

UNUSUAL OLIGOCENE *BRAARUDOSPHAERA* - RICH LAYERS OF THE SOUTH ATLANTIC AND THEIR PALAEOCEANOGRAPHIC IMPLICATIONS

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Abstract: The origin of the Oligocene *Braarudosphaera* layers over large ocean basins has remained a mystery since the question was raised almost three decades ago by the Deep Sea Drilling Project. A micropalaeontological study, coupled with oxygen and carbon isotope data, from Sites 363 and 522 in the S Atlantic Ocean have shed some new light on this question. Our *Braarudosphaera* abundance data correlate with oxygen isotope curves, suggesting that *Braarudosphaera* preferred cold waters. Variations in the relative abundance of sphenoliths (warm-water taxa), and longer *Coccolithus pelagicus* placoliths, also indicate colder water conditions during times of elevated *Braarudosphaera* deposition. Upwelling and mid-ocean overturn of cold, nutrient-rich, low-salinity water are suggested to be the most likely palaeoceanographic mechanisms for the deposition of *Braarudosphaera* layers.

Introduction

The genus *Braarudosphaera* includes calcareous nannoplankton species with a coccosphere of pentoliths, each comprising with five elements of basic trapezoidal shape. *Braarudosphaera* has a long stratigraphic range, from the Early Cretaceous to Recent. It is represented in the modern oceans by the type species, *Braarudosphaera bigelowii*, which is covered by twelve flat pentoliths.

Modern occurrences of braarudosphaerids (dominated by *B. bigelowii*) are mostly associated with nearshore, low-salinity marine waters (Bukry, 1974; Okada, 1992). High concentrations of modern representatives have been found in areas of relatively low salinities, such as the Gulf of Maine (31.8-32.7‰; Gran & Braarud, 1935) and Gulf of Panama (26.8-32.5‰) where it reached 1500 cells/litre of water (Smayda, 1966). Bukry (1974) noted that their affinity for low-salinity waters is well illustrated by their abundance in the Black Sea (salinity 17-18‰), and their absence in the Red Sea (salinity 37-41‰). They have sometimes been reported from open-ocean sites with normal salinities, but only at very low abundances, e.g. Okada & Honjo, 1973. Some braarudosphaerids have also been reported from the Persian Gulf (Martini, 1967) where surface salinities are high (34-40‰).

During Deep Sea Drilling Project (DSDP) Leg 3, in the S Atlantic Ocean, strong seismic reflectors were found in the Oligocene and the horizons were recovered in cores. Detailed examination of the cores revealed chalk intervals almost exclusively composed of *Braarudosphaera* (Maxwell *et al.*, 1970). These layers immediately aroused great interest, in geophysics as unusual extensive acoustical reflectors, and in sedimentology because of their significance in the study of sediment lithification and diagenesis (Wise & Hsü, 1971; Wise & Kelts, 1972). They also posed an intriguing palaeoceanographic question as to why this typically nearshore nannoplankton genus became so abundant in the open ocean.

Origin of *Braarudosphaera* layers

Salinity-reduction hypotheses

Several hypotheses have been proposed to explain these

unusual *Braarudosphaera* horizons. Most of these hypotheses address the problem from the standpoint of low-salinity conditions in the S Atlantic during the Oligocene, a view based on modern occurrences of this genus. Mechanisms suggested to reduce surface-water salinities over large areas include: an increase in the regional rainfall (Bukry, 1974); periodic fluxes of Oligocene glacial melt-waters to reduce near-surface salinity (Hsü *in* Bukry, 1978); high influx of fresh water from the Orange River into the Cape Basin, coupled with upwelling of nutrient-rich, intermediate or deep, low-salinity water (Bolli *et al.*, 1978); and initiation of the Benguela Current was postulated as the trigger for this upwelling process in the area of Leg 40 in the mid-latitude S Atlantic by Siesser (1978) and Melguen (1978).

Red tide hypotheses

Braarudosphaera blooms, analogous to modern day red-tide blooms but with longer duration, have also been proposed (Maxwell *et al.*, 1970). This type of interpretation is supported by analogy with the *Braarudosphaera* blooms from immediately above the Cretaceous/Tertiary boundary (Fischer & Arthur, 1977). In this context, they are considered to be 'opportunistic disaster forms' that took advantage of the available ecological niches and minimal competition from other groups. This hypothesis, however, does not explain the repetitive *Braarudosphaera* layers within normal pelagic oozes that occur in the Oligocene.

Upwelling

LaBrecque *et al.* (1983) suggested mid-ocean upwelling as the mechanism for enhanced productivity in the open ocean that could lead to these blooms. This would also account for their wide distribution in the S Atlantic. LaBrecque *et al.* (1983) suggested further that the opening of the Drake Passage, which appears to coincide with the Oligocene braarudosphaerid occurrence, could have caused the S Atlantic mid-ocean upwelling. The opening of the Drake Passage is associated with the start of circum-Antarctic winds and strong latitudinal temperature-

gradients that would have contributed to the upwelling. However, this does not explain the dominance of *Braarudosphaera* in the upwelling-induced blooms, nor the repetitive and temporary nature of the oozes. Siesser *et al.* (1992) suggested regional divergent upwelling, much like the Subtropical Divergence, to explain these braarudosphaerid occurrences. However, these divergence areas have not yielded any Recent *Braarudosphaera*-rich sediments (Lohman, 1986) and the present day species diversity among these sites appears to be normal (Okada & Honjo, 1973).

Berger (1981) suggested mid-ocean overturn as another possible mechanism to explain the blooms (see Discussion, below). This phenomenon occurs during times of instability in the water-column. Cyclonic circulation and winter seasonal cooling combine to bring about overturn of surface-waters and the delivery of cold, nutrient-rich waters from below.

Redeposition

Another hypothesis centres on redeposition of the braarudosphaerids to deeper waters. In DSDP Leg 3 reports, Maxwell *et al.* (1970) proposed that unusual oceanographic conditions might have triggered the transportation of shallow-water sediments bearing *Braarudosphaera* to deeper waters over a large area. Hsü *et al.* (1984), on the other hand, proposed that at Site 522 in the central S Atlantic, the braarudosphaerid pentaliths were transported by the ancestral Benguela Current to the open ocean from upwelling sites off the South African margins. However, this does not explain their wide geographical distribution and the cyclical nature of the occurrences. Moreover, there is neither a shallow-water source in the S Atlantic nor evidence of slumping or turbidite flow in the sediments where they were found (Wise & Kelts, 1972).

Diagenetic concentration

Selective dissolution of nannofossil species was discussed by Wise & Hsü (1971). They noted, however, that the low amount of terrigenous material in the braarudosphaerid chalk implies that minimal dissolution has taken place. Moreover, *Braarudosphaera* is highly susceptible to dissolution (Bukry, 1971; Wise & Kelts, 1972) and thus selective dissolution cannot account for the enrichment of *Braarudosphaera*.

Isotope data

Stable isotope analyses were performed by Lloyd & Hsü (1972) and by Siesser *et al.* (1992) on Oligocene braarudosphaerid-bearing samples from DSDP cores. Based on analyses of three bulk samples enriched in *Braarudosphaera* rosa, Lloyd & Hsü (1972) suggested growth of *Braarudosphaera* in cold surface-waters brought by upwelling Antarctic waters. However, the palaeotemperature of 6°C, as inferred from the oxygen isotope values, were thought to be too low for *Braarudosphaera* growth. Modern braarudosphaerids had not been recorded from waters below 10°C (Wise & Hsü, 1971). This led Wise & Hsü (1971) and Lloyd & Hsü (1972) to

conclude that the palaeotemperature they obtained represented bottom-water conditions where braarudosphaerid skeletons were diagenetically altered. Carbon isotope results by Siesser *et al.* (1992), from *Braarudosphaera*-rich bulk samples from the mid-latitude Indian Ocean, showed no clear correlation between $\delta^{13}\text{C}$ and *Braarudosphaera*. Their $\delta^{18}\text{O}$ measurements showed higher values in the *Braarudosphaera*-bearing intervals. Based on these oxygen isotope data, Siesser *et al.* (1992) suggested significant cooling of surface-waters in the Indian Ocean for the *Braarudosphaera*-bearing interval. However, *Braarudosphaera* made up less than 10% of the sediment in their samples. The low abundance of *Braarudosphaera* may have made the palaeoceanographic signal from the *Braarudosphaera*-bearing intervals too weak to be detected. Results from the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses of Siesser *et al.* (1992) are difficult to interpret for palaeoenvironment because bulk sediment samples were used for isotope studies and changes in assemblage composition could easily cause variations in the isotopic records.

Objectives of this study

This study concentrates on the Oligocene *Braarudosphaera* layers in the S Atlantic, where this phenomenon is best recorded. The objective was to better understand the palaeoceanographic conditions for the deposition of the braarudosphaerid layers by collecting and analysing quantitative nannofossil data and by synthesising oxygen and carbon isotope data collected previously (Mead, 1995).

In particular, two DSDP sites were investigated in detail (Figure 1). Site 363 in the Angola Basin (19°S, 09°E; 2248m water-depth) is a nearshore site, while Site 522 at Walvis Ridge (26°S, 05°W; 4441m water-depth) represents the mid-ocean occurrence of these deposits. Age determination was facilitated by the availability of magnetostratigraphy at Site 522.

Quantitative abundance patterns of key nannofossil taxa across the *Braarudosphaera* layers are documented for the first time. A census of cool-(chiasmoliths, *Reticulofenestra daviesii*, *Coccolithus pelagicus*) and warm-water taxa (discoasters, sphenoliths and helicosphaerids) was used to infer surface-water temperature fluctuations. In addition, coccolith size-variations downcore were examined for evidence of changes in surface-water temperature.

Material and methods

Sediment samples were taken from across eight *Braarudosphaera* layers in cores 5-7 at Site 363 (Figure 2). At Site 522, samples across the thickest *Braarudosphaera* layer were examined. These include samples from both Holes 522 and 522A. As the corresponding *Braarudosphaera* layer was recorded at slightly different subbottom depths in the two holes, sample depths from Hole 522A were corrected by adding 1.45m (Mead, 1995).

The three cores analysed from Site 363 have the following ages assigned by Proto Decima *et al.* (1978), based on the calcareous nannofossil zones of Martini (1971): Core 363-5, NP24 (*S. distentus* Zone); 363-6, NP23

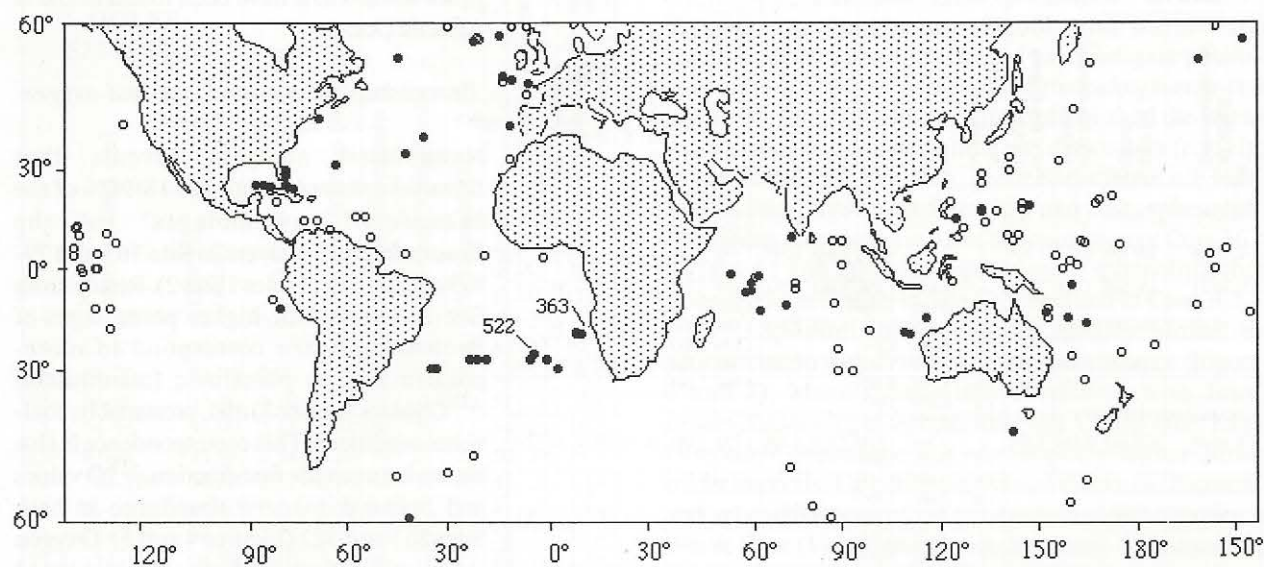


Figure 1: Location map of Oligocene *Braarudosphaera* occurrences as synthesised from DSDP/ODP reports. *Braarudosphaera* oozes and chalks are represented by black circles. Sites with noticeable *Braarudosphaera* are indicated by grey circles. Open circles represent sites with calcareous Oligocene sediments but practically no *Braarudosphaera*. The location of ODP Sites 363 and 522, studied in detail, are marked.

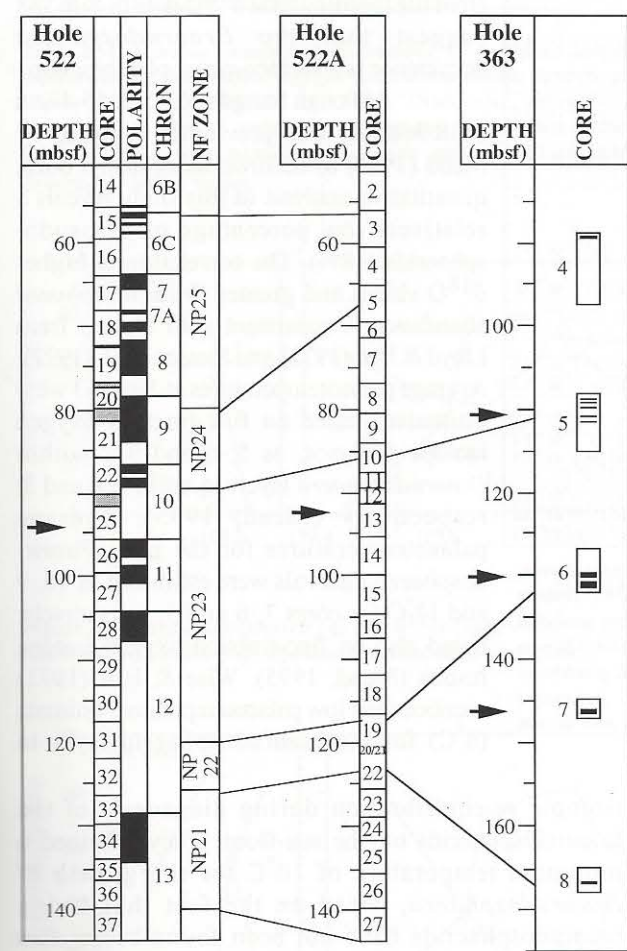


Figure 2: Cores 363, 522 and 522A sampled for this study. Arrows indicate cores used. Magnetostratigraphy of Site 522 is from Tauxe *et al.* (1984). Calcareous nannofossil zones are from Proto Decima *et al.* (1978) and Percival (1984). Tie-lines indicate calcareous nannofossil zone boundaries between cores. In Site 363, *Braarudosphaera* ooze/chalk layers are indicated by short horizontal lines within the core. Modified from Mead (1995).

(*S. predistentus* Zone); and 363-7, NP22 (*H. reticulata* Zone). Percival (1984) assigned cores 522-25 and 522A-13 to NP23. Based on the Sr-isotope age-model of Mead & Hodell (1995), cores 5-7 of Site 363 have an average age of 29.83-32.4Ma (ages converted to the timescale of Cande & Kent, 1995). Magnetostratigraphy of Site 522 suggests that cores 522-25 and 522A-13 correlate to Chron C10r (29Ma).

The duration of the *Braarudosphaera* occurrences studied from Sites 363 and 522 were calculated to be 7-46kyr, depending on thickness, using a constant sedimentation rate model, and 6-19kyr, assuming a non-constant sedimentation rate model. The non-constant sedimentation rate model assumed that the sedimentation rate of non-carbonate in the *Braarudosphaera* and non-*Braarudosphaera* intervals did not change, and used the variation of carbonate content to vary the sedimentation rate (Mead, 1995).

Smear-slides were made from fine-fractions (<63µm) and set in Norland optical adhesive. Microscope analyses were done at x1000 magnification under phase-contrast and crossed-nicols on a Zeiss Axioscop microscope. Nannofossil abundance counts are based on a total of 300+ specimens per slide.

Oxygen and carbon isotope results and methods are documented in detail by Mead (1995). Foraminiferal and fine-fraction isotope data are available for Site 363. However, foraminiferal isotope data were not generated for Site 522 due to evidence of carbonate diagenesis and the absence of *Chiloguembelina cubensis*. The following foraminifera, representing different water-column habitats, were analysed: *C. cubensis* (shallow planktonic), *Catapsydrax dissimilis* (deep-living planktonic) and *Cibicidoides* spp. (benthic).

SITE 363													
SAMPLE (core-section, cm)	DEPTH (mbsf)	$\delta^{18}\text{O}$ fine-fraction ($<63\mu\text{m}$)	$\delta^{13}\text{C}$ fine-fraction ($<63\mu\text{m}$)	Size-fractions of <i>C. cubensis</i>	<i>Chilodactylina</i> <i>cubensis</i>	<i>Catapsydrus</i> <i>dissimilis</i>	<i>Cibicides</i> <i>spp.</i>	<i>Braarudosphaera</i>	<i>Discoaster</i>	<i>Sphenoliths</i>	<i>Helicosphaera</i>	<i>C. pelagicus</i>	<i>C. pelagicus</i> length (μm)
5-2, 33-36	108.845	0.841	1.447	C	$\delta^{18}\text{O}$ $\delta^{13}\text{C}$	$\delta^{18}\text{O}$ $\delta^{13}\text{C}$	$\delta^{18}\text{O}$ $\delta^{13}\text{C}$	$\delta^{18}\text{O}$ $\delta^{13}\text{C}$	% %	% %	% %	% %	
5-2, 45-47	108.960	1.332	1.381	C	-0.177 1.159	0.857 0.269	1.623 0.528	0 3	51	2	44	7.6	
5-2, 64-66	109.150	0.210	1.324	c	-0.351 0.838	1.445 0.589	1.626 0.542	7 10	47	2	41	7.5	
5-2, 69-71	109.200	1.146	1.279	Ch	-0.443 0.970		1.626 0.542	56 8	53	4	35	7.7	
5-2, 79-82	109.305	0.464	1.236	Ch	-0.051 1.108	1.164 0.754	1.527 0.715	0 13	48	3	36		
6-3, 53-55	129.540	0.339	1.420	C	-0.282 0.739	0.672 0.962	1.356 0.356	0 13	48	3	36		
		0.174	1.562	Ch	0.049 0.894		1.575 0.473	3 9	42	1	48	7.6	
6-3, 83-86	129.845	1.644	1.918	c	0.098 1.483	0.811 0.956	1.948 0.834	36 6	38	0	55	8.4	
				Ch	1.705 0.767		1.906 1.067						
				Ch	-0.030 1.645								
				CH	0.351 1.723								
6-3, 89-91	129.900	1.758	2.419	c	0.564 1.818	1.010 1.226	1.730 1.081	36 6	38	0	55	8.4	
				Ch	0.624 1.880								
				Ch	0.666 1.916								
				CH	0.888 1.705								
				c	0.011 -0.137	1.014 1.371	1.193 0.976	71 8	37	1	55	8.1	
				c	1.411 0.750								
				c	1.322 0.844								
				Ch	0.154 2.006								
				Ch	0.404 1.943								
6-3, 96-99	129.975	2.153	2.232	c	0.519 1.838	1.019 1.264	1.374 1.103	73 12	25	1	62	8.5	
				C	0.212 1.641								
6-3, 104-106	130.050	2.131	2.506	Ch	0.235 1.594	1.197 1.313	1.502 1.218	78 15	23	0	63	8.4	
		1.733	2.582	CH	0.698 1.281								
6-3, 119-121	130.200	1.829	2.727	c	-0.015 1.770	1.040 1.232	1.115 1.047	80 9	22	1	68	8.5	
				Ch	-0.294 1.779								
6-3, 124-127	130.250	2.189	2.710	C	0.167 1.787	1.247 1.168	1.533 1.296	68 7	33	0	60	8.3	
6-3, 129-131	130.300	1.546	2.531	c	0.004 1.750	1.200 1.136	0.920 0.875	59 12	38	0	50	8.3	
				Ch	-0.018 1.811	1.112 1.277	1.082 0.845						
							1.046 0.855						
6-3, 140-142	130.410	1.034	2.085	c	-0.014 1.730	1.058 1.132	1.237 0.828	48 10	33	1	55	8.3	
				Ch	0.071 1.907		1.238 0.832						
				Ch	-0.027 1.784		1.055 0.909						
				CH	-0.166 1.874								
6-3, 144-146	130.450	1.997	2.464	c	0.517 1.885	0.997 1.272	1.545 0.951	63 11	35	0	53	7.3	
		1.568	2.519	Ch	0.665 1.897		1.830 0.932						
6-4, 4-6	130.550	1.481	2.386	c	0.077 1.799	0.869 1.192	1.078 0.968	45 7	46	1	46	7.9	
				c	-0.001 1.748								
				Ch	0.144 1.907								
				Ch	-0.044 1.766								
				CH	0.061 1.912								
6-4, 14-16	130.650	1.005	2.067	c	-0.023 1.617	0.876 1.214	0.979 0.787	33 5	38	1	56	7.2	
				Ch	0.113 1.790								
7-1, 49-52	145.505	0.165	1.208	c	-0.771 1.222	0.418 0.977	0.956 0.708	5 14	26	2	58	7.8	
				Ch	-0.146 1.496		1.301 0.582						
				Ch	-0.784 1.347		1.208 0.586						
				P	-0.328 1.097								
7-1, 89-91	145.900	0.968	2.709	P	0.119 0.902	0.983 1.087	1.267 1.089	65 25	28	1	46	8.6	
7-1, 90-93	145.915	0.827	2.152	c	0.440 1.994	0.363 1.223	1.659 0.979	46 20	29	1	50	8.7	
		0.681	2.404				1.160 1.099						
7-1, 109-113	146.110	2.180	3.527					92 27	21	0	52	9.6	
7-1, 115-120	146.175	2.091	3.697	P	1.773 1.739	0.000 1.386	1.325 1.490	96 29	15	1	56	9.4	
7-1, 128-133	146.305	2.366	3.675					95 34	19	0	47	8.7	
		1.855	3.581										
7-1, 133-135	146.340	1.949	3.663			0.438 1.642	1.503 1.574	93 34	13	0	53	8.6	
7-1, 146-149	146.450	2.451	3.662	P	0.458 0.441			94 45	11	0	44	10	
7-CC	146.500	2.436	3.668			0.129 1.365	1.279 1.441	98 50	13	0	37	9.3	

Table 1: Calcareous nannofossil abundances, *C. pelagicus* length measurements, fine-fraction and foraminiferal oxygen and carbon isotope data for Site 363. Isotope data are from Mead (1995). Different size-fractions of *C. cubensis* were analysed for isotopes and are designated by the following: c=104-125 μm ; C=104-150 μm ; Ch=125-150 μm ; CH=150-250 μm ; cC=104-250 μm ; P=125-150 μm (bulk planktonic foraminifera analysed). *Discoaster*, *sphenolith*, *Helicosphaera* and *C. pelagicus* percentages are fractions of the total of these four nannofossil groups and do not include *Braarudosphaera* values.

Results

Distribution of *Braarudosphaera* chalk

An extensive survey of DSDP and ODP nannofossil biostratigraphic literature revealed that occurrences of *Braarudosphaera* oozes and chalks appear to be distributed between $\sim 19^\circ$ to 30° latitude in the S Atlantic (Legs 3, 40 and 73; Figure 1). These oozes and chalks are assigned to calcareous nannofossil zones NP22-NP24 (Oligocene; Parker *et al.*, 1985). At Site 362 (Leg 40), at least 34 cyclic *Braarudosphaera* beds, with an interbed period of 100 000 years or less, were reported. Other Oligocene occurrences with lower abundances of

Braarudosphaera have been found in the N Atlantic Ocean.

Braarudosphaera abundance and oxygen isotope data

Nannofossil analysis reveals that *Braarudosphaera* comprises 18-98% of the nannofossil assemblages in the *Braarudosphaera* layers in Site 363 and 79-89% in Site 522 (Tables 1 and 2). Results from Site 363 show that higher percentages of *Braarudosphaera* correspond to more-positive shallow planktonic foraminiferal $\delta^{18}\text{O}$ values (Figure 3) and, presumably, cold-water conditions. This correspondence is also shown between the fine-fraction $\delta^{18}\text{O}$ values and *Braarudosphaera* abundance in both Sites 363 and 522 (Figures 4 and 5). Oxygen isotope values from the deeper planktonic and benthic foraminifera do not show any correlation with *Braarudosphaera* abundance (Spearman correlation coefficient, $r' = 0.073$ for the deeper planktonics and $r' = -0.072$ for the benthics). These results from the foraminiferal $\delta^{18}\text{O}$ data in Site 363 suggest that the *Braarudosphaera* occurrence is a surface-water phenomenon.

Although Sample 363-5-2, 45-47cm (108.96mbsf) was previously assumed by Mead (1995) to be *Braarudosphaera* ooze, quantitative analysis in this study reveals a relatively low percentage of braarudosphaerids (18%). The correlation of higher $\delta^{18}\text{O}$ values and greater *Braarudosphaera* abundance is consistent with reports from Lloyd & Hsü (1972) and Siesser *et al.* (1992). Average palaeotemperatures at Site 363 were estimated, based on fine-fraction oxygen isotope analyses, as 5, 6 and 9°C within *Braarudosphaera* layers in cores 7, 6 and 5, respectively (Mead, 1995). Average palaeotemperatures for the non-*Braarudosphaera* intervals were estimated as 10, 9 and 12°C for cores 7, 6 and 5, respectively, based also on fine-fraction oxygen isotope results (Mead, 1995). Wise & Hsü (1971) ascribed their low palaeotemperature estimate (6°C) for the braarudosphaerid layer to

isotopic re-equilibration during diagenesis of the braarudosphaerids on the sea-floor. They assumed a minimum temperature of 10°C for the growth of *Braarudosphaera*, based on the fact that living braarudosphaerids have not been found below this temperature. A plankton study in the English Channel, however, showed that *Braarudosphaera* was most abundant during the winter months (Boalch, 1987) when temperatures range from 5 to 10°C (Robinson *et al.*, 1979). This would be consistent with the relatively low palaeotemperatures estimated by Wise & Hsü (1971) and Mead (1995).

HOLES 522 & 522A									
SAMPLE (core-section, cm)	DEPTH (mbsf)	$\delta^{18}\text{O}$ fine-fraction (<63 μm)	$\delta^{13}\text{C}$ fine-fraction (<63 μm)	% Braarudosphaera	% Other Nannofossils	% Discoasters	% Sphenoliths	% C. pelagicus	C. pelagicus length (μm)
25-2, 37-39	93.48	0.61	1.97	0	100	24	49	27	10.6
13-1, 63-67	93.60			0	100	18	45	37	9.3
25-2, 68-70	93.79	0.90	2.27	0	100	25	42	34	9.5
13-1, 84-86	93.80	0.78	2.38	0	100	20	51	28	9.5
13-1, 94-96	93.90	2.48	2.41	80	20	23	54	23	10.5
25-2, 83-85	93.94	2.34	2.20	79	21	23	50	27	11.1
13-1, 104-106	94.00	2.37	2.35	88	12	35	42	24	13.4
25-2, 99-101	94.10	2.25	2.19	84	16	22	48	31	13.4
13-1, 114-116	94.10	2.25	2.25	85	16	44	35	21	13.4
13-1, 124-126	94.20	2.10	2.19	89	11	27	49	24	11.8
25-2, 116-118	94.27	0.81	2.13	6	94	21	49	30	9.4
13-1, 138-141	94.35	1.21	2.39	47	53	25	53	22	10
25-2, 137-139	94.48	0.82	2.29	0	100	22	53	26	10
13-2, 14-16	94.60	0.92	2.31	0	100	15	53	32	8.6
13-2, 24-27	94.70	0.91	2.37	3	97	20	56	24	10.4
13-2, 34-37	94.80	0.99	2.46	0	100	17	45	37	8.2
13-2, 44-46	94.90	1.08	2.61	0	100	14	58	28	8.9

Table 2: Calcareous nannofossil abundances, C. pelagicus length measurements, fine-fraction oxygen and carbon isotope data (from Mead, 1995) for Holes 522 and 522A. Discoaster, sphenolith, Helicosphaera and C. pelagicus percentages are fractions of the total of these four nannofossil groups and do not include Braarudosphaera values.

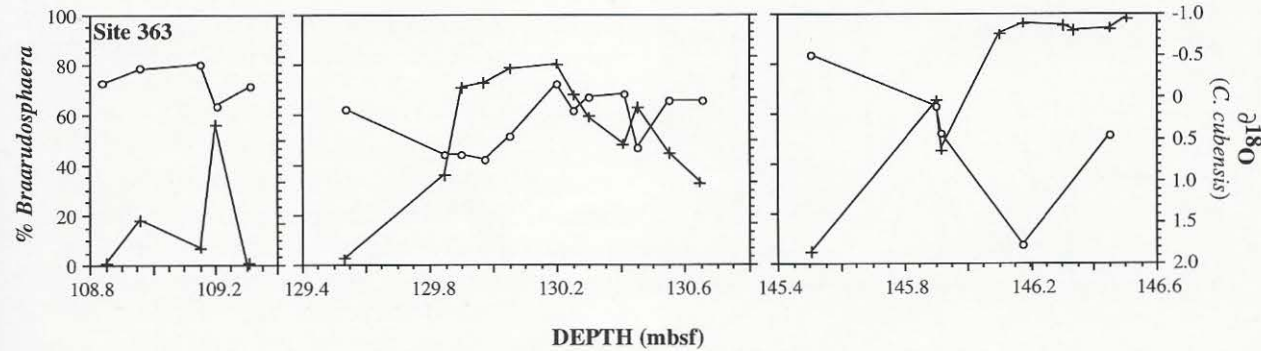


Figure 3: % Braarudosphaera (+) and $\delta^{18}\text{O}$ (open circle) of shallow planktonic foraminifer, Chilguembelina cubensis (104-125 μm size-fraction) in Site 363. Spearman's correlation coefficient, $r' = 0.624$.

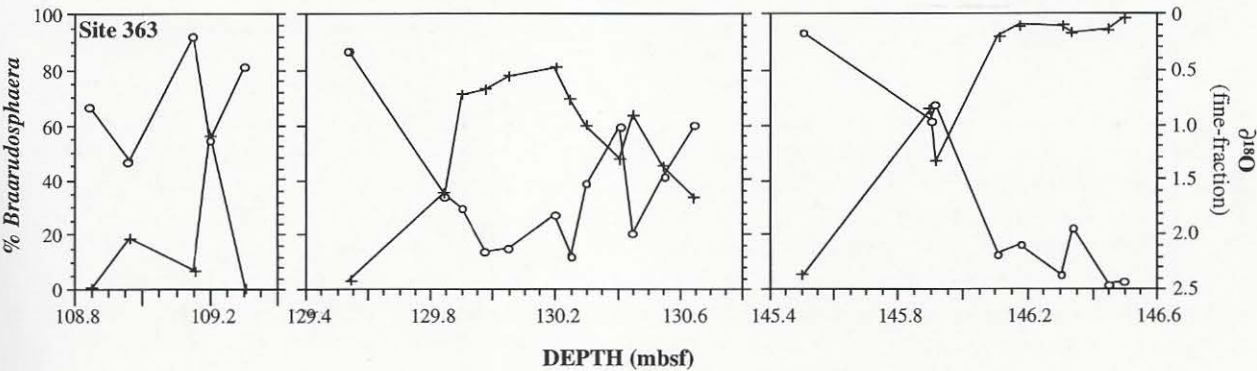


Figure 4: % Braarudosphaera (+) and fine-fraction $\delta^{18}\text{O}$ (open circle) from Site 363. Spearman's correlation coefficient, $r' = 0.874$.

Discoasters and sphenoliths

The relative abundances of cool- and warm-water nannofossil taxa were determined to investigate possible temperature changes across the Braarudosphaera-rich layers. Biogeographic studies have established the warm-water preference of sphenoliths and discoasters (e.g. Haq & Lohmann, 1976a, b; Haq, 1980; Backman et al., 1986; Wei & Wise, 1990). At Sites 363 and 522, sphenoliths outnumber discoasters in all of the cores except Core 363-7 (Tables 1 and 2). There are also more sphenoliths than Coccolithus pelagicus in Site 522 cores and in Core 363-5.

Sphenolith abundance clearly shows an anticorrelation with Braarudosphaera abundance (Figures 6 and 7). More sphenoliths correlated with fewer Braarudosphaeras in warmer intervals. On the other hand, Discoaster abundance was unexpectedly higher during colder intervals. This difference is also shown in Discoaster and sphenolith percentage curves in Site 522 samples in Wei & Wise (1990) but was not discussed. Consequently, sphenoliths should be considered as better palaeo-temperature indicators in these Early Oligocene S Atlantic waters than the discoasters.

Coccolithus pelagicus

Coccolithus pelagicus has been shown to prefer cool-water conditions (Haq, 1980; Raffi & Rio, 1981; Wei & Wise, 1990). Other cool-water indicators, such as Reticulofenestra daviesii and Chiasmolithus spp. are either absent or too rare to be used effectively in this study.

There is a significant difference in the range of C. pelagicus abundance between the two sites (Tables 1 and 2). At Site 522, C. pelagicus comprises 21-37% of the

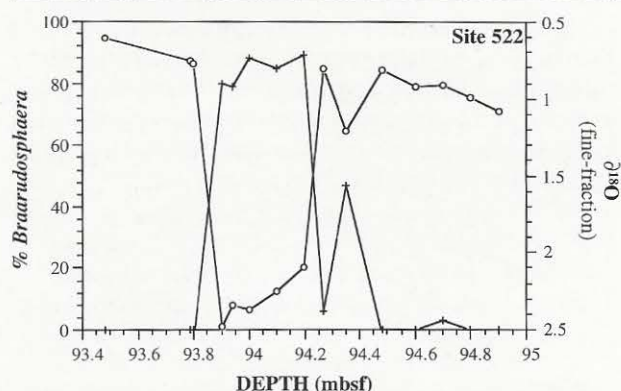


Figure 5: % *Braarudosphaera* (+) and fine-fraction $\delta^{18}\text{O}$ (open circle) from Site 522. Spearman's correlation coefficient, $r' = 0.768$.

nannofossil assemblage, excluding *Braarudosphaera*, while at Site 363, it ranges from 35–68%. In addition, at Site 363 there is a general positive relationship between *C. pelagicus* and *Braarudosphaera* abundance (Figure 8), that is, higher abundance of *C. pelagicus* corresponds to higher $\delta^{18}\text{O}$ (cold-water conditions). However, these two records show a general anticorrelation at Site 522 (Figure 9). We suspect that this may be related to the significantly lower abundance of *C. pelagicus* at this site compared to Site 363.

Coccolithus pelagicus size

Coccolith size may be related to surface-water temperature. Baumann (1995) documented an increase in the abundance,

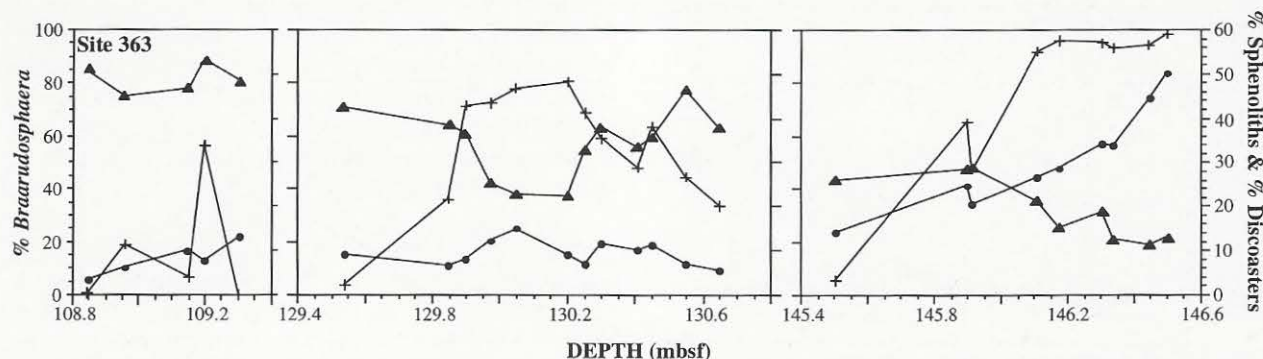


Figure 6: % Discoasters (closed circle), % Sphenoliths (closed triangle) and % *Braarudosphaera* (+) from Site 363.

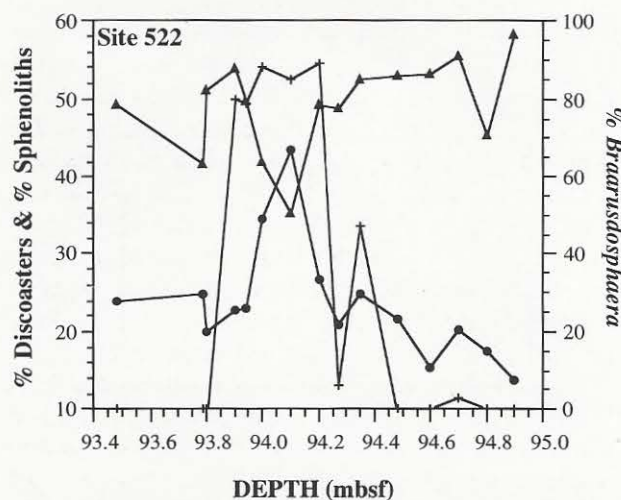


Figure 7: % Discoasters (closed circle), % Sphenoliths (closed triangle) and % *Braarudosphaera* (+) from Site 522.

and a marked decrease in the length, of *C. pelagicus* specimens in the Norwegian-Greenland Sea during the Holocene and Interglacial Stage 7. In this study, larger *C. pelagicus* correlates with a higher abundance of *Braarudosphaera* (Figures 10 and 11) at Sites 363 and 522. This suggests colder conditions for the *Braarudosphaera*-rich intervals.

Carbon isotope data

Braarudosphaera abundance generally correlates with foraminiferal carbon isotope values of *Catapsydrax dissimilis* and *Cibicidoides* spp. at Site 363 (Figures 12 and 13). Higher $\delta^{13}\text{C}$ values accompanied by higher braarudosphaerid abundance may be interpreted as evidence for increased productivity in the surface-waters, since lighter ^{12}C is preferentially taken up during photosynthesis. However, the $\delta^{13}\text{C}$ curve of the planktonic and benthic foraminiferal isotope values is inconclusive,

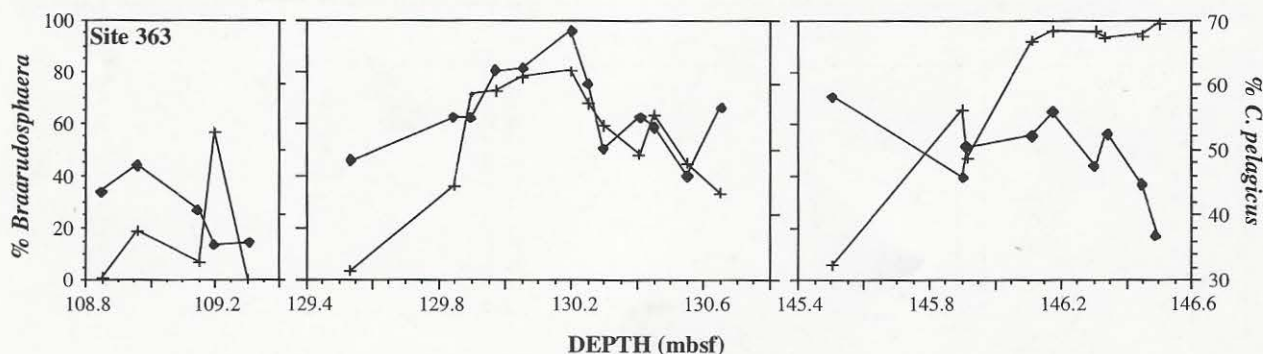


Figure 8: % *Braarudosphaera* (+) and % *C. pelagicus* (closed diamond) from Site 363.

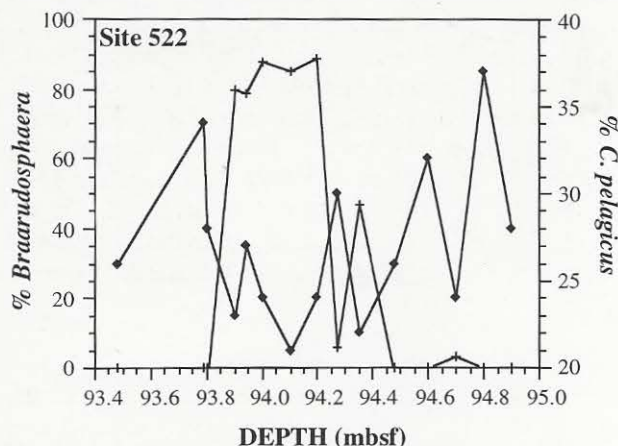


Figure 9: % Braarudosphaera (+) and % C. pelagicus (closed diamond) at Site 522.

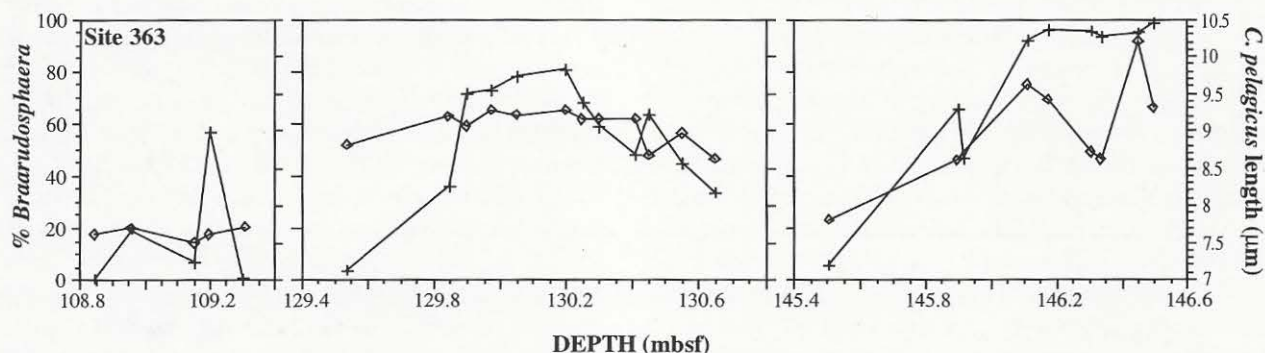


Figure 10: % Braarudosphaera (+) and length of C. pelagicus placoliths (open diamond) from Site 363.

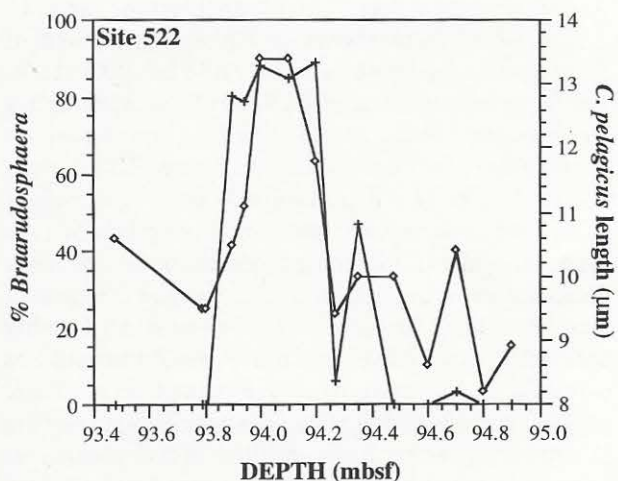


Figure 11: % Braarudosphaera (+) and length of C. pelagicus placoliths (open diamond) from Site 522.

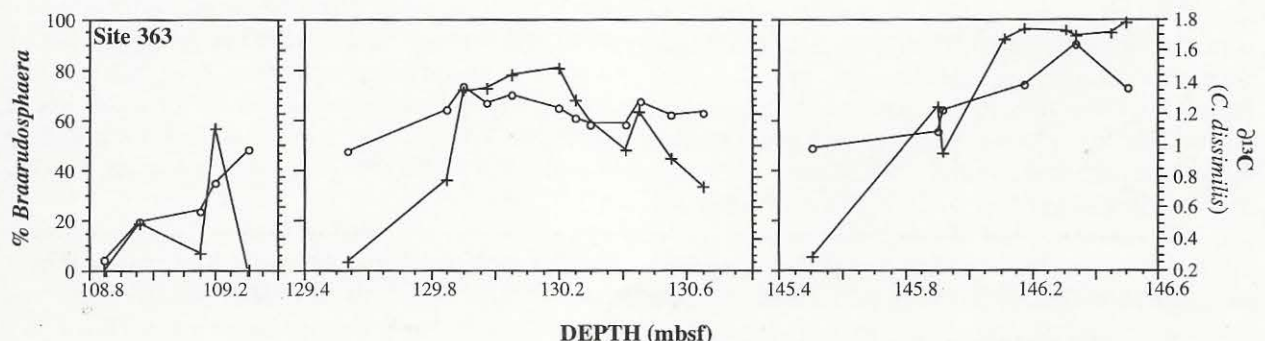


Figure 12: % Braarudosphaera (+) and δ13C (open circle) of Catapsydrax dissimilis from Site 363.

so the above interpretation, linking *Braarudosphaera* abundance and productivity of surface-waters, cannot be substantiated by these results.

There is a possibility that diagenesis controls the nannofossil taxa and isotopic variations. However, there were no significant secondary overgrowths on the *Braarudosphaera* pentaliths and on the foraminifera as verified by SEM examination (Mead, 1995). Moreover, the correlation between the size of *C. pelagicus* placoliths and % *Braarudosphaera* and, by inference, the $\delta^{18}\text{O}$ values argues against a significant diagenetic control on the isotope signal.

Another possibility is that the variation in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in the fine-fraction could be due to vital effects. Analyses on individual laboratory-cultured coccolith species (Dudley & Goodney, 1979) and fine-

fraction samples with coccoliths (Paull & Thierstein, 1987) have shown that vital effects influence their isotopic composition. Kinetic vital effects in calcareous organisms results in ^{13}C and ^{18}O depletion with rapid calcification (McConnaughey, 1989). The isotope record, however, indicates an increase rather than a decrease during the *Braarudosphaera*-rich intervals, where calcite production is the greatest, and therefore argues against the influence of vital effects on the fine-fraction isotope values.

The nannofossil abundance patterns and fine-fraction oxygen and carbon isotope variations as discussed above are, therefore, probably mainly a reflection of palaeoceanographic conditions. One of the proposed oceanic events discussed earlier involved a major fresh-water input into the S Atlantic from the continent to reduce salinity (Bolli *et al.*, 1978). Salinity decrease brought about by fresh-water input would have to be accompanied by

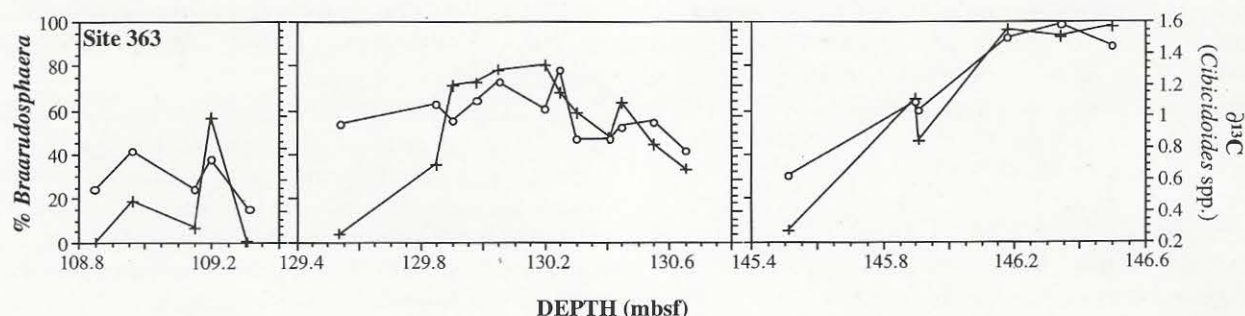


Figure 13: % *Braarudosphaera* (+) and $\delta^{13}\text{C}$ (open circle) of *Cibicidoides* spp. from Site 363.

additional cooling of the surface-waters, given that the isotopic values of planktonic foraminifera changed very little.

Discussion

Upwelling of low-salinity water

The hypothesis of upwelling as the mechanism for increased *Braarudosphaera* production in the S Atlantic during the Oligocene is supported by the nannofossil and isotopic evidence presented above. The correspondence of high *Braarudosphaera* abundances with low abundances of warm-water taxa (sphenoliths), longer *C. pelagicus* placoliths and high $\delta^{18}\text{O}$ values suggests colder water conditions during intervals of increased *Braarudosphaera* production. Modern braarudosphaerids are generally known to prefer low-salinity waters. So, a likely scenario is upwelling of cold, nutrient-rich and low-salinity waters into the S Atlantic, leading to *Braarudosphaera* blooms. The Antarctic region is the most likely source for cold, low-salinity waters. Antarctic Intermediate Water (AAIW) is currently formed below the Antarctic Polar Frontal Zone from the northward-flowing low salinity Antarctic Surface Water, and spreads northwards throughout the Southern Hemisphere and into the Atlantic as a tongue of low-salinity (34.2-34.3‰) water with its core at 800-1000m depth at 40°S (Pickard & Emery, 1982). There is no definitive evidence that AAIW existed during the Oligocene, but this has been speculated (Kennett & Stott, 1990; Diester-Haass, 1995). The presence of AAIW in the southern Indian Ocean was postulated from changes in carbon isotope distributions during the early Oligocene by Zachos *et al.* (1990).

Opening of the Drake Passage

The initiation of the Antarctic Circumpolar Current, as the Drake Passage opened and Australia continued its northward movement away from Antarctica, could have been the triggering mechanism for the rich *Braarudosphaera* beds in the Oligocene. The increased N-S circulation that this event has created in the Atlantic would have enhanced upwelling conditions.

The timing of opening of the Drake Passage has long been debated. Part of the debate centres on the interpretation of the Western Scotia Sea magnetic anomalies (LaBrecque & Rabinowitz, 1977). Barker & Burrell (1977) concluded that the opening of the Drake Passage started during Chron C8 (Late Oligocene). On the other

hand, LaBrecque & Rabinowitz (1977) placed this event during Chrons C10 (Early Oligocene) to C13 (Late Eocene), coincident with the time of *Braarudosphaera*-ooze deposition in the S Atlantic. However, Wright & Miller (1992) believed that analysis of the opening of the Scotia Sea alone may not have been sufficient because of the complexity of the opening of the Drake Passage. They suggested that a shallow opening of the Drake Passage may have been in existence since the earliest Oligocene, based on the relative movement between South America and the Antarctic Peninsula (Lawver *et al.*, 1992). Diester-Haass & Zahn (1996) concluded from their isotopic study that the Drake Passage was already open to intermediate depths as early as 37Ma (Late Eocene). Several studies, therefore, support the coincidence between the intervals of increased *Braarudosphaera* deposition and the presence of at least a shallow opening in the Drake Passage.

Mid-ocean overturn

The *Braarudosphaera* blooms may also be explained by mid-ocean overturn. Kennett & Stott (1990) suggested that the Oligocene ocean (proto-Oceanus) represented an intermediate condition between the Eocene halothermal and the Present Day thermohaline oceans. This type of transition has the potential to bring about instabilities in the water-column. Once instability in the water-column is present, mid-ocean overturn can occur as a result of seasonal cooling (Berger, 1981). This phenomenon has been observed off Toulon, in the W Mediterranean Sea (MEDOC Group, 1970; Anati & Stommel, 1970). Here, cyclonic circulation and winter surface-cooling combine to reduce the surface-layer stability of the waters and promote vertical mixing of the surface-layer. Winter storms build on this instability and bring about deep, penetrative convection in a narrow area of about 25 miles, reaching 1400m depth. When the storm ceases, the mixed water sinks quickly and spreads out horizontally. This process of seasonal overturn brings deep, nutrient-rich waters to the surface. The sporadic nature of this type of mid-ocean overturn process may encourage the growth of opportunistic algae, such as braarudosphaerids.

Further work

Further work to test the results from this study should include isotope analysis of isolated *Braarudosphaera* pentoliths. This may be possible using Paull & Thierstein's (1987) automated decanting device which separates the

fine-fraction particles into subfractions. The obvious size difference between the braarudosphaerids and the other taxa will be an advantage for such an analysis. The possibility of wind-induced upwelling can be tested by investigating climate proxies along the South African margin. Abundance changes of temperature-sensitive calcareous nannofossil taxa in short time-intervals, corresponding to the time of *Braarudosphaera* deposition, can also be investigated in other oceanic sites to trace water-mass movements in the S Atlantic.

Conclusions

Quantitative calcareous nannofossil data show that higher abundances of *Braarudosphaera* correlate with high $\delta^{18}\text{O}$ values and lower abundances of *Sphenolithus*, a warm-water genus. Increased *Braarudosphaera* abundance also corresponds to longer *C. pelagicus* placoliths and to elevated *C. pelagicus* abundance. These results appear to indicate that colder water conditions prevailed during times of elevated *Braarudosphaera* deposition in the S Atlantic.

All this suggests that the widespread Oligocene *Braarudosphaera*-rich layers are most likely the result of the upwelling of cold, nutrient-rich, low-salinity waters via AAIW, or seasonal overturn of an unstable water-column.

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