the occurrence of nannoplankton in the sedimentary record, this rippled smear-slide-based technique was used for preliminary recognition and a semiquantitative estimate of abundance.

Absolute abundances were subsequently determined on all samples that were found to contain nannofossils,

using the previous method. Slides were prepared according to the random settling procedure (Flores & Sierro, 1997), adapted for neritic (continental shelf) and paralic (estuarine and lagoonal) facies (Ferreira & Cachão, 2003) by modifying sediment weights and pipetted volumes. Quantification of the calcareous nannofossil content (nannofossil/g) of each sample was determined according to the equation:

$$N = n \times \frac{V}{Vp} \times \frac{Pa}{Oa} \times \frac{1}{W} \qquad (1)$$

where N = nannofossils/g, n = counted number of nannofossils, V = volume of the preparation bottle (10 000ml), Vp = volume pipetted into the Petri dish with coverslip, Pa = Petri dish area, Oa = observed area, and W = sediment weight.

Slides were observed with an optical polarising microscope (Olympus BX-40) at 1250x magnification. Core samples and slides are stored in the Nannofossil and Coastal Sedimentology Laboratories (NanoLab and ProCoast) of the Department of Geology, Faculty of Sciences, University of Lisbon.

4. Results
4.1 Minho Estuary
4.1.1 Surface-sediment samples
Only eight of the 23 surface-sediment samples collected from the Minho Estuary contained calcareous nannoplankton (Figure 3). Highest abundance and diversity was observed
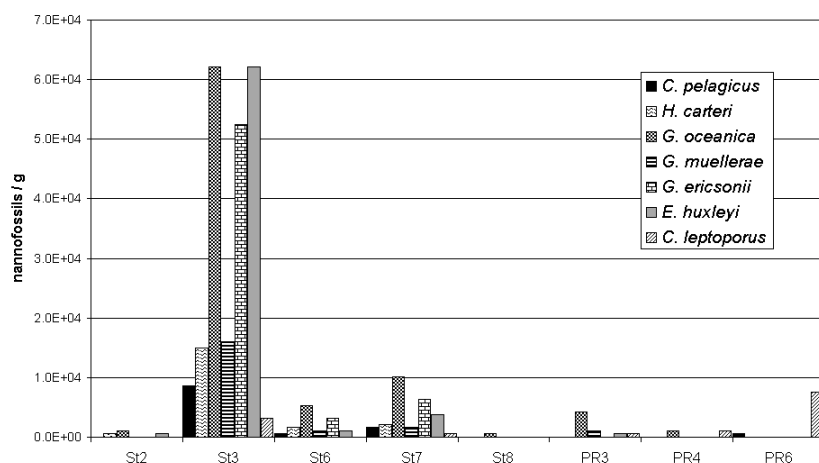
at Station 3 (14×10^6 nannofossils/g). A distinct predominance of *Gephyrocapsa ericsonii* (5×10^4 nannofossils/g), *G. oceanica* and *Emiliania huxleyi* (both with 6×10^4 nannofossils/g) was observed.

4.1.2 Core samples
M1 and M2 recovered the entire Holocene sedimentary sequence. Their lithologies, predominantly fine to very fine sands, display similar variation patterns with depth, reaching the granitic substrate at 28.7m and 21m, respectively (Figure 4). CPF1 consists of 11.6m of homoge-
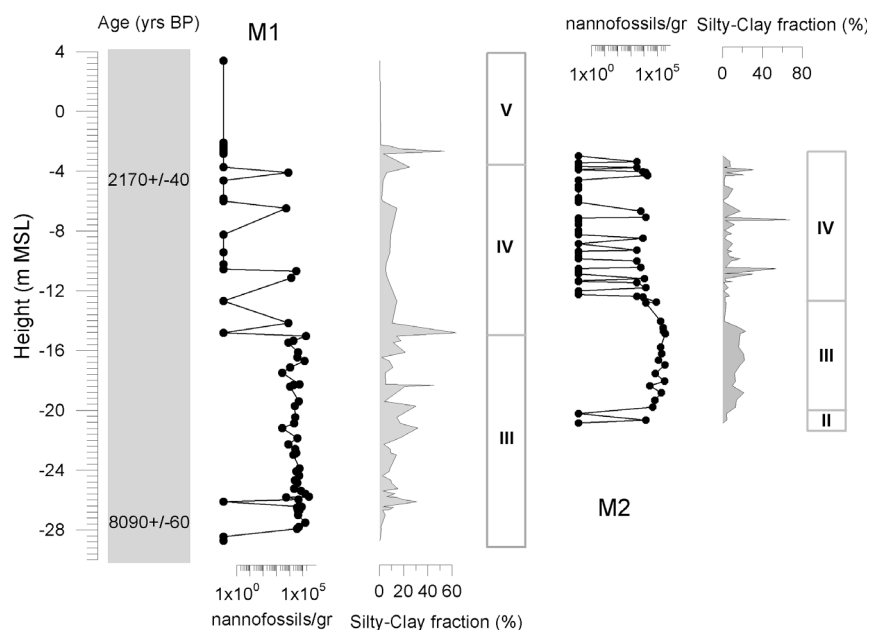

Figure 4: Absolute abundances of calcareous nannoplankton (nannofossils/g) and silty-clay fraction percentages, Cores M1 and M2, Minho Estuary. Model stages: II – first estuarine stage; III – flooded ria stage; IV – second estuarine stage; V – Present Day coastal drift-driven sedimentation stage. Radiocarbon ages in yrs BP

neous silty-clayey, organic-rich sediments (Figure 5).

Highest abundances were found in CPF1, with values reaching 5.2×10^6 nannofossils/g. Core M2 displayed maximum abundances of 4.2×10^5 nannofossils/g, whilst Core M1 had abundance peaks slightly $<3 \times 10^5$ nannofossils/g. Calcareous nannoplankton diversity is slightly higher in CPF1 (Figure 6) than in M1 and M2 (Figures 7 and 8, respectively), although within the same magnitude.

Maximum values of species abundance are (in decreasing order): *Gephyrocapsa* spp., with the predominance of *G. oceanica* (1.3×10^6 nannofossils/g), followed by *G. muellerae* (6.4×10^5 nannofossils/g) and *G. ericsonii* (4.7×10^5 nannofossils/g), *Helicosphaera carteri* (8.2×10^5 nan-

Figure 3: Absolute calcareous nannoplankton abundances (nannofossils/g) in surface sediment samples, Minho Estuary
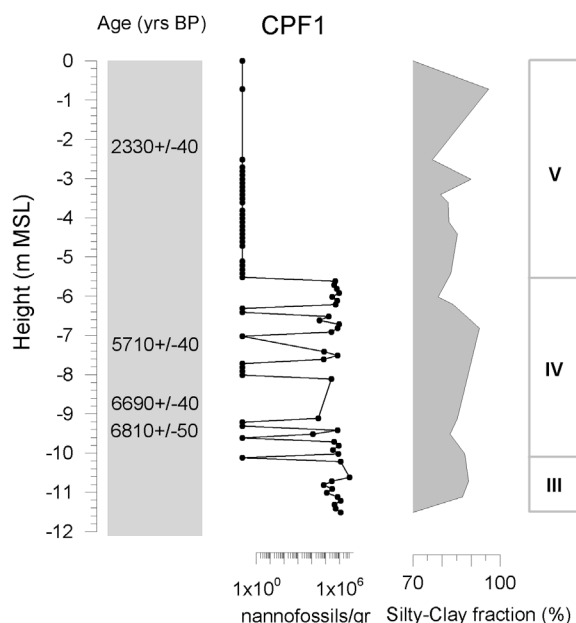
Figure 5: Absolute abundances of calcareous nannoplankton (nannofossils/g) and silty-clay fraction percentages, Core CPF1, Coura Estuary. Model stages: III – flooded ria stage; IV – second estuarine stage; V – Present Day fluvial stage. Radiocarbon ages in yrs BP

nofossils/g), *Emiliania huxleyi* (6.2×10^5 nannofossils/g), *Calcidiscus leptoporus s.l.* (8.8×10^4 nannofossils/g), *Syracosphaera* spp. (1.8×10^4 nannofossils/g), *Umbilicosphaera sibogae s.l.* (1.8×10^4 nannofossils/g), *Coccolithus pelagicus s.l.* (1.4×10^4 nannofossils/g) and *Braarudosphaera bigelowii* (5.4×10^3 nannofossils/g). Ascidian spicules were detected sporadically (1.2×10^4 spicules/g). Despite the fact that *Syracosphaera* spp., *U. sibogae* and ascidian spicules present higher maximum values than *C. pelagicus*, this latter species is generally more consistently present in the studied samples.

Both Cores CPF1 and M2 contain *G. oceanica* as the most abundant species, followed by *H. carteri*. In Core M1, this situation is reversed, with *H. carteri* showing slightly higher abundances.

4.2 Douro Estuary

Cores D1A, D1B and D2 recovered complementary sections of the sedimentary record of the distal Douro Estuary: D2 the lowermost part, D1B the intermediate portion and D1A the uppermost part (Figure 9).

Core D2 is practically barren of nannofossils, with the exception of the uppermost portion. Only the top of the core registered irregular abundances and modestly diverse assemblages, with a few tens of coccoliths per short traverse (<200 CAI). *G. muellerae* and *H. carteri* dominate these assemblages (Table 1).

Core D1B has more consistently present and abundant nannofossils. Above the initial portion, devoid of nannofossils, the middle part has modest and irregularly present assemblages (with magnitudes similar to those found in D2). Between -12m and -10m, a pronounced and persistent increase in nannofossils of two to three orders of mag-

nitude occurred, with assemblages majorly dominated by *H. carteri* (Table 1).

In Core D1A, only the lowest sample (-5.17m) was productive, containing modest numbers of nannofossils. *H. carteri* is present, but replaced in dominance by *G. oceanica*, *G. ericsonii* and *E. huxleyi* (Table 1).

4.3 NW Portuguese middle continental shelf

Recovered from the Portuguese middle continental shelf, Core FF1GM92 represents a typical neritic marine environment and thus its calcareous nannofossil abundance and diversity record is used here as a proxy for an environment that maintained proximity to the continental discharge from the Douro river-mouth (Figure 10). In the majority of the samples, *G. muellerae* is the dominant species, reaching absolute abundances $>1 \times 10^8$ nannofossils/g, followed by *E. huxleyi* (5.2×10^5 to 2.9×10^7 nannofossils/g), *G. oceanica* (1.4×10^5 to 2.3×10^7 nannofossils/g), *G. ericsonii* (9.0×10^4 to 3.0×10^7 nannofossils/g), and *H. carteri* (max. 1.0×10^7 nannofossils/g) (Figure 11). Core FF1GM92 contained higher numbers of nannoplankton than those from the estuaries, except for samples -2.61m, -0.66m and -0.31m, which contained <300 CAI. The calcareous nannoplankton assemblages are similar to those found in the estuarine cores, but with much higher absolute abundances. For example, *C. leptoporus* (max. 3.4×10^6 nannofossils/g), *C. pelagicus* (max. 8.7×10^6 nannofossils/g) and *Syracosphaera* spp. (max. 6.3×10^6 nannofossils/g) are significantly higher in abundance in shelf sediments than in the coastal estuarine sediments.

5. Discussion

Gephyrocapsa muellerae and *Emiliania huxleyi* are significantly abundant in samples from the western Iberia middle shelf. High abundances have been previously noted in temperate water-masses (*e.g.* Jordan & Kleijne, 1994) and are used as indicators of the Temperate Biogeographic Zone (Zone 2 of McIntyre & Bé, 1967; Winter *et al.*, 1994). Considering that the Portuguese continental shelf is located between the Temperate and Subtropical Biogeographic Zones, the high abundances of these two species is predictable in Portuguese waters (Cachão & Moita, 2000). The presence of species such as *Calcidiscus leptoporus* is probably related to waters coming from south of the Azores Front (Cachão & Moita, 2000). Despite obvious differences between nannofossil abundances in the estuaries and on the shelf, it is possible to interpret these variations for the last 14kyr in terms of dilution by variable sedimentary rates, caused by changes in fluvial discharge.

5.1 Taphonomy *versus* ecology of the calcareous nannoplankton in coastal domains

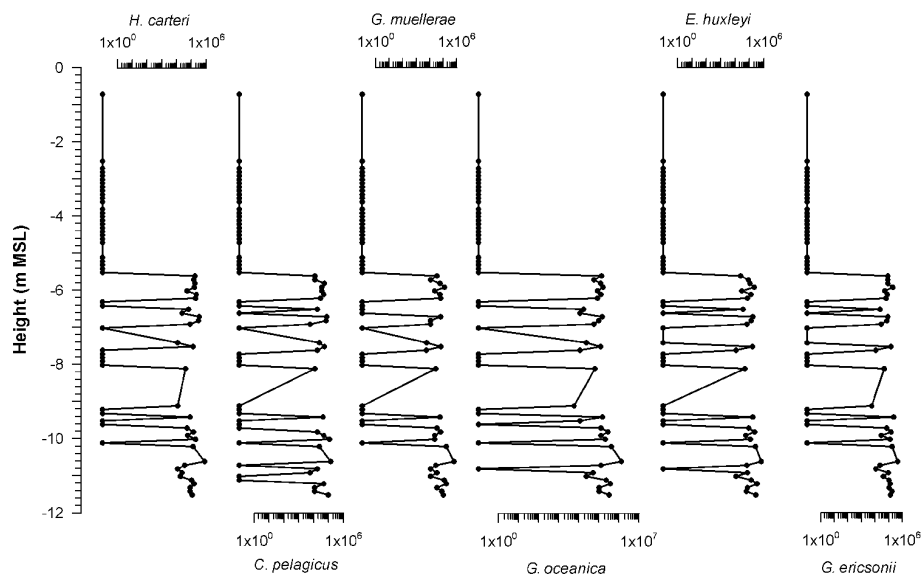Although subjected to the influence of oceanic advective

Figure 6: Absolute abundances (nannofossils/g) of the most important nannoplankton species found in Core CPF1, Coura Estuary
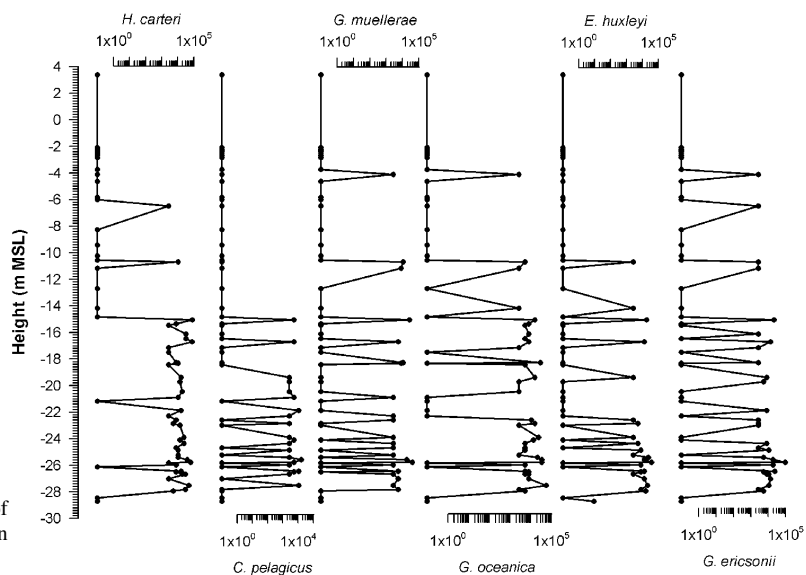

Figure 7: Absolute abundances (nannofossils/g) of the most important nannoplankton species found in Core M1, Minho Estuary
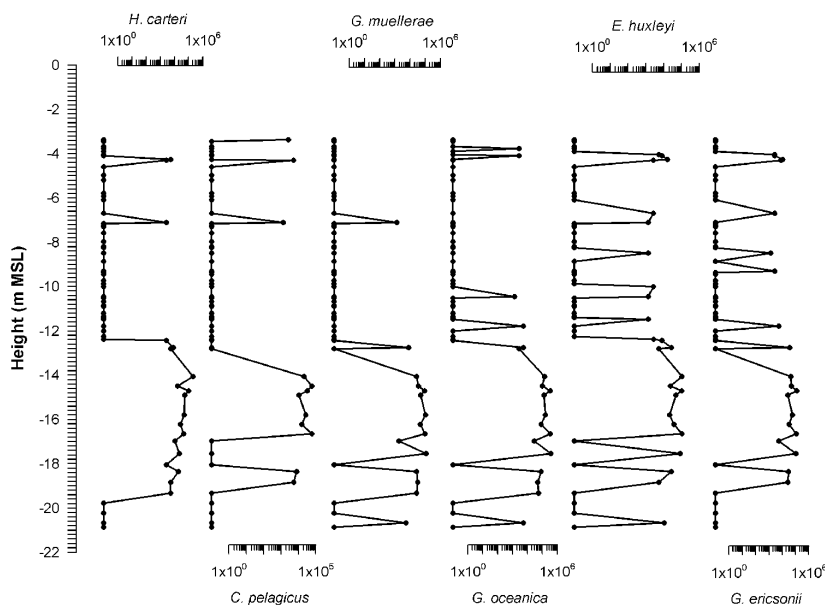

Figure 8: Absolute abundances (nannofossils/g) of the most important nannoplankton species found in Core M2, Minho Estuary

Table 1: Coccolith abundance index (CAI) of *C. pelagicus, H. carteri, G. oceanica, G. muellerae, G. ericsonii* and *E. huxleyi* in Cores D1A, D1B and D2, Douro Estuary. *H. carteri* percentage of total assemblage added for sample −10.71m

Core	Height (m)	C. pelagicus	H. carteri	G. oceanica	G. muellerae	G. ericsonii	E. huxleyi
D1A	-0.57	0	0	0	0	0	0
	-3.68	0	0	0	0	0	0
	-3.83	0	0	0	0	0	0
	-4.12	0	0	0	0	0	0
	-4.57	0	0	0	0	0	0
D1B	-5.17	27	6	53	9	56	54
	-10.55	30	2844	156	42	276	171
	-10.71	**27**	**4743 (84.4%)**	**135**	**45**	**180**	**324**
	-11.27	42	420	201	39	330	351
	-11.51	54	1323	63	81	567	432
	-11.69	45	621	135	45	216	369
	-11.83	45	522	81	27	198	171
	-12.18	0	0	0	0	0	0
	-12.35	0	0	0	0	0	0
	-12.66	2	2	6	0	0	0
	-12.74	0	0	0	0	0	0
	-12.88	0	0	0	0	0	0
	-13.38	0	0	0	0	0	0
	-13.47	4	7	10	0	2	7
	-13.58	3	2	7	3	4	18
	-13.83	4	18	8	2	1	6
	-14.08	0	0	0	0	0	0
	-14.26	0	0	0	0	0	0
	-14.41	0	0	0	0	0	0
	-14.81	0	5	4	5	3	13
	-15.18	1	0	21	0	2	6
	-15.53	4	5	32	7	4	15
	-16.07	0	0	0	0	0	0
	-16.18	0	0	21	1	1	3
	-16.58	0	0	0	0	0	0
	-16.85	0	0	0	0	0	0
	-17.50	0	0	0	0	0	0
	-18.15	0	0	0	0	0	0
D2	-18.60	0	0	0	0	0	0
	-24.87	0	11	2	9	1	1
	-25.06	1	2	4	15	1	2
	-25.30	5	47	4	46	4	5
	-25.58	0	0	0	0	0	0
	-25.82	0	0	0	0	0	0
	-26.00	2	14	0	49	7	3
	-26.14	0	0	0	0	0	0
	-26.36	0	22	1	36	9	11
	-26.71	4	27	7	40	7	4
	-27.08	0	0	1	4	0	0
	-27.48	0	0	0	0	0	0
	-28.95	0	0	0	0	0	0
	-29.25	0	0	0	0	0	0
	-29.70	0	0	0	0	0	0
	-30.04	0	0	0	0	0	0
	-30.28	0	0	0	0	0	0
	-30.53	0	0	0	0	0	0
	-30.65	0	0	0	0	0	0
	-30.90	0	0	0	0	0	0
	-31.50	0	0	0	0	0	0
	-31.78	0	0	0	0	0	0
	-31.86	0	0	0	0	0	0
	-32.00	0	0	0	0	0	0
	-32.11	0	0	0	0	0	0
	-32.30	0	0	0	0	0	0
	-32.44	0	0	0	0	0	0
	-32.53	0	0	0	0	0	0
	-32.57	0	0	0	0	0	0

blages are less diverse in comparison to open ocean assemblages (Roth & Berger, 1975). However, taxa such as *Coccolithus pelagicus s.l.*, *Helicosphaera carteri*, *Gephyrocapsa oceanica* and *E. huxleyi* may compete in coastal environmental conditions, and their productivity signals are high enough to be easily distinguished in paralic sediments, even when terrigenous sedimentary rates may be high.

Nannoliths are dimensionally and hydrodynamically equivalent to silt particles. Thus, their deposition necessarily implies the maintenance of low to null hydrodynamic bottom conditions. Such conditions are rarely present in high-energy coastal domains. However, the complex interplay of continental (terrigenous discharge, variations in availability of organic material, more or less important local changes in coastal morphology, *etc*.) and marine (storm-surge episodes; dissolution processes related to transport from the plankton production area to the coast; possible seasonal variations that may have affected productivity, *etc*.) factors implies that only the general total nannofossil curve is robust enough to allow interpretation of global eustacy in the NW sector of the Portuguese littoral zone.

Along the coast, the settling of nannofossils in marshes and other favourable depositional environments has taphonomic and ecological meaning. Taphonomically, this may reflect a more or less extended biostratonomical advection by tides, storm-induced oceanic downwelling currents, and/or coastward wave movements, whilst diagenetically, they are exhibiting a significant resistance to chemical dissolution and breakage processes, caused by organic matter oxidation in sediments typical of coastal environments. Their abundances also reflect dilution by terrigenous fluvial discharges, both inside and outside the estuaries.
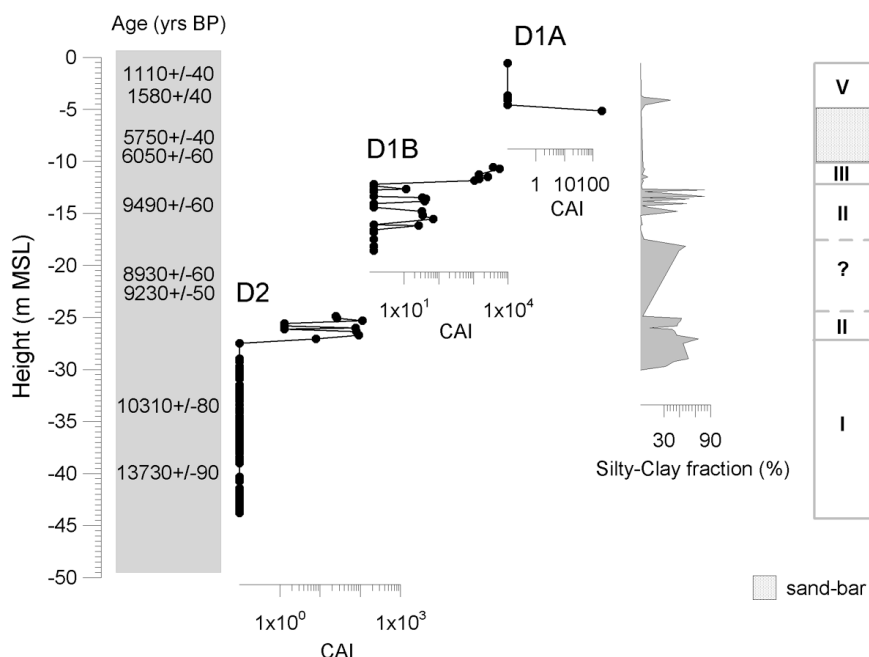
transport mechanisms, nannoplankton species densities and relative abundances in pelagic environments show good correlation between the water-column and the sediment (Kinkel *et al*., 2000). Coastal nannoplankton assem-

Figure 9: Coccolith Abundance Index (CAI) and silty-clay fraction percentages in Cores D1A, D1B and D2, Douro Estuary. Model stages: I – initial fluvial stage; II – first estuarine stage; III – flooded ria stage; V – Present Day coastal drift-driven stage. Radiocarbon ages in yrs BP
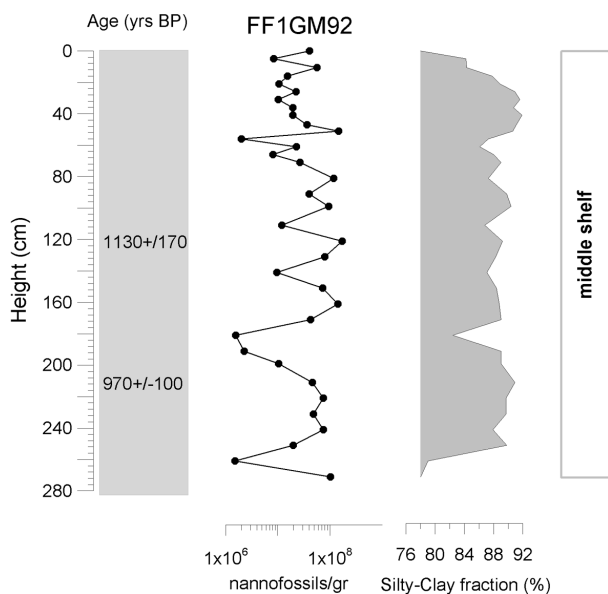

Figure 10: Absolute abundances of calcareous nannoplankton (nannofossils/g) and silty-clay percentage of Core FF1GM92, Portuguese middle continental shelf. Radiocarbon ages in yrs BP

Ecologically, assemblage composition is particularly influenced by species that proliferated in the water-column close to shore, just prior to *post mortem* transport and deposition. These taxa are in competition for nutrients with other neritic phytoplankton groups, such as diatoms and dinoflagellates.

Despite the fact that various calcareous nannoplankton species may indicate certain (palaeo)environmental/ecological influences (*e.g.* temperature, turbulence, nutrient

availability), in most cases only a taphonomical analysis is extractable. This is the case for the assemblages found in the surface-sediment samples of the Minho Estuary and from the cores that were recovered off the Minho and Douro Estuaries, with the exception of Core D1B (Douro Estuary), which has revealed a sufficiently high abundance of *H. carteri* to be inferred as a palaeoecological record.

There is no evidence for the occurrence of significant dissolution in the studied coastal cores, since both more and less resistant species are present in almost all samples (with the exception of a few surface sediment samples from the Minho Estuary). The observed abundances of *E. huxleyi* and *G. ericsonii* are a good indication of no significant diagenetic elimination, since these nannofossils, due to their small size and low resistance to dissolution, are usually the first to be affected by chemical corrosion in the water-column, at the sediment/surface interface, or within the sediment (Schmidt, 1978).

Only eight surface-sediment samples had calcareous nannoplankton, all from the terminal part of the Minho Estuary, close to the ocean. Samples from Porto da Capitania (Station 3) had the higher abundances, mainly because this was a more silty facies, potentially more favourable to the deposition of nannofossils, in contrast to the remaining samples that varied from fine to coarse sands.

It was predictable to find *G. oceanica* and *H. carteri* in surface-sediment samples below such high-energy depositional conditions, because of their robustness. However, high abundances of *E. huxleyi* and *G. ericsonii* were also registered, indicating that, although coccoliths of these species may be affected by dissolution, they seem to endure these coastal hydrodynamic conditions.

Although *G. oceanica*, *E. huxleyi* and *G. ericsonii* generally predominate, *C. leptoporus* was the dominant species at Station PR6 (Figure 3). This species is practically absent from all remaining samples. Since *C. leptoporus* is directly related to oceanic water-masses off the Iberian shelf, approaching the coast mainly during winter downwelling conditions (Oliveira *et al.*, 2000), its dominance inside the estuary may be related to a storm event.

5.2 The Holocene palaeoenvironmental evolution model
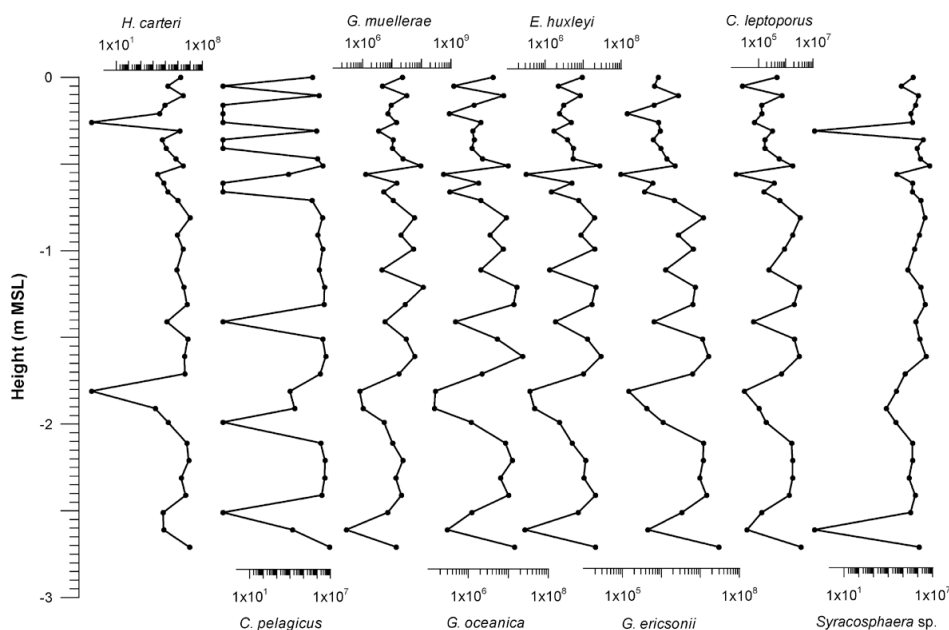
Over the shelf, nannofossil assemblages from Core

Figure 11: Absolute abundances of *C. pelagicus, H. carteri, G. muellerae, G. oceanica, G. ericsonii, E. huxleyi, C. leptoporus* and *Syracosphaera* spp. (nannofossils/g) of Core FF1GM92, Portuguese middle continental shelf

FF1GM92 are not significantly different from those that characterise the Present Day water-masses of the Portuguese middle continental shelf (Cachão *et al.*, 2000), and one may assume that similar oceanographic characteristics prevailed during the time-interval (475yr) registered by this core. As already mentioned, although coastal depositional conditions may have varied considerably, the overall similarities in nannofossil variation patterns in all cores of the Minho (CPF1, M1 and M2) and Douro Estuaries (D1A, D1B and D2) can be interpreted as a primarily depositional signal, caused by changes in marine-driven sedimentation and bottom hydrodynamism, enabling determination of their variations in space and time for this sector of the northern Portuguese coast.

5.2.1 Minho Estuary

Nannofossils are present from almost the base of Cores M1 and M2 . The presence of nannofossils at the earlier stage of the sedimentary record in these cores indicates sedimentation is marine, being initiated soon after the coastline passed over these core locations. The different depths at which Cores M1 and M2 reached the substrate (Figure 4) reflect their relative positions inside the Minho palaeo-valley. Due to these altimetric differences, marine sedimentation started later in M2 (-19m MSL; Stage III in Figure 4), a time when marine sedimentation was already developing in M1, located in a deeper section of the palaeo-valley (Stage III in Figure 4). A short stage of weak and intermittent nannofossil record in the base of M2 is interpreted as a palaeo-estuary sedimentation stage at this more external part of the palaeo-valley (Stage II in Figure 4). Upwards, nannofossils soon become persistent in both cores.

Upwards, at -15m and -13m depth in Cores M1 and

M2, respectively, the nannofossil record began to oscillate during a well-defined sector, 8 to 10m thick (Stage IV; Figure 4). This is interpreted as reflecting estuarine conditions, which, in this distal section of the palaeo-valley, are mainly controlled by coastal drift-driven sedimentation. This indicates that the coastal sedimentary system started to prograde, probably due to the Holocene deceleration in sea-level rise (Dabrio *et al.*, 2000; Lario *et al.*, 2002), marking a regressive trend of the coastline. In the final 2-3m (Core M1), nannofossils are absent. This is interpreted as reflecting the complete recovery of terrigenous sedimentation by coastal drift at this location in the estuary (Stage V; Figure 4).

Core CPF1 (Sapal do Coura; Figure 5) showed an overall nannoplankton abundance pattern similar to those observed in Cores M1 and M2. However, because Core CPF1 did not reach the substrate, it does not record the entire sedimentary sequence, particularly the pre-ria stage. Nannoplankton are significant and persistent from the base of the core, compatible with marine-influenced sedimentation within a flooded section of the palaeo-valley, reflecting the ria stage at the beginning of its sedimentary record (Stage III; Figure 5).

At around -10.2m, a transition from persistently high nannofossil abundances to oscillating abundances was noted. This is interpreted as evolution towards an estuarine stage, which seems to have occurred at a slightly higher depth than the beginning of the coastline progradation in M1 and M2 (Stage IV; Figure 5). Core CPF1's persistent nannofossil record began between 8.9 and 8.2ka, about 3.35 and 4kyr before M1 and M2, respectively. This indicates that (1) marine sedimentation ended much earlier in the inner sector of the Minho Estuary, which is plausible, or (2) the age models for CPF1 and/or M1+M2 are not accurate enough.

In all these cases, the same general pattern of nannofossil abundance was obtained. A first stage (not registered at CPF1), in which the nannofossil record is sparse and irregular, attributed to the beginning of marine-influenced sedimentation in that region, is interpreted as a more-or-less open estuary. In the second stage, nannofossils are well represented and have a persistent record, moving towards a marine-influenced environment, which is interpreted as a flooded ria. The third stage is charac-

terised by the return to an irregular profile of nannofossil abundance and diversity. This is interpreted as reflecting sediment progradation and silt-up over the coastal area due to a deceleration of sea-level rise, between 8ka (for CPF1) and 5 to 4ka (for M1 and M2). This time-interval is in agreement with the first symptoms of sand-barrier confinement in coastal lagoons on the SW Portuguese coast, registered at 5.4ka (Cearreta *et al*., 2003; Freitas *et al*., 2003). This third stage is interpreted as a return to an estuarine sedimentary environment. A fourth stage, better documented at CPF1 than at M1 (not analysed in M2), is characterised by a sequence of barren samples, which is interpreted as reflecting fluvial sedimentation (CPF1) or coastal drift-driven sedimentation (M1, M2, D1A and D1B).

Samples from Core CPF1 contain higher absolute abundances of all species in samples from its palaeo-estuary stage (Stage IV; Figure 5) than from the Present Day Minho Estuary, except for *G. ericsonii*. This means that the palaeo-estuary probably was broader than the Present Day estuary, with lower sand content, and therefore providing better conditions for nannoplankton deposition.

Abundances in Core CPF1 are one order of magnitude higher than those registered at M1 and M2. These higher values are related to the marshy conditions of the Coura River, from which Core CPF1 was recovered. This region is characterised by low hydrodynamics, with a propensity for silt and clay deposition. On the contrary, Cores M1 and M2 were recovered off the Minho river-mouth, in a higher-energy environment, interpreted as the palaeo-valley of the Minho River. Although closer to the ocean, Cores M1 and M2 contain less abundant and diverse nannoplankton assemblages, indicating that near-bottom hydrodynamic conditions are the primary parameter controling settling and the fossil record in coastal environments. This corresponds to favourable conditions for nannofossil deposition in an inner estuary, compared to the coastal region.

5.2.2 Douro Estuary

Cores D1A, D1B and D2 combined exhibit CAI abundances and general distribution patterns similar to those observed in the cores from the Minho Estuary. Abundances within the Douro Estuary (a few tens of nannofossils per short traverse) suggest an environment in which marine sedimentation was beginning to dominate the region (Stage II; Figure 9), but which was still showing significant ecological restrictions, compatible with a lagoon system or confined estuary of some sort. An increase in abundance of two to three orders of magnitude occurred between -12m and -10m (Core D1B), suggesting that the previously restricted marine conditions developed into open-marine sedimentation (Stage III; Figure 9). This order of nannofossil abundance shows similar magnitudes to typical Present Day inner shelf marine environments, with the exception that, in this case, assemblages are mainly dominated by *H. carteri* (>80%). According to the

Core D1B sedimentary record, environmental conditions must have changed drastically soon after this high abundance of *H. carteri* in the Douro Estuary, probably as a result of the development of a sand-bar (Naughton *et al*., 2002; Figure 9).

5.3 The opportunistic behaviour of *Helicosphaera carteri* in coastal environments

The high abundance of *H. carteri* reported above (Figure 12) is interpreted as opportunistic behaviour in a coastal environment since: 1) it completely dominates the assem-
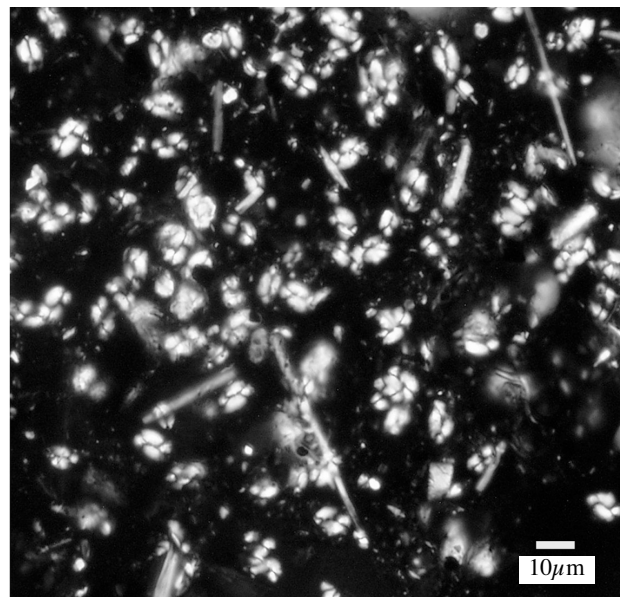

Figure 12: Example of the abundance of helicoliths (seen in crossed-nicols), together with terrigenous minerals, in Sample -10.71m (Core D1B, Douro Estuary; for location see Figure 2)

blages, reaching 84.4% and abundances of 2.4×10^8 coccoliths/g, relative to the silty-clay fraction, or 3.2×10^7 coccoliths/g, relative to the bulk sample (Core D1B, Sample -10.71m); 2) there is no known current mechanism able to either separate a single nannoplankton species from offshore, or to resuspend a single species from nearby marine sediments, for deposition elsewhere. Additionally, there is no possibility of reworking from upstream, since the geological units carved by the Douro River watershed are Palaeozoic metamorphic or magmatic lithologies (Cachão & Moita, 2000); 3) samples from surrounding offshore areas show relatively lower amounts of helicoliths. In fact, samples from the oceanic domain of seamounts close to the Madeira Archipelago (32˚14'N, 16˚51'W) disclosed abundances of helicoliths of around 7×10^7 coccoliths/g. Samples from the Galicia Sea-mount Core N3KF21 (30-32cm; Figure 13A) disclosed 4.3×10^7 coccoliths/g, while top-core samples from MD95 2040 (Figure 13A) disclosed 1.2×10^8 coccoliths/g (Cachão *et al*., 2002); 4) previous study of the Portuguese continen-

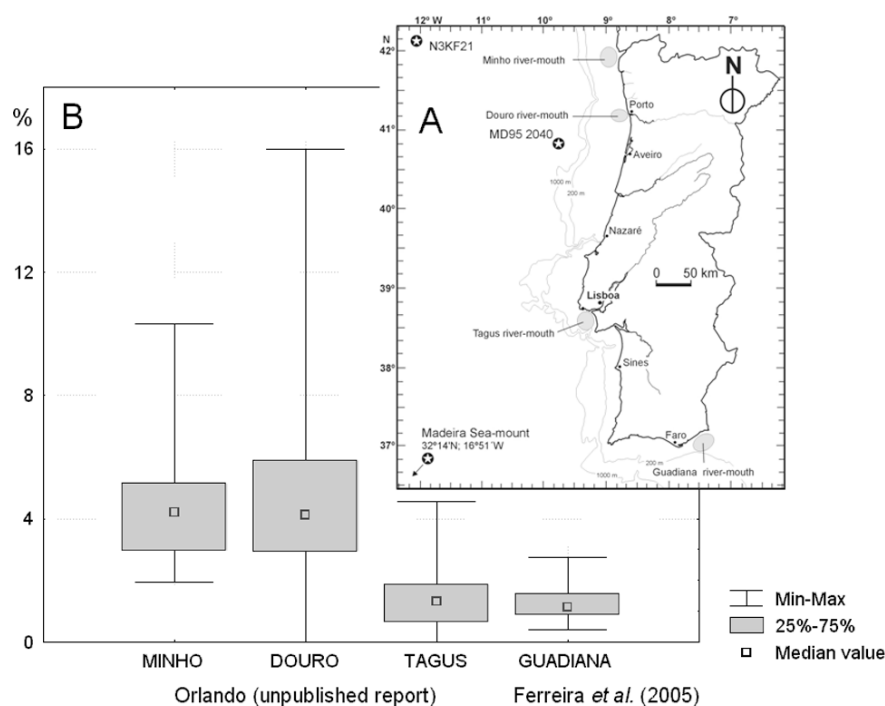**Figure 13**: Statistical data of *H. carteri* percentages (assemblages of 300 coccoliths >3μm length), surface-sediment samples, Minho, Douro, Tagus and Guadiana Estuaries. Location map of Cores N3KF21 (Galicia Sea-mount), MD95 2040 (~WSW of Douro Estuary), and from a sea-mount in the Madeira Archipelago. Data for Guadiana Estuary from Ferreira *et al*. (2005); data for Minho, Douro and Tagus Estuaries from Orlando (unpublished report)

tal shelf has revealed that *H. carteri* is more abundant in surface sediments from northern sectors (~30 to 40%) than in the south (<20%; Cachão, 1993). *H. carteri*, although fluctuating, is also revealed to be one of the two most abundant nannoplankton species represented in the cores recovered off the Minho Estuary and FF1GM92 (Figure 11), but never reaching abundances of >50%. Complementary data from the immediately surrounding areas of the estuaries of the Minho, Douro, Tagus and Guadiana (Figure 13B) indicate a tendency for higher values of helicoliths in the northern estuaries compared to the southern ones. On the other hand, sediments from the northern inner shelf have shown that *H. carteri* does not have a distinct record in sediments affected by river outlets, unlike *C. pelagicus* (Cachão & Moita, 2000).

These findings raise new questions concerning the palaeoecological behaviour of this species. *H. carteri* is commonly present, both as an extant and fossil component, in Quaternary coastal and oceanic thanato- and taphocoenoses. In the oceanic domain, its relative abundances rarely exceed 20%, with maxima in the mesostrophic Eastern Equatorial Tropical Divergence belt (Ziveri *et al*., 2004). Regions influenced by river discharge (*e.g.* the estuarine Ebro River: Cros, 2002), with low salinity and nutrient-richness (Giraudeau, 1992), or that show moderate to high coccolithophore productivity rates (Ziveri *et al*., 1995, 2004), namely, the upwelling area off NW Africa (Ziveri *et al*., 2001), all have high abundances of *H. carteri*. Cores recovered from the Vigo

Ria (at Galici; Figure 2), north of the Minho Estuary, show a brief interval (from about 1693 to 578yrs BP), in which increases in *H. carteri* relative abundance have been recorded, although never reaching >20% of the total assemblage (Alvarez, 2000). In addition, the two moments in which *H. carteri* increases in abundance inside the Vigo's ria and the Douro Estuary do not coincide in time, which indicates these are local, rather than regional, events.

From the evidence given above, it is suggested that the preferential predominance of *H. carteri* in the Douro Estuary cannot be attributed to particularly favourable offshore oceanic or neritic marine conditions, but rather to local particular and specific palaeoenvironmental conditions inside the estuary that allowed the proliferation of *H. carteri* in such a transitional domain. At the present stage of knowledge, a certain degree of confinement and nutrient enrichment is suggested as having provided suitable conditions that allowed the opportunistic behavior of *H. carteri* in these coastal areas.

6. Conclusions

Although calcareous nannoplankton are mostly confined to oceanic environments, the results obtained from the NW Portuguese littoral zone indicate that certain taxa can be used as proxies for interpreting marginal palaeoenvironments. Here, specifically, we have used them to interpret fluctuations between the relative predominance of oceanic *versus* terrestrial sedimentation that have affected the Portuguese coast as a result of eustatic sea-level rise that followed the last deglaciation.

Core FF1GM92, recovered from the Portuguese middle continental shelf, contains typical shelf calcareous nannofossil assemblages. The presence of both temperate (*Gephyrocapsa muellerae*, *Emiliania huxleyi*) and subtropical (*Gephyrocapsa oceanica*, *Calcidiscus leptoporus*) species is in accordance with the location of the shelf in the marginal eastern Atlantic, between the Temperate and Subtropical Biogeographic Zones.

With respect to the solution-prone *E. huxleyi* and *Gephyrocapsa ericsonii*, their presence in our material, and indeed their similar abundances to the more robust

Gephyrocapsa oceanica, *G. muellerae* and *Helicosphaera carteri*, allows us to infer that the nannofloras reflect depositional conditions rather than post-depositional diagenesis. This has allowed us to use the assemblages to interpret variations in the marine influence through time on our sampled locations.

The unexpectedly high numbers of *H. carteri* in the Douro Estuary are probably related to a degree of local environmental restriction, which may have concentrated nutrients, thus allowing what we interpret to be opportunistic behaviour.

Marine-driven sedimentation within the Present Day estuarine environments of NW Portugal has changed through time, as indicated by variations in counts of the nannofloral assemblages, which were similar between the studied cores. Palaeogeographically, the pattern of variation through time of nannofossil abundances in these coastal sediments can be interpreted as follows: 1) a basal set of barren samples representing fluvial sedimentation during the early stages of sea-level rise, but with the coastline still at some distance; 2) a gradual (and oscillatory) increase in the nannofossil content, indicating the movement of the coastline into the area of the core locations, with the palaeoenvironment indicating estuarine conditions; 3) persistently higher amounts of nannofossils (reaching 5×10^6 nannofossils/g) related to marine palaeoenvironmental conditions produced by the flooding of pre-existing valleys, forming rias; 4) a gradual increase in the intermittency of nannofossil abundances in the next phase indicates a regressive trend, with recovery of estuarine conditions; followed by 5) a final set of barren samples, indicating movement towards a more terrestrial (fluvial and littoral drift-driven sedimentation) regime (Figure 14).

The described cycle of increase/decrease in nannofossil abundance is correlatable with a positive global eustatic trend. The 'fluvial I - estuarine I - ria' increase phase is interpreted as a response to an initially rapid sea-level rise, while the 'ria – estuarine II – fluvial II' decrease was a response to deceleration of sea-level rise, from about 6000 to 4500yrs BP. This led to a change in coastal morphology, mainly the building-up of sand-bars (Figure 14).
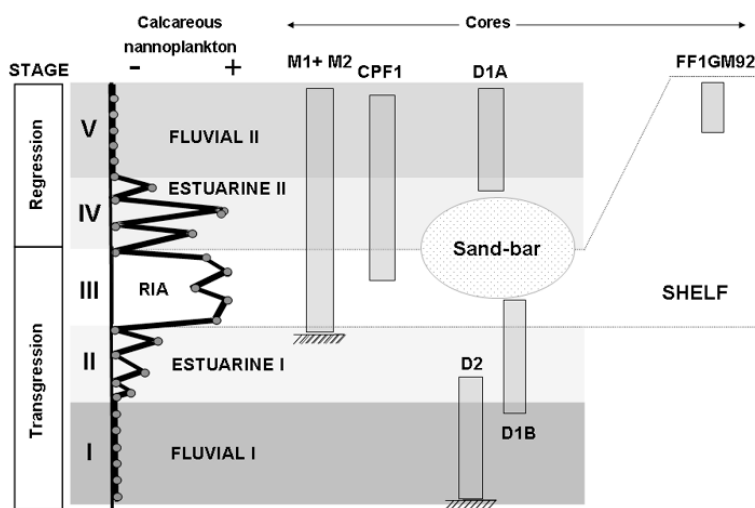
Acknowledgements

Figure 14: Schematic diagram representing the proposed Holocene palaeoenvironmental evolution model for the studied region

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Taxonomic appendix

For taxonomic references, see Jordan *et al*. (2004) and Monniot & Buge (1971).

Kingdom Chromista Cavalier-Smith, 1986
Division Haptophyta Hibberd, 1972
Class Prymnesiophyceae Hibbert, 1976 emend. Cavalier-Smith *et al*., 1996

Order Coccolithales **Schwartz, 1932 emend. Edvardsen *et al*., 2000**

Family CALCIDISCACEAE Young & Bown, 1997
Genus *Calcidiscus* Kamptner, 1950
Calcidiscus leptoporus sensu lato includes:
Calcidiscus leptoporus (Murray & Blackman, 1898) Loeblich & Tappan, 1978
Calcidiscus quadriperforatus (Kamptner, 1937) Quinn & Geisen *in* Sáez *et al*., 2003
Genus *Umbilicosphaera* Lohmann, 1902
Umbilicosphaera sibogae senso lato includes:
Umbilicosphaera sibogae (Weber-van Bosse, 1901) Gaarder, 1970
Umbilicosphaera foliosa (Kamptner, 1963) Geisen *in* Sáez *et al*., 2003

Family COCCOLITHACEAE Poche, 1913 emend. Young & Bown, 1997
Genus *Coccolithus* Schwartz, 1894
Coccolithus pelagicus sensu lato includes:
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930
Coccolithus pelagicus subsp. *braarudii* (Gaarder, 1962) Geisen *et al*., 2002
Coccolithus pelagicus subsp. *azorinus* (Gaarder, 1962) Parente & Cachão *in* Parente *et al.,* 2004

Order Isochrysidales **Pascher, 1910 emend. Edvardsen & Eikrem *in* Edvardsen *et al*., 2000**

Family NOELAERHABDACEAE Jerkovic, 1970 emend. Young & Bown, 1997
Genus *Emiliania* Hay & Mohler *in* Hay *et al*., 1967
Emiliania huxleyi (Lohmann, 1902) Hay & Mohler, 1967
Genus *Gephyrocapsa* Kamptner, 1943
Gephyrocapsa ericsonii McIntyre & Bé, 1967
Gephyrocapsa muellerae Bréhéret, 1978
Gephyrocapsa oceanica Kamptner, 1943

Order Syracosphaerales **Hay, 1977 emend. Young *et al*., 2003**

Family SYRACOSPHAERACEAE (Lohmann, 1902) Lemmermann, 1903
Genus *Syracosphaera* Lohmann, 1902
Syracosphaera pulchra senso lato includes:
Syracosphaera histrica Kamptner, 1941
Syracosphaera pulchra Lohmann, 1902

Order Zygodiscales **Young & Bown, 1997**

Family HELICOSPHAERACEAE Black, 1971 emend. Jafar & Martini, 1975
Genus *Helicosphaera* Kamptner, 1954
Helicosphaera carteri var. *carteri* (Wallich, 1877) Kamptner, 1954

Nannolith-bearing taxa

Family BRAARUDOSPHAERACEAE Deflandre, 1947
Genus *Braarudosphaera* Deflandre, 1947
Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947

Kingdom Animalia
Phylum Chordata
Subphylum Urochordata
Class Ascidiaceae

Order Aplousobranchiata **Berril, 1950**

Family DIDEMNIDAE Giard, 1872
Fossil ascidian spicules
Genus *Micrascidites* Deflandre & Deflandre-Rigaud, 1956
Micrascidites vulgaris Deflandre & Deflandre-Rigaud, 1956