Morphometry of *Coccolithus pelagicus s.l.* (Coccolithophore, Haptophyta) from offshore Portugal, during the last 200 kyr.

Aurea Parente\(^1\), Mario Cachão\(^2\), Karl-Heinz Baumann\(^3\), Lucia de Abreu\(^4\) and Jorge Ferreira\(^5\)

\(^1\)PhD scholarship SFRH/BD/8944/2002; Centre Geology Univ. Lisbon, Building C6, 6.4.67, Campo Grande, 1749-016 Lisboa, Portugal

\(^2\)Centre Geology Univ. Lisbon and Dep. Geology, Fac. Sciences, Univ. Lisbon, Building C6, 6.4.55, Campo Grande, 1749-016 Lisboa, Portugal

\(^3\)Department of Paleoeceanography and Sedimentology, University of Bremen, Klaggenfurter Strasse, Postfach 33 04 40, D – 28334 Bremen, Germany

\(^4\)Godwin Laboratory, Univ. Cambridge, Pembroke Street - New Museums Site, Cambridge CB2 3SA, United Kingdom

\(^5\)Centre of Geology Univ. Lisbon, Building C6, 6.4.67, Campo Grande, 1749-016 Lisboa, Portugal

email: aureanarciso@clix.pt

---

ABSTRACT: A morphometric study of *Coccolithus pelagicus s. l.* coccoliths was performed on 98 samples from a long sediment core recovered off the Portuguese margin (MD95-2040) and 29 more surface samples from an extensive area of the North Atlantic. The core allowed following in detail morphometric changes of this species through the last two glacial cycles while surface samples were used to analyse biogeographic distribution of the morphotypes. The main purpose of the present work is to identify and characterize the existence of distinct morphotypes of the species *Coccolithus pelagicus s.l.* and test the presence of its two extant subspecies (*C. pelagicus pelagicus* and *C. pelagicus braarudii*) in the studied area. For each sample maximum placolith diameters of one hundred randomly selected specimens were tabulated into 1µm morphons. The behavior of these morphons, characterized by R-mode Factor Analysis, allows defining morphotypes as groups of highly correlated morphons.

Surface sample data set showed the existence of three morphotypes: a small (7-10µm), an intermediate (11-13µm), and a large morphotype (15-16µm). The factor scores distribution shows that at present day, the smallest morphotype mainly occurs above 60ºN, the intermediate is predominant in the West coast of Iberia, whereas the largest one tends to occur in areas surrounding the Azores region.

Data from MD95-2040 also allowed the identification of three morphotypes: a small (6-9µm), an intermediate (10-13µm) and a large (14-15µm) morphotype. The small morphotype shows significant similarities to the records of the two independent proxies for the periodic influence of cold waters off Iberia, the abundances of left-coiling *N. pachyderma* and ice-rafted detritus (IRD). These confirm its positive response to subpolar influxes off western Iberia, its direct relationship to *C. pelagicus pelagicus* and thus its future use as a proxy for cold waters. The intermediate morphotype is related to *C. pelagicus braarudii* and to the upwelling conditions off Iberia while the predominance of a larger morphotype (here described as *C. pelagicus azorinus*) in the Azores region may allow its future use as a proxy of the influence of the Azores current in Eastern North Atlantic.

---

INTRODUCTION

Coccolith morphometry has already been performed to address questions such as taxonomy, biostratigraphy and palaeoecology of several calcareous nanoplankton (e.g. Samtleben 1980; Backman and Hermelin 1986; Young 1990; Wei 1992; Baumann 1995; Knappertsbusch 2000; Colmenero-Hidalgo et al. 2002). This method is based on the fact that heterococcoliths (hereafter simply referred as coccoliths) are produced intracellularly, and so have their final proportions prior to being extruded to the coccosphere (e.g. Westbroek et al. 1984; Young et al. 1999; Young and Henriksen 2003), hence their dimensions may be considered an intrinsic property of a particular species or ecophenotype.

*Coccolithus pelagicus* (Wallich) Schiller has been generally considered as a cold water species, since it is mainly known from the present day North Atlantic subpolar and polar water masses (McIntyre and Bé 1967), particularly in the Arctic influenced of Greenland Sea (Baumann 1995; Andruleit 1997). According to Okada and McIntyre (1979) and Winter et al. (1994), *C. pelagicus* is well represented in cold waters at temperatures ranging from –1.7 to 15°C, and the optimum growth condition for this species has been established as between 2 and 12°C (Okada and McIntyre 1979). However, its biogeography also includes upwelling regions, agreeing with Cachão and Moita (2000) that showed that the occurrence of this species off Iberia was related to moderate fronts, namely those driven by upwelling conditions.

Geisen et al. (2002) presented life cycle evidence for the existence of two extant subspecies of *C. pelagicus*: *C. pelagicus* ssp. *pelagicus*, the arctic form, and *C. pelagicus* ssp. *braarudii*, the temperate form. They can be recognized by the size of their placoliths with the former being smaller (7-10m), and the latter larger (10-16m). More recently Sáez et al. (2003) adding as a new argument genetic differences, raised these subspecies to species level.

The main purpose of the present work is to test the existence of distinct morphotypes within the traditional *Coccolithus pelagicus s.l.* off Western Iberia, during the last two glacial cycles, and relate these morphotypes to the palaeoceanographic condi-
tions of the area. Thus, the traditional approach of considering it as a single species was initially assumed.

**MATERIAL AND OCEANOGRAPHIC SETTING**

A set of samples was selected and studied to recognize present day morphotypes of *C. pelagicus* on surface samples from North and Central Atlantic. This set included Holocene samples from: (1) the ETHZ, selected during the EU TMR “CODENET” workshops; (2) University of Bremen and (3) University of Lisbon sample archives. This last archive includes samples from the Azores region (Saldanha seamount) collected as part of project AMAR-Praxis XXI nº 2/2.1/MAR/1743/95 described in Barriga et al. (1998). These samples are plotted in text-figure 1 and table 1 gives their locations and water depths.

The Holocene samples covered an extensive area of the North Atlantic (text-fig. 1), with distinct oceanographic characteristics, but always controlled by the large North Atlantic Gyre. This gyre includes the North Equatorial Current that moves westward parallel to the equator. Near the South American coast this water mass joins the South Equatorial Current, flowing northward. These currents split into two, the Antilles Current that flows along the Atlantic side of the West Indies and the Caribbean Current, which passes through the Yucatan Channel into the Gulf of Mexico. These two masses reconverge as the Florida Current, which moves in a northeasterly direction and becomes the Gulf Stream near the Cape Haterras (30N). The Gulf Stream extension located further eastward propagates to the south originating the Azores Current (Krauss and Kase 1984), meridionally bordered by the Azores front.

At Azores, part of the samples was retrieved from the Saldanha hydrothermal field. Located at the Mid Atlantic Ridge this hydrothermal field was discovered in 1998 during the SALDANHA cruise. At the summit of the seamount, hydrothermal fluid venting through centimetric orifices in the ocean floor, cover an area of approximately 50m² at depths ranging between 2200 and 2220m, (Barriga et al. 1998).

Most of the Gulf Stream water mass flows northeast to the Grand Banks of Newfoundland, being called the North Atlantic Drift after it reaches about 40-50ºN. Across the North Atlantic part of the North Atlantic Drift joins with the cold water from the Labrador Current. After this mixing two other currents are formed: the Irminger Current, which flows along Iceland’s west coast; and the Norwegian Current, which moves northward along Norway’s coast. The other part of the North Atlantic Drift crosses the North Atlantic and turns southward along the west coasts of Iberia and North Africa, to become the Portugal and Canaries Currents. This last water mass eventually joins the North Equatorial Current, completing the gyre.

Samples of the core MD95-2040 recovered off the Portuguese margin (40º34.91’N; 09º51.67’W) (text-fig.1), were used to analyse morphometric changes during isotope stages 1 to 7 (de Abreu 2000; de Abreu et al. 2003). This core, recovered in July
1995 east of the Oporto Seamount, from a depth of 2465 metres below sea-level (mbsl), is 35.24m long and was collected with the Calypso giant piston corer during the IMAGES MD101 cruise aboard the R/V Marion Dufresne (Bassinot and Labeyrie 1996). The core provides a continuous pelagic record apparently unaffected by erosion by bottom currents or significant chemical dissolution (de Abreu 2000).

The Oporto Seamount is a hydrodynamically active area, where water masses of different sources and properties converge and interact, following a dynamic vertically stratified pattern, established as a function of temperature, salinity and dissolved oxygen content (de Abreu 2000). In this eastern part of the subtropical gyre, the properties of modern surface water are influenced by the descending branch of the North Atlantic Drift (Portugal Current) and by a seasonal upwelling regime during summer months. This upwelling system is driven by the increase in the intensity and steadiness of northerly winds (Portuguese Trade Winds), as the Azores anticyclone intensifies and moves westward during summer (Fiúza 1998). This region is thus highly influenced by the North Atlantic Oscillation (NAO) in such a way that low NAO indices are related to higher atmospheric moisture in western Iberia, coeval with warm temperatures over Greenland, while high NAO values are associated with Iberian dryness and cold temperatures over Greenland (Hurrel 1995; Rodó et al. 1997).

1995 east of the Oporto Seamount, from a depth of 2465 metres below sea-level (mbsl), is 35.24m long and was collected with the Calypso giant piston corer during the IMAGES MD101 cruise aboard the R/V Marion Dufresne (Bassinot and Labeyrie 1996). The core provides a continuous pelagic record apparently unaffected by erosion by bottom currents or significant chemical dissolution (de Abreu 2000).

The Oporto Seamount is a hydrodynamically active area, where water masses of different sources and properties converge and interact, following a dynamic vertically stratified pattern, established as a function of temperature, salinity and dissolved oxygen content (de Abreu 2000). In this eastern part of the subtropical gyre, the properties of modern surface water are influenced by the descending branch of the North Atlantic Drift (Portugal Current) and by a seasonal upwelling regime during summer months. This upwelling system is driven by the increase in the intensity and steadiness of northerly winds (Portuguese Trade Winds), as the Azores anticyclone intensifies and moves westward during summer (Fiúza 1998). This region is thus highly influenced by the North Atlantic Oscillation (NAO) in such a way that low NAO indices are related to higher atmospheric moisture in western Iberia, coeval with warm temperatures over Greenland, while high NAO values are associated with Iberian dryness and cold temperatures over Greenland (Hurrel 1995; Rodó et al. 1997).

METHODOLOGY

A total of 121 samples were analysed for this study: 98 selected from MD95-2040 core, covering isotope stages 1 to 7; and 29 surface samples. Smear slides were prepared and observed under an optical polarizing microscope (OLYMPUS BX-40), at a 1250 magnification, connected to a digital camera (OLYMPUS DP11). Overall percentages of C. pelagicus were computed relative to assemblages of more than 300 (>3/c109 m) coccoliths, determined over randomly selected rows of the smear slide. Absolute abundances were determined on slides prepared according to the random settling procedure, defined by Flores and Sierro (1997). For morphometry, 100 placoliths were randomly selected throughout the slide of each sample, and their maximum diameters were measured (text-fig. 2).

An image analysis program (Scion-Image) with a suite of routines (www.nhm.ac.uk/hosted_sites/ina/CODENET/Coccobiom), subsequently adapted to PC, was used to: (1) group the images in mosaics, allowing the visualization of multiple coccoliths in a single composite image; (2) measure the main axis of each coccolith; and (3) copy results to a spreadsheet for subsequent statistical analysis. The morphometric parameters were directly measured on framegrabber captured digital images at magnifications of about 2500. The measurement-associated error is 0.1µm. For statistical analysis of palaeoecological distribution specimens were assigned to 1µm size intervals, hereafter referred as morphons. In this sense, morphon 10 include all specimens which maximum diameter is inside the interval [10, 11] microns.

A morphometric data matrix, with samples as rows and morphons as columns, was subjected to R-mode Factor Analysis. This analysis tests which contiguous morphons show high positive correlation and thus define a specific morphotype. A factor may be characterized by a single morphotype, with a particular and distinguishable behaviour along the entire data set, or by the combined or opposite behaviour between two or more distinct morphotypes. Based on the percentage of the variance (of the initial data matrix) that each factor represents, the user
can decide if a factor is relevant or not, allowing testing of the existence and representation of a particular morphotype in the data set. This procedure allows: (1) to statistically test the existence of distinct morphospecies; and (2) to analyse their relative proportions along the time series.

The age model of MD95-2040 core was established from a combination of oxygen isotope stratigraphy, 14C dating and synchronisation of the sea-surface temperature (SST) records and the GISP2 18O data (de Abreu et al. 2003). Isotopic stages are recognised and ages assigned in accordance with the standard curve SPECMAP of Martinson et al. (1987). The detailed stratigraphy for the last deglaciation and the Holocene is consistent with the planktonic 18O record from the nearby core SU81-18 (37°46’N, 10°11’W) described in Bard et al. (1989) (de Abreu 2000; de Abreu et al. 2003).

The palaeotemperature estimates for MD95-2040 are from de Abreu (2000) and were obtained with both the CLIMAP transfer function equation FA20 (Imbrie and Kipp 1971) and with a modern analogue technique SIMMAX28 (Pflaumann et al. 1996).

RESULTS

Morphometric analysis on surface samples

Factor Analysis of the surface sample morphometric data matrix (http://correio.fc.ul.pt/~mcachao/papers/Cpelagicus/Appendix1.htm) when displayed as factor loadings against coccolith length (text-fig. 3), indicates that the first factor (variance 38%) is related to morphons 7 to 10, corresponding a coccolith length interval that characterizes the smallest morphotype.

Factor 2 (variance 23%) is strongly related to morphons 11, 12 and 13 (with absolute loadings higher than 70%) which characterizes an intermediate morphotype.

Factor 3 (variance 13%) defines a third and largest morphotype since it is more strongly related to morphon 16 (table 2).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphon 6</td>
<td>0.09353</td>
<td>0.19221</td>
<td>0.59822</td>
</tr>
<tr>
<td>Morphon 7</td>
<td>0.76561*</td>
<td>0.03092</td>
<td>-0.19639</td>
</tr>
<tr>
<td>Morphon 8</td>
<td>0.97109*</td>
<td>0.14286</td>
<td>-0.04722</td>
</tr>
<tr>
<td>Morphon 9</td>
<td>0.90196*</td>
<td>0.25808</td>
<td>-0.05324</td>
</tr>
<tr>
<td>Morphon 10</td>
<td>0.92731*</td>
<td>0.16180</td>
<td>0.01213</td>
</tr>
<tr>
<td>Morphon 11</td>
<td>0.31670</td>
<td>-0.77161*</td>
<td>-0.09077</td>
</tr>
<tr>
<td>Morphon 12</td>
<td>-0.36085</td>
<td>-0.84086*</td>
<td>0.05611</td>
</tr>
<tr>
<td>Morphon 13</td>
<td>-0.48819</td>
<td>-0.81507*</td>
<td>0.08457</td>
</tr>
<tr>
<td>Morphon 14</td>
<td>-0.55041</td>
<td>-0.58868</td>
<td>0.27172</td>
</tr>
<tr>
<td>Morphon 15</td>
<td>-0.41808</td>
<td>-0.27896</td>
<td>0.57526</td>
</tr>
<tr>
<td>Morphon 16</td>
<td>-0.03302</td>
<td>-0.09846</td>
<td>0.75115*</td>
</tr>
</tbody>
</table>

| Expl.Var  | 4.15902  | 2.5519   | 1.38916  |
| Prp.Totl  | 0.37809  | 0.23199  | 0.12629  |

The score distribution pattern for F1, F2 and F3 factors (related to the smallest, intermediate and largest morphotypes, respectively) (text-figs. 4a, b and c) shows that the smallest mainly occurs above 60°N, the intermediate is predominant in the west coast of Iberia, whereas the largest one tends to occur in areas surrounding the Azores region.

Overall analysis on MD95-2040

Considered as a single species, Coccolithus pelagicus (overall) percentage shows an irregular gradual decrease from the base of isotope stage 6 towards the present day. This sequence is composed of three increasing – decreasing cycles from the top of isotope stage 7 to the end of Holocene (text-fig. 5). The first cycle shows a strongly alternating increase from the warmer isotope stage 7 at 2200cm to around 2020cm core-depth (with an extrapolated age around 174 kyr). Above this point, percentages and abundances oscillate towards a minimum at 1500cm that coincides with isotope substage 5e, corresponding to the Eemian optimum climatic stage. During this interval, absolute abundances only disclose the alternating pattern with maxima and minima more or less coincident with percentage values, but no secular change in abundance.

Upwards from 1500cm a second and more regular increase of C. pelagicus percentages is registered to 1010cm, near the beginning of isotope stage 3 close to Heinrich layer 5 (HL5), which is shortly preceded by a strongly pronounced increase in abundance. After this both percentage and abundance records show pronounced highs and lows, until 600cm, the end of isotope stage 3, between HL3 and HL2.
A slight recovery in *C. pelagicus* percentages is seen in the first half of isotope stage 2 (600-300 cm) followed by an abrupt increase in percentages abundances at the beginning of the Last Glacial Maximum (LGM). Percentages remain relatively high till the Younger Dryas (YD) after which they decrease to below 10%. During this same time interval absolute abundances reach a maximum shortly before the LGM then drop until the end of isotope stage 2. During the YD and shortly after they show an irregular behaviour to finally decrease towards present day.

The comparison between *C. pelagicus* overall percentage and absolute abundance against estimated sea surface temperatures for the last 200 kyr (de Abreu 2000; de Abreu et al. 2003) shows no meaningful linear relationship (text-fig. 6; table 3). Although no clear temperature signal can be retrieved, maximum percentage and abundance values are achieved when cold season palaeotemperatures are between 10 and 12°C (text-figs. 6a and b) respectively, and during warm season between 15 and 18°C (text-figs. 6c and d).

**Morphometric analysis on MD95-2040**

Factor Analysis of the morphometric data matrix of MD95-2040 ([http://correio.fc.ul.pt/~mcachao/papers/Cpelagicus/Appen-dix1.htm](http://correio.fc.ul.pt/~mcachao/papers/Cpelagicus/Appen-dix1.htm)) showed that factor 1 (variance 38%) (text-fig. 7; table 4) is strongly influenced by morphons 6 to 9 (with loadings > 70%) and thus characterizes a small morphotype. It also shows important negative correlation to morphons 12 and 13, a larger morphotype in palaeoecological conflict with the first.

Factor 2 (variance 14%) is directly related to morphons 14 and 15 (with loadings > 70%), consequently describing the presence of a distinct and potentially meaningful larger morphotype with coccolith lengths longer than 14.0μm.

Factor 3, with 11% of the total variance, is directly related to morphons 10 and 11, describing an independent intermediate morphotype with distinct behaviour.

The analysis of these three factors (F1, F2 and F3 roughly corresponding to the smallest, largest and intermediate morphotypes, respectively) against sea surface temperatures (warm and cold) (text-fig. 8) shows only a slight negative correlation between the smaller morphotype and the temperature of surface waters (text-figs. 8a and b).

Further studies consisted of plotting and analysing the scores of the three factors found in the core samples against depth. For F1...
(the smallest morphotype) scores were plotted together with other cold water proxies, such as Neogloboquadrina pachyderma sinistral and IRD, obtained from previous studies (de Abreu 2000; de Abreu et al. 2003) (text-fig. 9). Thus, this smaller morphotype shows an increment mainly during cold isotope stages 2, 4, and 6, being the most important peaks coincident with the highest peaks of the other proxies, associated with the “Heinrich events”. An increase of the smaller morphotype is also observed in the beginning of isotope interglacial stage 5, with an estimated age of 120 kyr.

The scores for F2, the largest morphotype, show that there is a strong variation in the relative importance of this morphotype, through the last 200 kyr, with a more or less well defined trend to a progressive decrease towards the beginning of isotope stage 2. Here it experiences a significant recovery, at around 20 kyr, to diminish again towards the top of the core (text-fig. 10). The relative importance of the intermediate morphotype (F3) seems to decrease in the middle of isotopic stage 6 and in the beginning of stage 2. After that this morphotype presents an opposite behaviour when compared with the largest one, showing an increment till present day (text-fig. 10). An interesting feature resides on the existence of a meaningful decrease of both these morphotypes, intermediate and larger, during the HL2 and HL3, a moderate decrease during the HL1 and during the cold event at about 43 kyr, and a slight decrease of both forms during the HL5 and HL6.

DISCUSSION

Although C. pelagicus overall percentage and abundance shows some response to major climatic events defined in this core, namely during the Eemian, LGM and YD, no clear or even con-
flicting palaeotemperature signals can be retrieved from these time series (text-fig. 6; table 3).

As previously mentioned, Geisen et al. (2002) characterize two extant subspecies of Coccolithus pelagicus: C. pelagicus pelagicus, with the smaller placoliths (7-10µm) and living in the Subarctic North Atlantic region (Baumann 1995), and C. pelagicus braarudii, with the larger placoliths (10-16µm) and dwelling in temperate water masses (e.g. west coast of Iberia; Cachão and Moita 2000). Our results partially converge to this conclusion: the existence of distinct entities within C. pelagicus. However, Factor Analysis of our data shows at least three distinct morphotypes.

The results of our Factor Analyses of coccolithophores show that the extracted factors are not simple morphometric entities since they may reveal information from several non-contiguous morphons. Thus, as previously mentioned, a factor it’s not necessarily a morphotype (it can be, only if it reflects the behaviour of a single group of highly positively correlated contiguous morphons). In our study, some factors combine information from one morphotype and the correlative part of others (e.g. for the core samples, the extracted factor 1 shows that the small morphons – the smaller morphotype - are negatively correlated to some of the morphons of the intermediate morphotype) and so have more palaeoceanographic information than just the groups morphons themselves.
In both the core and the surface sample data sets, the most important extracted factor is directly related to a small morphotype, although defined by slightly different length limits: 6 to 9 for MD95-2040 and 7 to 10 for North Atlantic surface sediments.

From our results the record of the small morphotype, mainly expressed by F1 scores, shows significant similarity to the records of the two proxies for cold waters, left-coiling *N. pachyderma* and IRD (text-fig. 9), particularly evident during isotope stages 2, 4 and lower half of 5, confirming its positive response to subpolar influxes off western Iberia. Thus a systematic increment of the smaller morphotype during most of the iceberg discharges into the North Atlantic, known as “Heinrich events” (Broecker et al. 1992), shows that this subspecies of *C. pelagicus* can be used as a proxy for cold waters, similar to that shown by *N. pachyderma* sinistral and IRD. On the other hand only moderate negative correlations to estimated palaeotemperatures (r = -0.44 and -0.36 for cold and warm season SST’s, respectively) can be derived.

A reduced southward influence of polar water masses is interpreted for isotope stage 6, when compared to isotope stages 4 and 2 (e.g. Lebreiro et al. 1996; Lebreiro et al 1997; Cayre et al. 1999; Calvo et al. 2001). This explains the decrease in *N. pachyderma* percentages (de Abreu et al. 2003) and the lesser contribution of the smaller morphotype of *C. pelagicus* during this stage.

Several mechanisms have been proposed to explain the Heinrich events including insolation changes (Heinrich 1988), sea level changes (Bond and Lotti 1994), global temperature changes (Bond and Lotti 1995), and ice-sheet dynamics (Broecker 1994; McManus et al. 1999). However, in spite of the main cause of these events being related to an increase of temperature at higher latitudes, at lower latitudes there would be a cooling of the water masses attributed to the migration and melting of icebergs. Entire coccospheres (or just isolated placoliths) of the smaller morphotype (directly related to subspecies *C. pelagicus pelagicus*), may then have been passively transported from the subarctic North Atlantic, or extended its geographic range, towards the Iberian margin reflecting a cold water influx. Thus, this morphotype is the best to reflect variations of seawater temperature in relative terms.

Several authors have inferred that the Polar Front position changed through time, playing an important role in the Iberian palaeoclimate (e.g. Fatela 1995; Zazo et al. 1996). For instance, during the last glaciation, Ruddiman and McIntyre (1981) suggested that maximum southward advance of the Polar Front reached 42ºN, whereas the studies of Duprat (1983), allowed establishing a limit of 38ºN for the same period. Later, Bard et al. (1987) conclude that during the earliest retreat of the last glaciation, the Polar Front moved from 35ºN to 55ºN. In contrast, Fatela et al. (1994) showed that during the last glaciation the Polar Front did not migrate south of 42ºN and that during the last glacial maximum SST’s there were probably as warm as today. Thus, a southward shift of the Polar Front during the last glaciation could also move the ecological niche of *C. pelagicus pelagicus* closer to Iberia. However, if its ecological position had been moved to a place around Iberia, an increment of this morphotype should be observed in this core during this period and not only during the Heinrich layer 1, as can be seen in text-fig. 9. Thus, a southward migration of the Polar Front does not necessarily imply a shift of *C. pelagicus* palaeobiogeography towards Iberia, but most probably its reduction or disappearance from the North Atlantic region, as already McIntyre et al. (1970) suggested for the Antarctic frontal system.

Cachão and Moita (2000) showed that at present day and recent past the taxon now known as *C. pelagicus braarudii* is present off the western coast of Iberia, where there is a seasonal coastal upwelling system. Along the MD95-2040 time series *C. pelagicus* overall percentage and abundances are highest for moments with palaeotemperatures (text-fig. 6) compatible to those considered as the optimum developing conditions for the above subspecies (Cachão and Moita 2000). Thus, one may conclude that, occasionally, *C. pelagicus braarudii*
(dimensionally equivalent to an intermediate morphotype of *C. pelagicus* s.l.), heavily contributes with placoliths to the region from the above time series was retrieved.

Thus, according to Cachão and Moita (2000), the presence of the intermediate morphotype is predicted to be related to changes in the upwelling intensity and/or position of the front. The organic matter content of the sediments on the Iberian margin (Thomson et al. 2000), only partly produced from coccolithophores, shows that during most of the 75-15kyr interval the upwelling was relatively intense, suggesting high concentrations of productivity indicators and colder SST than under modern conditions (Pailler and Bard 2002; de Abreu et al. 2003). During the lower part of this time interval (eq. to core depth of 200 to 1280cm; see text-figure 10) the intermediate morphotype is highly represented as indicated by high positive scores of F2 (correlative of the presence of morphon 10) and negative F1 scores (correlative of an increment on morphon 12). Upwards F2 scores disclose an irregular but gradual decrease until HL2 after which it experiences a sudden jump to drop again by HL1. Thus, a decrease of the intermediate morphotype (reflected by a decrease on F2 scores and an almost simultaneous increase in F1 scores) seems to be coincident with almost all Heinrich events (text-fig. 10), which are characterised by very low values of productivity proxies (Pailler and Bard 2002).

Termination II and termination I seem to correspond to a strong but transient intensification of the upwelling, while the opposite is verified for MIS 5 and the Holocene (Pailer and Bard 2002). Results from the intermediate form (Factor 2 scores; text-fig. 10) show sudden increments and a change to a pattern of more consistent positive values some time before terminations II and I.

Abrantes (1991) detected changes in the position of the Iberian upwelling front during stage 2, and its intensification during both glacial episodes 2 and 6 relative to interglacial intervals.

For the first half of isotope stage 2 our results show low abundances of the intermediate form (represented by F3 scores around 2) followed by an increase towards the LGM where it reaches a local maximum (F3 scores around -1). During isotopic stage 6 abundances of the intermediate morphotype are relatively low. On the other hand, the record of the larger morphotype, strongly represented in the Azores region, shows a strong increment during this stage (text-fig. 10). To interpret these results we speculate that the intensification of the oceanographic circulation, that is responsible for the increase in the intensity of the upwelling system, could also be responsible for the increase of the Azores Current and, consequently, the migration of larger forms towards Iberia restricting the development and record of the intermediate forms to the shelf itself.

Studies conducted around the Azores islands confirmed the predominance of the larger morphotype of *C. pelagicus* in samples from this region (Parente 2002). Since the main oceanographic characteristic of the area is the Azores Current and Front, oscillations observed in this morphotype’s record could be related to a higher or lower influence of water masses driven from this region towards Eastern North Atlantic. Thus, an intensification of the Azores high pressure cell, and consequently the NAO, enhance the Azores Current and Front, which would imply an increase of the larger morphotype in the region off western Iberia. Current research in the Azores-Iberian region will test the validity of this palaeoceanographic interpretation.

**CONCLUSION**

Results from the statistical morphometric analysis of *Coccolithus pelagicus* s.l. of both surface sediments of the North Atlantic region and core MD95-2040 off Iberia, showed that it was possible to identify three morphotypes: a small (6-10µm), an intermediate (10-13µm) and a large one (14 to 16µm). Each of these showed potential to be used as a paleo-
oceanographic proxy for the influence of distinct ocean water masses, currents and oceanographic mechanisms. Thus, the morphometry of this taxon is a useful tool to reconstruct the palaeoceanographic conditions occurred off Western Iberia during the last two glacial cycles. Following the above results the smaller morphotype (essentially equivalent to *C. pelagicus* *pelagicus*) may be used as a proxy of the influence of subpolar Atlantic water masses, the intermediate morphotype (interpreted as *C. pelagicus braarudii*) may be related to changes in the intensity and/or position of coastal upwelling off Iberia, while the larger morphotype (here defined as *C. pelagicus azorinus*) seems to indicate the influence of water masses driven directly from the Azores front, which changes may be more or less directly related to NAO.

### SYSTEMATIC APPENDIX

**Coccolithus pelagicus azorinus** Parente and Cachão n. subsp.  
Plate 1, figures 1-5

**Diagnosis:** Coccolithus pelagicus subspecies producens coccolithos 14µm longior (maximus placolithos diametrum)

A subspecies of *Coccolithus pelagicus* producing coccoliths over or equal to 14µm long (maximum diameter of the placoliths).

**Holotype:** Plate 1, figure 1. Type specimens are preserved in permanent mounting media, slide GeoFCUL-nanolab SF13 (Saldanha), deposited in the Department of Geology of the Faculty of Sciences of the University of Lisbon.

**Paratype:** Plate 1, figures 2, 3 and 4.

**Type locality:** Saldanha seamount. Lat: 36°33.8’N; Long: 33°20.6’W (West-Southwest of the Azores archipelago).

**Etymology:** The sub-specific epithet “azorinus” (from Azores) refers to the region where it is found in present day surface samples.
Description: Large more or less elliptical placolith with a thin and curved bicyclic smaller proximal shield and an elliptic central area opening surrounded on the distal side by a shingling of thin laths; only the proximal shield and central area birefringe as is characteristic of members of the genus. In light microscope examination, both the rim and central area are prominent. A bridge parallel to the smaller axis of the placolith may be present. Major diameter ranges from 14 to 16µm.

Remarks: This subspecies has the largest placoliths of all other extant forms described for this genus, namely the C. pelagicus ssp. pelagicus which is the species type. It displays some morphometric resemblance to the fossil species C. miopelagicus.

* Coccolithus pelagicus braarudii * (Gaarder 1962) Geisen et al. 2002 emended

Results from the present work restrict the length of the maximum diameter of the placoliths of the subspecies C. pelagicus braarudii to less than 14µm.

**ACKNOWLEDGMENTS**

This work was funded by the projects CANAL (FCT POCTI/32724/99) and CRIDA (FCT PLE/8/00) and by the scholarship SFRH/BD/8944/2002. We would like to express our thanks to Professor Fernando Barriga and Agata Dias for access to samples from the Azores thermal vent of Monte Saldanha, to Professor Sir Nicholas J. Shackleton for granting access to IMAGES core MD95-2040 and to Mike Hall from the Godwin Laboratory (Cambridge) for the vast number of stable isotope measurements presented in this paper. Contribution of Bruno Ribeiro (CANAL’s BTI scholarship) is also gratefully acknowledged by the authors. The text benefited from extended refereeing remarks from José-Abel Flores and Jeremy Young. The authors also thank Manuel João Pinto for advice on Latin text.

**REFERENCES**

PLATE 1
Magnification scale bar for all figures = 5 μm.

1a Distal view of *C. pelagicus azorinus* coccolith (holotype) observed under parallel light (PL). Sample from Saldanha seamount, SF13.

1b The same specimen as in Figure 1a (holotype), seen under crossed polarized light (XPL).

2a Distal view of *C. pelagicus azorinus* coccolith observed under PL. Sample from Saldanha seamount, SF13.

2b The same specimen as in Figure 2a, seen under XPL.

3a Distal view of *C. pelagicus azorinus* coccolith observed under PL. Sample from the MD95-2040 core, at a depth of 1370-1371m.

3b The same specimen as in Figure 3a, seen under XPL.

4a Distal view of *C. pelagicus azorinus* coccolith observed under PL. Sample from the MD95-2040 core, at a depth of 1370-1371m.

4b The same specimen as in Figure 4a, seen under XPL.

5 *C. pelagicus azorinus* partial coccosphere observed in a sample from the MD95-2040 core, at a depth of 1370-1371m.