DIATOM THANATOCOENOSIS IN A MIDDLE GALICIAN RÍA: SPATIAL PATTERNS AND THEIR RELATIONSHIP TO THE SEASONAL DIATOM CYCLE IN THE WATER COLUMN AND HYDROGRAPHIC CONDITIONS

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Abstract. Modern diatom distribution patterns in the surface sediment of the Ferrol Ría and their relationship to the hydrography and diatom patterns in the water column were studied to determine the hydrographic influence on the record of these biogenic components. Diatom abundance in the water column was assessed for different oceanographic periods and compared with the biosiliceous sedimentary record. Very low abundances were found in the water column during the winter, whereas in spring and summer diatoms proliferated. *Chaetoceros* spp. formed the bulk of the water column community during spring and summer, followed by *Thalassionema nitzschioides* and *Rhizosolenia* spp. *Nitzschia longissima* represented a significant portion of the winter assemblage, together with *Paralia sulcata* and benthic taxa. *Leptocylindrus danicus*, *N. longissima* and *Skeletonema costatum* characterized the autumn campaign, when stratification of the waters occurs, with *Leptocylindrus danicus* being especially abundant in the outer ría.

Seasonal hydrographic and associated productivity patterns govern the abundance and assemblage of the diatoms preserved in surface sediments. Samples located in the inner ría area and its margins exhibited the highest abundances of diatoms, and were primarily dominated by benthic species. The freshwater group, crysophycean cysts and phytoliths were present in the landward stations influenced by river runoff. The middle ría was characterized by *P. sulcata*, and *Thalassiosira* spp., with minor occurrences of the benthic and freshwater group. *Chaetoceros* R.S., *L. danicus* R.S. and *T. nitzschioides* typified the outer ría, an assemblage that corresponds to nutrient-rich coastal areas of high productivity influenced by oceanic waters, demonstrating the impact of oceanic waters flowing into the embayment due to enhanced tidal mixing through the narrow channel. Therefore, sediment diatom assemblages reflect diatom production patterns in the water column of the Ría. However, we must proceed with caution when interpreting the paleorecord in the inner area due to the high contribution of allochthonous taxa, which is indicative of low water depths. This paper contributes to a better understanding of diatom thanatocoenosis in the Galician Rías, where very few studies of this kind have been done to date.

Keywords: diatoms, surface sediments, water column, ría, Ferrol, Galicia

1. Introduction and objectives

The Ría systems, i.e. small coastal embayments that characterize the Galician coast, are fertilized by two sources of nutrients, upwelling and continental runoff (Prego et al., 1999a). In addition, rías are characterized by changing hydrographic conditions, salinity gradients, stratification and the mixing of waters.

Much of the primary production of these nutrient-replete areas is carried out by diatoms (Nelson et al., 1995) resulting in significant settling fluxes of these biosiliceous organisms. Diatoms are one of the most common microfossils in the sediments underlying coastal upwelling areas (Schuette and Schrader, 1981a, b; Abrantes, 1988; Bao et al., 1997; Bárcena and Abrantes, 1998; Abrantes and Moita, 1999; Nave et al., 2001; Romero and Hebblen, 2003; Lopes et al., 2006). The abundance of diatom species in the water column and sediments shows definite regional distribution patterns associated with oceanographic conditions (Pokras and Molfino, 1986; Abrantes and Moita, 1999). Since biogenic silica is severely affected by dissolution in the undersaturated ocean water (Nelson et al., 1995, Ragueneau et al., 2000), a clarification of the connection between the seasonal and spatial variations in assemblages of biosilicate organisms in the water column and those found in the sediment is especially important (Sancetta and Calvert, 1988; Romero et al., 2000; Koning et al., 2001; Abrantes et al., 2002; Bárcena et al., 2004).

A combined analysis of the diatom abundance and assemblage composition found in surface sediments and the water column provides an opportunity to help unravel the question of how diatoms are incorporated into seafloor sediments and how modern environmental conditions are reflected therein (van Iperen et al., 1987). Understanding these processes is very important in coastal regions with marked hydrographic gradients and where freshwater and marine conditions alternate, such as in rías and estuaries. Moreover, coastal and small embayment areas are key zones for paleoclimate reconstructions.

A large number of papers dealing with diatom thanatocoenosis distribution patterns in the surface sediment have been carried out in continental shelf sediments, on the continental slope and in deep sea upwelling-influenced areas (Schuette and Schrader, 1981a, b; Pokras and Molfino, 1986; van Iperen et al., 1987; Abrantes, 1988; Bao et al., 1997; De Sève, 1999; Bao et al., 2000; Jiang et al., 2001; Nave et al., 2001; Romero and Hebblen, 2003; Jiang et al., 2004; Armand et al., 2005; Crosta et al., 2005; Romero et al., 2005; Lopes et al., 2006). However, there is a lack of information

on these hydrographic indicators from coastal and estuarine systems and ría environments (Prego et al., 1995, Lapointe et al., 2000; McQuoid, 2002; Hay et al., 2003, McQuoid and Nordberg, 2003). Moreover, very little information concerning the seasonal succession of the diatom community and related production patterns has been published on the Galician Rías, in particular the Middle Rías and Rías Altas (Bode and Varela, 1998a, b, Casas et al., 1999; Varela et al., 2001; Varela and Prego, 2003; Varela et al., 2005; Bode et al., 2005a, b). In general, these studies have focused on the effect of upwelling and river-derived nutrients on phytoplankton production and their ecology. Therefore, in order to improve our knowledge on these questions, our first objective was to quantify the abundance of these biosiliceous components and how diatoms are incorporated on the seabed, as well as to document their regional distribution patterns. On the basis of this information, the second objective was to relate the abundance and distribution of diatoms in the sediments to the seasonal diatom community in the water column and the main oceanographic ría conditions.

2. Study area

The Ferrol Ría is one of the eight small embayments belonging to the Galician Middle Rías located between Cape Ortegal and Cape Finisterre. It therefore provides a representative contrast to the four large rías situated to the south of Cape Finisterre (Western Rías) in terms of morphology, physical oceanography, river contributions and primary production dynamics (Torre Enciso, 1958; Rio and Rodriguez, 1992; Castaing and Guilcher, 1995; Prego et al., 1997; Prego et al., 1999a; Varela et al., 2005). On a plan view it is funnel-shaped, covering an area of 27 km² with a longitudinal axis 15 km in length and a maximum width of ~3 km. Depth varies from 32 m at the mouth to a few meters at the innermost part (Figure 1). From a physiographic point of view, the Ferrol Ría can be divided into different zones (Figure 1):

(1) The innermost zone, characterized by wide mudflats in a very shallow environment.

This area extends from As Pias Bridge to the ría head. The exchange of water and organic material between the mid and inner zone is reduced by this structure (deCastro et al., 2004). Freshwater runoff is mainly supplied by the two principal rivers located at the innermost part, the Grande de Xubia and

1 Belelle Rivers. Average river flow volumes are 6 and 0.8 m³ s⁻¹ respectively
2 (Rio and Rodríguez, 1992; deCastro et al., 2004). The annual river discharge
3 versus the total volume of the ría is 0.8 (deCastro et al., 2004).

4 (2) The middle zone, extending from As Pias Bridge longitude to the beginning
5 of the Ferrol strait covers most of the ría area;

6 (3) The outermost area extends from the mouth to the narrow channel, i.e. the
7 Ferrol Strait, which is 2 km long, 0.35 km wide and 20 m in depth. The water
8 exchange between the ría and the shelf occurs through this channel.

9 The hydrographic behaviour of this ría differs from that of other Western Rías. Here the
10 water circulation, which is strongly dependent upon the tide, may be considered
11 periodic, since river inflow is very low (deCastro et al., 2003). The occasional
12 occurrence of wind-induced currents is another factor controlling residual circulation in
13 the ría, but it only affects near the surface (deCastro et al., 2003). A well-mixed water
14 column is found at the mouth, where high velocity tides enhance mixing. In contrast,
15 the middle and inner parts of the Ferrol Ría seem to be partially stratified during the wet
16 season (deCastro et al., 2004). The intrusion of nutrient-rich water (ENACW) from the
17 shelf is hard due to the orientation of the ría and the narrow shape of the channel
18 (Bode et al., 2005a). The topographic features of the Artabro Gulf cast a shadow on the
19 ría which limits the exchange of ría-shelf water leaving it virtually isolated from
20 upwelled seawater (Prego and Bao, 1997; Prego and Varela, 1998; Prego et al.,
21 1999b).

22 From a geological standpoint, watersheds are formed by igneous rocks, dominated by
23 schists, gneisses and granites. The sediment contained in the ría basin is of continental
24 and marine origin, derived from the biological activity in these waters and the riverine
25 discharge supply. The type and grain size of the sediment varies throughout the ría
26 (Figure 1, Cobelo-García and Prego, 2004) and depends on the hydrography and
27 velocity of the currents. At the mouth and in the main channel of the ría, the sediments
28 are predominantly made up of fine sand, with a low content of organic matter (1.7–2.5
29 wt.%). Conversely, the sediments located in the inner and middle parts of the ría are
30 composed of muddy fractions and higher concentrations of organic matter (3.7–13.2
31 wt.%).

34 **3. Materials and Methods**

3.1. Water column sampling and processing

Four seasonal cruises were carried out in the Ferrol Ría onboard the R/V *Lura* in 2000 22nd February, 16th May, 11th July and 5th September (Figure 2), covering three different zones of the ría (Figure 1). Water samples were collected using 5 litre 'General Oceanics' Niskin bottles at Stations O, C and M (Figure 1).

Samples collected from these stations were preserved in a Lugol's solution and assemblages composition determined using a Nikon microscope, following the technique described by Uthermöhl (1958). A magnification of 100× was used for large forms, 250× for intermediate and 400× and 1000× for small species.

3.2. Surface sediment sampling and analytical procedures

Surface sediment samples were taken at 35 sites from the R/V *Mytilus* (Figure 1 and Table 1). Two different sizes of Van Veen grab samplers were used. Only the surface layer of the sediment was collected (<1-cm) with polyethylene spatulas. The samples were stored at 4°C and later oven-dried at < 50°C.

Opal content in the surface sediments was determined following the method of alkaline digestion by Mortlock and Froelich (1989) optimized to the sediment of rías, as devised by Bernárdez et al. (2005). The subsequent analysis of the dissolved silicate in the extract obtained was carried out using the method reported by Hansen and Grasshoff (1983). Total organic carbon (TOC) was determined by calculating the difference between the total carbon (TC) measured in a Perkin Elmer elemental CNH analyzer and the total inorganic carbon (TIC) analyzed by calcination loss at temperatures ranging from 550 to 975°C. Total organic nitrogen (TON) was also determined with the same equipment at the University of Coruña. Data are presented in Cobelo-García and Prego (2004) (Table 1, Figure 3).

The sediment samples were prepared for diatom count according to the technique described by Abrantes et al. (2005). To prepare the slides, a known volume of solution, previously stirred for homogenization (Battarbee, 1973), was spread evenly onto two clean circular cover slips placed in a circular evaporation tray. After the dishes were dried, the smear slides were removed and assembled with Permount™ mounting medium onto permanently labelled slides.

3.3. Taxonomic identification

The identification of diatoms found in the water column was based on a variety of taxonomic monographs, but mainly the work of Hasle and Syvertsen (1996). Total abundance is expressed as cells ml⁻¹ and the relative percentage of each species and ecological group was also calculated.

Our taxonomic identification (genera and species) of the diatoms found in the surface sediments is based mainly on ecological characteristics using several floral keys and specific bibliography (Taxonomic appendix). Schrader and Gersonde's (1978) guidelines were followed for diatom counts and total number estimates. Hence, only diatoms that were essentially complete were counted. At least 300 diatom valves were identified in each sample to ensure the proper assessment of diatom abundance. Absolute abundances are expressed in number of valves per gram of dry sediment. In a few cases, difficulties arose in distinguishing between two or more species, so these species were combined into one count group or genus group. Taxa were grouped into three different types: dominant taxa, species of the same genus living in similar environments and species showing a comparable ecology and distribution, i.e. common ecological meanings, such as freshwater and benthic. *P. sulcata* is not included in the benthic assemblage since it is considered to be tychopelagic.

The number of diatom fragments, silicoflagellates, sponge spicules, palynomorphs, phytoliths, crysophycean cysts and radiolaria per gram of sediment was also assessed. In addition, we calculated the relative contribution of each biosiliceous component versus their total number per gram of sediment.

The distribution of diatoms and siliceous components was plotted using the Golden Software Surfer v. 8.0 package for Windows, according to the Kriging method for data interpolation.

4. Results

4.1. Planktonic diatom composition in the water column

Phytoplankton abundance was high all year round except in February, when the number of diatoms was very low, ~1000 times lower than in the other periods (82–122 cell ml⁻¹). No differences in diatom concentration were found between stations for the

1 same sampling date, with the exception of the outer station during the July cruise,
2 when diatom abundance was between six and ten times lower than in the other
3 stations. The highest diatom abundances were sampled in May and September. Only
4 the most representative species found in the water column were plotted in Figure 5.

5 The main component of the diatom assemblage was *Chaetoceros* spp., whose
6 contribution ranged from 42 to 99% in May and July. In summer (July cruise)
7 *Chaetoceros* spp. appeared together with *Rhizosolenia* spp., *Thalassiosira* spp. and *T.*
8 *nitzschoides*. In contrast, *Chaetoceros* spp. practically disappeared in February and
9 September.

10 The *N. longissima* group showed a trend opposite to that of *Chaetoceros* R.S. This
11 group accounted for the greatest percentage of total diatoms during the February and
12 September cruises, especially in the samples taken from the outermost station. The
13 February campaign was also characterized by the appearance of benthic taxa and the
14 thycopelagic species *P. sulcata* (1.5–3%) in the water, particularly in stations O and C.

15 *L. danicus* was the third most important component of the diatom assemblage in the
16 water column. It was absent during all the sampling periods and stations, except for
17 September when it appeared in high abundances. On this cruise, *L. danicus* accounted
18 for around 75% of the total diatoms from station O and ~35% for sites C and M.

19 The contribution of *S. costatum* to the diatom community was also relevant during
20 September (3195–12166 cell ml⁻¹), with the highest occurrence of this species found in
21 the innermost station (16%). However, *S. costatum* was absent in February and May
22 when the riverine discharge was high.

23 *Thalassiosira* spp. were present in high percentages (39.3%) and abundance (5299
24 cells ml⁻¹) during the July cruise in station M. It is important to note that only the large
25 species of *Thalassiosira* were included in this group. However, most of the small
26 centric diatoms (<30 µm) probably belong to this genus.

27 *T. nitzschoides* showed relative percentage of up to 4.8% in station M in July. This
28 species also displayed significant percentages during the February cruise (absolute
29 abundance <100 cell l⁻¹) due to water column mixing and river-derived nutrient supply.
30 It disappeared completely in May and September.

31 *Rhizosolenia* spp. were found in station O during the July cruise, accounting for 4.5%
32 of the assemblage.

33 No evidence of freshwater diatoms in the water column was recorded throughout the
34 sampling period.

4.2. Diatom assemblages and biosiliceous material in the surface sediments

The diatom signal in surface sediments depict a clear W–E pattern, following the opal content distribution (Cobelo-García and Prego, 2004) (Figure 3, Table 1). The distribution patterns of diatom valves abundance show high generalized values in the inner ría and A Malata Bay (4.2×10^6 valves g^{-1}) (Figure 3). On average, the abundance is 1.1×10^6 valves g^{-1} , which accounted for 30.7% of the total biosiliceous components found in the sediment. This mean value is representative of the middle ría. Low abundances characterize the channel and outer ría (down to 1.4×10^6 valves g^{-1}). At stations located along the middle ría connecting the inner area and the outer-channel zones, diatom concentration is relatively constant and lower than what was found at stations located in the inner areas. The distribution pattern of the diatom fragments is similar to that of complete valves, accounting, on average, for 22.8% of the sediments total biosiliceous component. Other fragments of diatoms, such as cingulum (diatom girdle bands) are also found in significant abundance (averaging 5.8% of the BSi) in the middle areas of the ría and along the northern margin (Figure 3).

The benthic assemblage dominate the superficial sediment, averaging 55.5% (range 16.4–86.2%) (Figure 4). The highest values are found in the inner ría as well as in A Malata Bay close to the city of Ferrol. High percentages are recorded all along the margins, whereas low values characterize the main channel and the station located outside the ría.

Chaetoceros R.S. is the second more important component to the diatom assemblage, accounting for an average of 23%. In general, the highest values are found in the main channel and outer areas, particularly from station 8 towards the mouth of the ría (Figure 4).

P. sulcata account for up to 31.3% of the association, with a mean percentage of 11.1% (Figure 4). Very low percentages are found in the inner ría (0–8%), backwards As Pías Bridge. This species is prevalent in the middle area on the southern margin (~20%), where shallow waters are found, and throughout the outer ría.

L. danicus R.S. is found in the sediment in small quantities. Maximum percentages (~3.7%) are observed in the outer and middle ría, and this species is virtually absent from the stations found in the innermost areas (Figure 4).

T. nitzschioides represent an average of 1.4% of the total diatom community. Its distribution is irregular throughout the ría (Figure 4). Maximum values (~5%) were

1 located at the outermost stations and in the main channel. It is also found (1–2%) in
2 some sampling sites close to the Grande de Xubia River in the inner ría area.

3 Other diatom genera such as *Thalassiosira* spp., *S. costatum* and *Rhizosolenia* spp.
4 occasionally appear in the surface sediment. In general, *Thalassiosira* spp. is present
5 in the middle ría (Figure 4), whereas *S. costatum* and *Rhizosolenia* spp. (not shown)
6 are found in very low (<2%) on the margins of the ría and in the outermost station.

7 Freshwater taxa is restricted to the areas receiving the main river flow (up to 13.5%)
8 (Figure 4). Throughout the rest of the ría, percentages are low, amounting to around
9 2%. The distribution of the freshwater group coincided with the important occurrence of
10 other biosiliceous components such as phytoliths and crysophycean cysts, also
11 considered to be run-off tracers (Figure 3). The phytolith content (silica-rods bodies
12 derived from grass) in the ría sediments is relatively high, accounting for 11.5% of the
13 total biogenic silica. It remain relatively constant in terms of abundance throughout the
14 middle-inner ría, exhibiting a homogeneous distribution, with maximum values of
15 9.7×10^5 specimens g^{-1} in the middle ría and in stations located close to the northern
16 margin while abundance values of less than 2.0×10^5 specimens g^{-1} are found in the
17 outermost sampling sites and in the central channel. Crysophycean cysts, however,
18 made up a small percentage of the biosiliceous material. Maximum abundances
19 ($\sim 5 \times 10^4$ specimens g^{-1}) are sited at the mouth of the Grande de Xubia River and on the
20 northern margin of the ría. Abundances of around $1\text{--}2 \times 10^4$ specimens g^{-1} are found in
21 the rest of the sampling sites.

22 Other siliceous components in the sediment present a complex geographical
23 distribution (Figure 3). One of the main contributors to biogenic silica are the remains of
24 sponge spicules (averaging 29.9%). Their abundance was low in the outer area and in
25 some of the innermost stations. High contents are found in the middle zone (2.0×10^6
26 specimens g^{-1}) and in A Malata Bay. Silicoflagellates are present in very low
27 concentrations (maximum value of 2.5×10^4 specimens g^{-1}), with a scattered distribution
28 pattern. Quantities of the dinoflagellate *Actiniscus pentasterias* in the surface
29 sediments are very low (mean 3.3×10^3 specimens g^{-1}). This organism appears in the
30 ría sediments in stations located along the northern margin of the outer area and in the
31 main channel.

32 Palinomorphs abundance is low, displaying a patchy distribution with higher values in
33 stations located in the inner-middle areas in the central zone of the longitudinal channel
34 (Figure 3). The maximum value is 3.7×10^4 specimens g^{-1} from station 53.

5. Discussion

The abundance of diatom valves in the surface sediments is in accordance with what was recorded in the seabed of the Rías Baixas and from the continental shelf (Prego et al., 1995, Bao et al., 1997). The geographical pattern in diatom distribution is also similar to that of other rías, with maximum values located close to the ría head. In general, diatom assemblages of ría-estuarine environments are characterized by the low percentages of open ocean taxa, in contrast to what has been observed on the Galician-Portuguese shelf (Abrantes, 1988; Bao et al., 1997; Abrantes and Moita, 1999).

On the basis of recent diatom and biosiliceous component distributions, several zones have been recognized:

5.1. Estuarine domain (Zone 1)

This zone of the ría extends from the mouths of the Beelle and Grande de Xubia Rivers up to As Pías Bridge. The most representative species in the sediments of this area were the benthic and freshwater groups with small occurrences of *T. nitzschioides* and *P. sulcata*. *T. nitzschioides* also traced the nutrient supply from oceanic waters in the outer station during the summer sampling, but it was diluted by fast-blooming species such as *Chaetoceros* spp (Figure 5). Hence, the higher contribution of *T. nitzschioides* in the outer ría is indicative of the influx of nutrient-rich offshore shelf waters (Hay et al., 2003). However, their appearance in the water column in the inner ría could be controlled by the input of fluvial-derived nutrients (Pokras and Molfino, 1986; Abrantes, 1988), which reflects this species' adaptation to the innermost areas of estuarine-like systems (Figure 5). In the Ferrol Ría, it has a relatively low contribution to the sediment in the innermost areas, owing to the great abundance of benthic and freshwater taxa, which veils the effectiveness of this species as a tracer of past changes in river discharge.

The high abundance of benthic and freshwater taxa in the inner zone in sediments is typical of small embayments, fjords and estuarine environments with protected inner areas (Hay et al., 2003; Lapointe, 2000; Bernárdez et al., 2006). On the other hand, the high surface area of intertidal environments favours the growth of benthic diatoms in sediments. In this way, this group can be used as a reliable proxy of shallow waters

1 and intertidal environments, especially in this enclosed and protected environment.
2 Therefore, percentages of up to 60% found in a marine paleoclimatic record recovered
3 in the ría could be indicative of shallow waters (approximately below 5 m depth).
4 Besides, the higher amounts of fine sediments and organic carbon (Cobelo-García and
5 Prego, 2004) (Table 1) permit the establishment of reducing conditions that will lead to
6 appropriate settings for diatom conservation.

7 A large number of crysophycean cysts, phytoliths and palinomorphs were also detected
8 in this zone, which would point to the existence of strong riverine influence. Moreover,
9 freshwater diatoms are indicators of sources of continental material and reduced
10 salinity resulting from freshwater drainage from land. In fact, the lithogenic components
11 were more prevalent in this area, reflected by the presence of mud and high Fe levels
12 in the surface sediments (Cobelo-García and Prego, 2004). However, the restricted
13 exchange between the inner ría and the middle areas due to the presence of As Pías
14 Bridge may impede the transport of these taxa. Moreover, strong tidal currents during
15 ebb tide could transport a few specimens in the surface waters to the open ocean.

18 **5.2. Middle ría (Zone 2)**

20 The area extends from As Pías Bridge to site 10. The sediments in this zone are
21 characterized by a diatom assemblage dominated by *P. sulcata* and *Thalassiosira* spp.
22 *Thalassiosira* spp. appeared in the water column in July, and is therefore strongly
23 related to high productivity conditions (Figure 5). However, *Thalassiosira* spp. also was
24 found in relatively high abundances in the winter season all along the Portuguese
25 coast, as a response to the continuous input of nutrients (Abrantes and Moita, 1999).
26 The spatial distribution of *P. sulcata* in the sediments was similar to that of
27 *Chaetoceros* R.S., meaning that it is better adapted to the outer and middle areas of
28 the ría where oceanic influence is high. In fact, this species is indicative of the influence
29 of upwelling and high productivity conditions (Lapointe, 2000; Mcquoid and Nordberg,
30 2003 and references therein).

31 The freshwater and benthic groups (~3% and ~50% respectively) were also present in
32 the sediments, together with high concentrations of porifera and phytoliths.

33 Therefore, this zone represents a combination of both marine and freshwater
34 influences. In fact, phytoliths are certainly an indication of transport from the inner
35 areas in the low-saline surface layer. The abundance of all of these markers at sites

remote from the river would indicate that this area is influenced both by river discharge and upwelling.

5.3. Oceanic domain (Zone 3)

This zone extends from sampling site 10 towards the open sea, covering the outer area and the main channel. Our results show that the surface sediments of this area are characterized by *Chaetoceros* R.S., *L. danicus* R.S. and *T. nitzschioides*. In the water column, *Rhizosolenia* spp. were typical of the summer blooms in the outer ría zone, but disappear with the appearance of *Chaetoceros* spp. taxa.

Chaetoceros spp. was representative of the spring and summer blooms (Figure 5), when primary productivity is enhanced by the nutrient input of oceanic waters and solar irradiance. In the case of the Ferrol Ría, the input of nutrient-rich central waters (ENACW) was low during the study period, even when upwelling was well developed in the Galician shelf area. In fact, the upwelling of shelf water only affected the water layer below 15 m in the outer ría during summer (Varela et al., 2003). Downcore concentrations of *Chaetoceros* spp. R.S. would accurately reflect episodes of high spring and summertime productivity.

The sediment distribution of *L. danicus* in this area reflects its proliferation in the water column in September, in that it only appeared in the outer stations (Figure 5). Oceanographic patterns during the September cruise were characterized by reduced runoff and the absence of northerly winds, which would point to the stratification of the water column (Figure 2). A thin layer of nutrient-rich shelf water entered the ría through the bottom, provoking the blooming of this fast-growing competitor, *L. danicus* (Bode et al., 2005b). Ecologically, it represents the input of nutrient-rich shelf waters and water column stratification. Therefore, as reported by Bárcena et al., (2001), this species may be used in the sedimentary record as an indicator of the late upwelling period and beginning of stratification.

S. costatum, which appears mostly in the middle station in September, can be used as indicative of late summer blooms, (Figure 5). In the Rías Baixas (Tilstone et al., 2000; Varela et al., 2005) and A Coruña Bay (Varela and Prego, 2003), its occurrence is linked to high nutrient concentrations. However, ecologically, *S. costatum* is linked to the supply of nutrients from riverine discharge since it appears occurs in association with low salinities (Varela et al., 2005) and the nutrient-enrichment of the rías in winter caused by the high freshwater input (Casas et al., 1999; Rodríguez et al., 2003;

deCastro et al., 2006; Prego et al., 2007). This species was found in low percentages (< 2%) in the sediments of this area (not shown).

Therefore, the water column diatom assemblage and sediment record of this area is mainly determined by marine influence. However, A Malata Bay, while located in the outer ría, presents characteristics that are typical of the inner areas, with high percentages of benthic assemblages, as well as elevated concentrations of crysophycean cysts and phytoliths. This zone is affected by the harbour area, and it is relatively well-protected from the inflow of marine waters and the mixing of the water column through the channel.

The main channel and the outer station also make an important contribution to the benthic assemblage (~20%), due to transport from the innermost areas as a result of the strong tidal influence and low residence time of the waters in the ría (deCastro et al., 2003; deCastro et al., 2004).

5.4. Thanatocoenosis-biocoenosis links

Diatom percentages found in the water column and in the sediment were compared, using the average percentages of each species for all sampling campaigns and their relative concentration in the underlying sediment (Middle-St 11, Channel-St 7, Outer-St 42, Figure 6).

The sediment assemblage differs from its pelagic counterpart in the middle-inner areas, where benthic and freshwater assemblages dominate. In this area, all the species showed a reduced relative contribution, due to the high abundance of the benthic taxa. *P. sulcata*. And *T. nitzschioides* showed higher percentages in the sediment than in the water column in stations C and O. Their abundance and corrosion resistant valves would justify their use as a paleoceanographic proxy (Tanimura, 1999). Similarly, *T. nitzschioides* was also found in greater abundance in the sediment trap material in the Pontevedra Ría (Varela et al., 2004).

The relative contribution of *Chaetoceros* R.S. in the sedimentary record is always overestimated due to their high resistance. The contribution of this group to the seabed in the main channel and outer ría was slightly higher than in the water column. An interesting point for paleoreconstructions is that when this species is found in percentages lower than ca. 20% we may conclude that the sediment corresponds to the innermost areas of the ría, assuming that hydrographic conditions do not change with time.

A pattern common to all sampling stations is the absence of *N. longissima* in the sediments. Winter conditions, (reduced light and mixing of waters), were characterized by the presence of *N. longissima* in surface waters (Figure 5), as observed in other rías (Prego et al., 2007). This species could be a good indicator of the winter conditions in the ría, but dissolution of this species has removed this signal from recent sediments. In this sense, the appearance of *N. longissima* in sediments would be indicative of good preservation conditions. Moreover, the presence of low silicified species such as *S. costatum* and *Rhizosolenia* spp. (not shown) in the sediments is very low (under 2%), which also prevents their use as environmental tracers. As reported in the case of *N. longissima*, their occurrence would reflect both adequate oceanographic conditions for growth and high preservation efficiency in the sediments.

In brief, many processes, such as differential dissolution, lateral advection and transport, in addition to hydrographic conditions, complicate the relationship between the living diatom assemblage and the one found in the underlying sediments. In this way, inferences regarding paleoenvironmental conditions must be based on several diatom species together with other proxies e.g. geochemical, sedimentological and biological. The next step in this study will attempt to generate a paleoecological transfer function to characterize the relationships between modern diatom assemblages and the hydrographic conditions of the Ferrol Ría.

6. Conclusions

Water column diatom community production patterns followed hydrographical changes throughout the sampling period. Abundance was variable depending on location and season, and linked to runoff supply, water dynamics and circulation within the ría. Diatom production was high, except during the winter season, due to the low residence time of ría waters and the constant input of river-derived nutrients. *Chaetoceros* spp. was dominant in spring and summer in the water column, together with *T. nitzschioides* and *Rhizosolenia* spp. *N. longissima*, *P. sulcata* and benthic taxa characterized winter season, whereas *L. danicus* was abundant in autumn.

The distribution pattern of diatoms in surface sediments reflects hydrographic conditions and water column productivity. The sedimentary diatom assemblage is composed of the most solution-resistant of the species found in the water column. The dominant diatom species in the sedimentary assemblage are those associated with the benthic environment and with spring and summer blooming conditions. Assemblage

1 composition allows a differentiation to be made between oceanic-influenced sediments
2 and those in the inner-ría. Diatoms are abundant in the inner sediments of the ría,
3 influenced by freshwater runoff and low depths, which favors the proliferation of benthic
4 diatom assemblage. The transition from the stations affected by oceanic waters to the
5 ones located in the inner area can be detected in the middle ría. Diatoms are in low
6 abundance in outer ría sediments, where planktonic diatoms make up the dominant
7 assemblage. Hence, paleoceanographic reconstructions based on sediment cores from
8 the inner ría would provide detailed records of fluctuations in ría environments and sea
9 level changes, whereas cores recovered in the outer ría would yield more information
10 on general patterns of coastal upwelling generated primary production.

11 *Chaetoceros* R.S. and *L. danicus* R.S. may be used as indicators of the oceanic waters
12 flowing into the ría. *L. danicus* R.S. also tracks the stratification conditions of the water
13 column with reduced upwelling. *N. longissima*, if found in the sediments, is
14 representative of winter conditions and a well mixed water column. *T. nitzschioides* is
15 linked to high production conditions during summer and the nutrient supply from
16 oceanic waters. However, it also points to the occurrence of nutrient-enrichment from
17 continental waters, but it is better preserved in the sediments of the outer areas. These
18 observations can be used for future paleoenvironmental reconstructions of the coastal
19 changes and the spatial and -temporal evolution of ría environments.

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Figure 1. Map of the study area. The position of the bed sediment sampling (black circles) is shown. The diamond shapes indicate the stations where the water column phytoplankton sampling was carried out. The contour plot shows the mud content in the surface sediments (modified from Cobelo-García and Prego (2004)). The dotted white line represents the longitudinal axis. Water depth variation along the longitudinal axis of the ría is also shown.

Figure 2. The solid line indicates the Grande de Xubia River daily discharge during the year 2000 (values in $\text{m}^3 \text{s}^{-1}$). Grey bars show the daily variations of the Upwelling index ($Q_x \text{ m}^3 \text{s}^{-1} \text{km}^{-1}$) at point $43^\circ 11''$ kindly provided by Jose Manuel Cabanas (IEO). Dashed lines indicate the water column sampling dates.

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4 Figure 3. Contour plots of the abundance per gram of the sediment of different
 5 sediment components. Variation in the abundance of each componente along the
 6 longitudinal axis is also shown A) *Actiniscus pentasterias*, B) Porifera, C) Cingulum,
 7 D) Phytoliths, E) Cryosphycean cysts, F) Palinomorphs, G) Diatom valves, H)
 8 Silicoflagellates, I) Opal content
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Figure 4. Maps showing the distribution of the main diatom species found in the surface sediment of the Ferrol Ría as well as the variation in their relative percentages along the longitudinal axis.

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Figure 5. Temporal variations of the standing stocks of total diatoms and the abundance of the main diatom groups in the water column (white symbols, cell ml⁻¹) at the three sampling sites. Bars show the relative percentage of each species or group. Note the logarithmic scale in the diagram showing the total diatom. Also note that there are no data for the outer station in the sampling survey for May.

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Figure 6. Mean value of the relative contribution of the diatom taxa in the water column during the sampling period and percentage of diatoms accumulated in surface sediment at sites 42 (Outer), 7 (Channel) and 11 (Middle).

1 **Tables**

2

3 Table 1. Sediment characterization of the sampling sites.

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Sediment sample	Latitude N	Longitude W	Depth (m)	Mud (%)	POM (%)	TOC (%)	TON (%)	Opal (%)	CaCO ₃ (%)	C/N
3	43°27.465'	8°18.221'	15	3.97	5.80	0.84	0.1	0.04	72.14	8.40
6	43°28.364'	8°15.457'	15	17.88	11.20	2.7	0.18	0.73	30.82	15.00
7	43°28.183'	8°14.768'	19	4.26	7.90	1.63	0.09	0.55	35.99	18.11
8	43°28.189'	8°14.391'	14	4.91	12.50	4.65	0.18	0.34	43.82	25.83
9	43°28.163'	8°13.618'	13	13.72	13.50	2.94	0.24	0.81	23.49	12.25
10	43°28.222'	8°12.725'	6	21.73	15.70	3.5	0.39	0.33	8.66	8.97
11	43°28.427'	8°12.083'	4	21.72	12.10	3.01	0.24	0.24	8.33	12.54
12	43°28.687'	8°11.368'	7	10.02	10.70	2.24	0.17	0.20	19.99	13.18
13	43°28.854'	8°10.698'	3	15.61	9.70	2.34	0.14	0.25	24.66	16.71
14	43°29.71'	8°10.432'	2	25.60	9.80	2.28	0.23	0.50	3.67	9.91
15	43°29.84'	8°10.123'	1	11.63	11.10	2.32	0.2	0.23	17.16	11.60
16	43°30.23'	8°10.02'	2	17.83	18.10	3.93	0.47	1.01	8.66	8.36
17	43°30.83'	8°09.902'	1	12.66	17.30	4.01	0.45	1.28	6.83	8.91
22	43°27.703'	8°15.802'	9	8.37	6.60	1.07	0.07	0.42	28.32	15.29
23	43°27.76'	8°14.558'	6	11.41	9.90	2.04	0.14	0.25	25.16	14.57
24	43°27.745'	8°13.504'	4	23.98	12.50	2.44	0.21	0.07	20.83	11.62
25	43°28.033'	8°12.594'	4	13.92	15.20	3.93	0.26	1.13	15.99	15.12
26	43°28.222'	8°11.83'	3	12.08	11.80	2.32	0.24	0.78	13.49	9.67
27	43°28.34'	8°11.423'	4	13.83	14.40	2.51	0.3	1.28	12.00	8.37
28	43°28.653'	8°10.487'	2	8.99	18.40	3.71	0.51	1.86	9.50	7.27
29	43°30.521'	8°09.802'	2.5	15.90	22.40	5.92	0.63	1.83	6.50	9.40
30	43°31.12'	8°09.43'	1.5	13.55	8.30	2.19	0.2	1.08	2.50	10.95
42	43°27.973'	8°19.038'	19	4.41	5.50	0.71	0.06	0.65	29.99	11.83
43	43°28.643'	8°15.139'	14	12.31	12.70	4.25	0.2	1.33	30.99	21.25
44	43°28.864'	8°15.359'	5	28.93	14.50	3.01	0.3	1.83	10.83	10.03
45	43°29.52'	8°15.139'	2	18.10	13.30	3.91	0.26	1.42	11.33	15.04

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46	43°29.831'	8°15.034'	1	28.14	13.10	2.29	0.32	1.81	6.50	7.16
47	43°28.471'	8°14.23'	8	14.00	12.70	3.01	0.2	1.52	22.32	15.05
48	43°28.496'	8°13.824'	9	19.64	14.80	2.93	0.33	2.23	13.66	8.88
49	43°28.663'	8°12.77'	4	17.79	13.80	2.79	0.29	1.83	11.50	9.62
50	43°29.42'	8°11.121'	1	23.89	11.20	2.12	0.27	1.53	7.16	7.85
51	43°29.781'	8°10.751'	1	23.63	9.10	1.69	0.17	1.31	9.50	9.94
52	43°30.621'	8°10.223'	1.5	19.08	19.60	4.59	0.54	2.34	7.50	8.50
53	43°31.02'	8°09.982'	1	17.67	17.70	3.89	0.45	2.12	7.16	8.64
44b	43°28.931'	8°15.06'	7	22.36	14.70	3.23	0.29	1.83	11.50	11.14
Max				28.93	22.4	5.92	0.63	2.34	72.14	25.83
Min				3.97	5.5	0.71	0.06	0.04	2.5	7.16
Mean				15.81	12.79	2.88	0.27	1.06	17.67	11.91

1 Taxonomic appendix

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Benthic group	M	C	O	Sediment
<i>Achnanthes</i> spp. Bory 1822				X
<i>Amphora</i> spp. (Ehrenberg) Kützing 1844				X
<i>Auliscus sculptus</i> (Smith) Ralfs in Pritchard 1864				X
<i>Campylodiscus</i> spp. Ehrenberg ex Kützing 1844				X
<i>Cerataulus turgidus</i> Ehrenberg 1843				X
<i>Cocconeis</i> spp. Ehrenberg 1837				X
<i>Cocconeis distans</i> Gregory 1855				X
<i>Cocconeis placentula</i> Ehrenberg 1838				X
<i>Cocconeis scutellum</i> Ehrenberg 1838	X	X		X
<i>Dimeregramma minor</i> (Gregory) Ralfs in Pritchard 1861				X
<i>Diploneis</i> spp. (Ehrenberg) Cleve 1894				X
<i>Diploneis bombus</i> (Ehrenberg) Ehrenberg ex Cleve 1894				X
<i>Diploneis didyma</i> (Ehrenberg) Cleve 1894				X
<i>Diploneis smithii</i> (Brébisson ex Smith) Cleve 1894				X
<i>Grammatophora angulosa</i> Ehrenberg 1840				X
<i>Grammatophora</i> spp. Ehrenberg 1840				X
<i>Grammatophora marina</i> (Lyngbye) Kützing 1844		X		X
<i>Grammatophora serpentina</i> (Ralfs) Ehrenberg 1844				X
<i>Gyrosigma</i> spp. Hassall 1845	X			X
<i>Hantzschia</i> spp. Grunow 1877				X
<i>Navicula</i> spp. Bory 1822				X
<i>Navicula digitoradiata</i> (Gregory) Ralfs in Pritchard 1861				X
<i>Navicula distans</i> (Smith) Ralfs in Pritchard 1861				X
<i>Navicula forcipata</i> Greville 1859				X
<i>Navicula palpebralis</i> (de Brébisson) Smith 1853				X
<i>Navicula transitrans</i> (Grunow) Cleve 1883		X	X	
<i>Opephora</i> spp. Petit 1888				X
<i>Petroneis monilifera</i> (Gregory) Stickle & Mann 1990				X
<i>Plagiogramma staurophorum</i> (Gregory) Heiberg 1863				X
<i>Pleurosigma acutum</i> Norman ex Ralfs in Pritchard 1861			X	

<i>Pleurosigma</i> spp. Smith 1852	X	X	X	X
<i>Podosira stelligera</i> (Bailey) Mann 1907				X
<i>Psammodiscus nitidus</i> (Gregory) Round and Mann 1990				X
<i>Rhabdonema minutum</i> Kützing 1844				X
<i>Surirella fastuosa</i> (Ehrenberg) Kützing 1844				X
<i>Toxarium</i> spp. Bailey 1854				X
<i>Trachyneis aspera</i> (Ehrenberg) Cleve 1894		X		X
<i>Trachyneis</i> spp. Cleve 1894	X		X	
<i>Tryblionella</i> Smith (1853)				X
<i>Tryblionella coarctata</i> (Grunow) Mann in Round et al., 1990				X
<i>Tryblionella punctata</i> Smith 1853				X

Freshwater group	M	C	O	Sediment
<i>Achnanthes lanceolata</i> (de Brébisson in Kützing) Grunow in Cleve et Grunow 1880				X
<i>Achnanthes minutissima</i> Kützing 1933		X		
<i>Aulacoseria</i> spp. Thwaites 1848				X
<i>Aulacoseria granulata</i> (Ehrenberg) Ralfs in Pritchard 1861				X
<i>Cyclotella</i> spp. (Kützing) de Brébisson 1838				X
<i>Cymbella</i> spp. Agardh 1830				X
<i>Diatoma</i> spp. Bory 1824				X
<i>Diatoma hyemalis</i> (Roth) Heiberg 1863				X
<i>Eunotia</i> spp. Ehrenberg 1837				X
<i>Eunotia pectinalis</i> (O.F. Müller) Rabenhorst, 1864				X
<i>Fragillaria</i> spp. Lyngbye 1819				X
<i>Gomphonema</i> spp. Ehrenberg 1832				X
<i>Gomphonema acuminatum</i> Ehrenberg 1832				X
<i>Hannaea arcus</i> (Ehrenberg) Patrick 1966				X
<i>Pinnularia</i> spp. Ehrenberg 1843				X
<i>Sellaphora</i> spp. Mereschkowsky 1902				X
<i>Staurosirella</i> spp. Williams and Round 1988				X
<i>Staurosirella pinnata</i> (Ehrenberg) Williams and Round 1987				X
<i>Stephanodiscus</i> spp. Ehrenberg 1845				X
<i>Synedra</i> spp. Ehrenberg 1830				X
<i>Synedra ulna</i> (Nietzsche) Ehrenberg 1838				X

<i>Tabellaria</i> spp. Ehrenberg 1840	X
<i>Tabellaria flocculosa</i> (Roth) Kützing 1844	X

Other species	M	C	O	Sediment
<i>Actinoptychus senarius</i> (Ehrenberg) Ehrenberg 1843				X
<i>Actinoptychus splendens</i> (Shadbolt) Ralfs ex Pritchard 1861				X
<i>Anaulus</i> spp. Ehrenberg 1844				X
<i>Asterionellopsis glacialis</i> (Castracane) Round in Round et al., 1990	X	X	X	
<i>Bacteriastrium</i> spp. Shadbolt 1854		X		
<i>Bacteriastrium delicatulum</i> Cleve 1897	X	X		
<i>Bacteriastrium hyalinum</i> Lauder 1864	X	X	X	
<i>Biddulphia alternans</i> (J.W. Bailey) Van Heurck 1885				X
<i>Biddulphia obtusa</i> (Kützing) Ralfs in Pritchard 1861				X
<i>Cerataulina pelagica</i> (Cleve) Hendey 1937	X	X		
<i>Chaetoceros</i> spp. Ehrenberg 1844	X		X	
<i>Chaetoceros</i> spp. R.S. Ehrenberg 1844	X		X	X
<i>Chaetoceros affinis</i> Lauder 1864	X		X	X
<i>Chaetoceros brevis</i> Schütt 1895	X	X	X	
<i>Chaetoceros curvisetus</i> Cleve 1889	X	X	X	
<i>Chaetoceros danicus</i> Cleve 1889	X	X	X	
<i>Chaetoceros decipiens</i> Cleve 1873	X	X	X	
<i>Chaetoceros densus</i> Cleve 1901	X	X		
<i>Chaetoceros diadema</i> (Ehrenberg) Gran 1897				X
<i>Chaetoceros didymus</i> Ehrenberg 1845	X	X	X	
<i>Chaetoceros lauderi</i> Ralfs in Lauder 1864	X			
<i>Chaetoceros lorenzianus</i> Grunow 1863		X		
<i>Chaetoceros simplex</i> Ostfeld 1901			X	
<i>Chaetoceros socialis</i> Lauder 1864	X	X	X	
<i>Coscinodiscus</i> spp. (Ehrenberg) Hasle and Sims 1986	X	X	X	X
<i>Coscinodiscus argus</i> Ehrenberg 1838				X
<i>Coscinodiscus decrescens</i> Grunow in Schmidt 1878				X
<i>Coscinodiscus radiatus</i> Ehrenberg 1841				X
<i>Detonula pumila</i> (Castracane) Schütt 1896	X	X	X	
<i>Eucampia zodiacus</i> Ehrenberg 1840	X	X		
<i>Guinardia delicatula</i> (Cleve) Hasle 1996	X	X	X	

<i>Guinardia flaccida</i> (Castracane) Peragallo 1892	X	X	X	
<i>Guinardia striata</i> (Stoltherfoth) Hasle1996	X	X	X	
<i>Hemidiscus cuneiformis</i> Wall 1860		X		
<i>Lauderia annulata</i> Cleve 1873		X		
<i>Leptocylindrus danicus</i> Cleve 1889	X	X	X	
<i>Leptocylindrus danicus</i> R.S. Cleve 1889				X
<i>Leptocylindrus minimus</i> Gran 1915	X	X	X	
<i>Lioloma pacificum</i> (Cupp) Hasle 1996	X	X	X	
<i>Nitzschia</i> spp. Hassall 1845				X
<i>Nitzschia bicapitata</i> Cleve 1901				X
<i>Nitzschia longissima</i> (de Brébisson in Kützing) Ralfs in Pritchard 1861	X	X	X	
<i>Odontella mobiliensis</i> (Bailey) Grunow 1884	X	X		X
<i>Paralia sulcata</i> (Ehrenberg) Cleve 1873	X	X	X	X
<i>Proboscia alata</i> (Brightwell) Sundström 1986	X	X	X	
<i>Pseudonitzschia</i> spp. Peragallo in Peragallo 1900	X			
<i>Pseudonitzschia</i> cf. <i>pungens</i> (Grunow ex Cleve) Hasle 1993	X	X	X	
<i>Pseudonitzschia subpacifica</i> (Hasle) Hasle 1993		X	X	
<i>Pseudonitzschia</i> cf. <i>delicatissima</i> (Cleve) Heiden in Heiden and Kolbe 1928	X	X	X	
<i>Rhizosolenia</i> spp. Brightwell 1858				X
<i>Rhizosolenia setigera</i> Brightwell 1858	X	X	X	
<i>Rhizosolenia shrubsolei</i> Cleve 1881	X	X		
<i>Skeletonema costatum</i> (Greville) Cleve 1878	X	X	X	X
<i>Stephanopyxis turris</i> (Greville and Arnott) Ralfs ex Pritchard 1861	X			
<i>Thalassionema nitzschioides</i> (Grunow) Mereschowsky 1902	X	X	X	X
<i>Thalassionema frauenfeldii</i> (Grunow) Hallegraeff 1986	X			
<i>Thalassiosira</i> spp. (Cleve) Hasle 1973	X	X		X
<i>Thalassiosira angulata</i> (Gregory) Hasle 1978	X	X	X	
<i>Thalassiosira anguste-lineata</i> (Schmidt) Fryxell et Hasle 1977	X	X	X	
<i>Thalassiosira fallax</i> Meunier 1910		X	X	
<i>Thalassiosira levanderi</i> Van Goor 1924		X	X	
<i>Thalassiosira rotula</i> Meunier 1910	X	X		
<i>Triceratium</i> spp. Ehrenberg 1839				X