Deciphering the paleoceanographic significance of Early Oligocene *Braarudosphaera* chalks in the South Atlantic

D.C. Kelly\textsuperscript{a,}\textsuperscript{*}, R.D. Norris\textsuperscript{b}, J.C. Zachos\textsuperscript{c}

\textsuperscript{a} Department of Geology and Geophysics, University of Wisconsin, Madison, WI 53706, USA
\textsuperscript{b} Scripps Institution of Oceanography, University of California – San Diego, La Jolla, CA 92093, USA
\textsuperscript{c} Earth Sciences Department, University of California – Santa Cruz, Santa Cruz, CA 95064, USA

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Abstract

The recurrence of *Braarudosphaera* chalks in the lower Oligocene sequences of the subtropical South Atlantic has been a long-standing conundrum, with many hypotheses having been advanced to explain the genesis of these exotic nanofossil assemblages. Here, we evaluate different paleoceanographic models within the context of stable isotope ($\delta^{18}$O, $\delta^{13}$C) data measured from bulk-sediment samples and well-preserved foraminifera. Two closely-spaced *Braarudosphaera* layers from a lower Oligocene (foram Subzone P21a, 29.4–28.5 Ma) section drilled in the southeastern Atlantic (DSDP Site 363) are investigated. Maximum durations for the blooms that deposited the lower and upper *Braarudosphaera* layers are estimated to be 1.1 and 2.2 k.y., respectively. Bulk-sediment samples enriched in braarudosphaerid carbonate exhibit pronounced $\delta^{18}$O increases on the order of 0.6–1.0$\times$, which we attribute to isotopic disequilibria driven by braarudosphaerid vital effects. The two *Braarudosphaera* layers straddle a single peak in benthic foraminiferal $\delta^{18}$O values, suggesting that these blooms may recur on glacial/interglacial timescales. This same pair of braarudosphaerid layers also occurs as a couplet bundled with prolonged (~6.7 k.y.) thermocline cooling, evidence that these stratigraphically distinct deposits may represent a ‘split signal’ for a single paleoceanographic/paleoclimatic event. Subsumed within this episode of subsurface cooling are two short-lived, negative excursions (~0.5$\times$) in the $\delta^{13}$C record of a thermocline-dwelling planktonic foraminifer that coincide with the braarudosphaerid layers. Thus, benthic-to-thermocline $\delta^{18}$O and $\delta^{13}$C gradients were reduced during the braarudosphaerid blooms, a hallmark signature for strengthened upwelling. Both braarudosphaerid layers are marked by transient divergences in the stable isotopic signals of two shallow-dwelling species of planktonic foraminifera. These transient $\delta^{18}$O offsets may reflect subtle differences in the depth ecologies of these two mixed-layer species. If so, then braarudosphaerid deposition events may represent ‘subsurface blooms’ that took place within the lower parts of the euphotic zone. Alternatively, these transient $\delta^{18}$O offsets may reflect periods of pronounced seasonality, with braarudosphaerid blooms occurring during spring upwelling. The recurrence of *Braarudosphaera* blooms on both sides of the South Atlantic is believed to reflect rhythmic changes in the vigor and configuration of gyre circulation. We speculate that the termination of *Braarudosphaera* blooms in the South Atlantic near the end of the Early Oligocene may be related to paleoceanographic change caused by the crossing of a critical threshold in the tectonic opening of the Drake Passage and the development of the Antarctic Circum-Polar Current.

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* Corresponding author. Tel.: +1-608-262-1698; Fax: +1-608-262-0693.
E-mail address: ckelley@geology.wisc.edu (D.C. Kelly).

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1. Introduction

The time interval spanning the Late Eocene to Early Oligocene (28.5–36.8 Ma) witnessed the gradual transformation of Earth from a minimally glaciated, green-house planet into an ‘ice-house’ world. Antarctic ice sheets of this period manifest themselves as conspicuous increases in foraminiferal $\delta^{18}O$ values and glacio-eustatic falls in global sea level (Matthews and Poore, 1980; Keigwin and Corliss, 1986; Haq et al., 1987; Miller et al., 1987, 1991, 1993; Zachos et al., 1994, 1996, 2000). Glacio-marine deposits and ice-rafted debris found in sediments surrounding Antarctica indicate that Earth’s climate had plunged full-scale into its ice-house mode by the earliest Oligocene (e.g. Barrett et al., 1989; Breza and Wise, 1992; Zachos et al., 1992). Furthermore, dramatic changes to Southern Ocean circulation were unfolding at this time as the Australo–Antarctic Passage continued to widen (Kennett and Shackleton, 1976; Kennett, 1977; Corliss, 1979; Kennett and Barker, 1990).

Biotic diversity among marine microinvertebrates (ostracoda, benthic and planktonic foraminifera) declined steadily during this extended period of ocean/climate change (e.g. Cifelli, 1969; Corliss, 1979; Benson et al., 1984). Intensification of latitudinal gradients in climate variation led to a major restructuring of calcareous nannoplankton paleobiogeographies with Oligocene nannofloras exhibiting pronounced provinciality (Haq et al., 1977; Wei and Wise, 1990; Wei, 1991; Aubry, 1992). One of the more extreme examples of this increased provincialism is displayed by the calcareous nannofossil genus *Braarudosphaera*. Repeated blooms by this nannofossil group during the Early Oligocene delimit a narrow, latitudinal belt that is concentrated within the subtropics (19–35$^\circ$S) of the South Atlantic Ocean (e.g. Parker et al., 1985). The seismic signature of lower Oligocene *Braarudosphaera* chalks has been traced laterally for nearly 2800 km across the subtropical South Atlantic (Maxwell et al., 1970a; Emery and Uchupi, 1984). One of these seismic reflectors – the ‘Maxwell Marker’ – has been described as a ~50-cm-thick, chalky layer containing a monospecific nannoplankton assemblage composed solely of *Braarudosphaera* (Maxwell et al., 1970a). In the open ocean, such monospecific nannoplankton assemblages are very rare, and indicate that unusual sea-surface conditions prevailed throughout the subtropical South Atlantic during the Early Oligocene.

Here, stable isotope data measured from well-preserved foraminifera are used to investigate the paleoceanographic conditions that fostered the genesis of these atypical, South Atlantic deposits. Foraminiferal stable isotope data provide a line of geochemical evidence that is unfettered by assumptions about the paleoecological affinities of fossil braarudosphaerids, and lend paleoceanographic meaning to the long-standing micropaleontological conundrum of the Early Oligocene *Braarudosphaera* chalks.

1.1. Background

Despite having living representatives, the biology of modern braarudosphaerids is poorly understood. Complete braarudosphaerid ‘skeletons’ resemble compact dodecahedra (Fig. 1A) that consist of multiple layers of calcareous pentaliths (Wise and Kelts, 1972; Mai et al., 1997). Each pentalith is, in turn, composed of five trapezoidal elements (Fig. 1B). The constructional design and imperforate texture of braarudosphaerid ‘coccospheres’ are unlike those produced by coccolithophorids, and more closely resemble a calcareous cyst grown to encase a dinoflagellate cell (e.g. Siesser, 1993). It is quite common for fossil pentaliths to disintegrate into isolated elements that become disseminated throughout the sediments (Fig. 1C). Thus, a single *Braarudosphaera* cell can contribute a substantial quantity of carbonate to marine sediments.

Pelagic (open-ocean) occurrences of braarudosphaerid-enriched sediments are unusual for a
number of reasons. First, the geologic range of the family Braarudosphaeraceae spans some 140 m.y. (Early Cretaceous–Recent) and is best expressed in nearshore sedimentary facies (Perch-Nielsen, 1985a,b). Open-ocean excursions by braarudosphaerids have occurred sporadically during this lengthy history, but most of these represent isolated cases that pale in significance compared to their dominance in the lower Oligocene sequences from the South Atlantic. Thus, the recurrence of *Braarudosphaera* deposits in the Early Oligocene sections of the South Atlantic constitutes a conspicuous paleobiogeographic anomaly.

Secondly, modern braarudosphaerids seem to be most abundant in low-salinity waters (Gran and Braarud, 1935). Smayada (1966) reported finding braarudosphaerid concentrations ranging up to 1500 cells per liter in the low-salinity (26.8–32.7‰) waters of the Gulf of Panama. In contrast, *Braarudosphaera* are rare to absent in today’s pelagic environment (Okada and McIntyre, 1977; Okada and Honjo, 1973; Nishida, 1979). The presence of braarudosphaerids in Quaternary sediments of the hyposaline Black Sea led Bukry (1974) to conclude that living braarudosphaerids have an ecological affinity for low-salinity waters. Hence, ecological studies of living braarudosphaerids lend support to the tacit assumption that fossil forms preferred low-salinity, coastal waters. This ecological generalization has

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**Fig. 1.** (A) Reconstructed *Braarudosphaera* ‘cyst’ (after Wise and Kelts, 1972). (B) Scanning electron micrograph of *Braarudosphaera* pentalith from lower Oligocene sediments of the southeastern Atlantic (DSDP Site 526, Core 35-2, 110 cm). (C) Scanning electron micrograph showing *Braarudosphaera* remains scattered throughout a lower Oligocene sample from the southwestern Atlantic (DSDP Site 516F, Core 30-5, 6 cm). Note the presence of numerous trapezoidal elements and that arrows indicate intact pentaliths.
fueled much speculation about the paleoceano-
graphic conditions that fostered the recurrence
of Early Oligocene braarudosphaerids in mid-
ocean regions of the South Atlantic (e.g. Bukry,
1974; Siesser, 1978; Bolli et al., 1978; Emery and
Uchupi, 1984). Thirdly, the scarcity of other nanoplankton
taxa in many of the South Atlantic
Braarudosphaera deposits lends an exotic quality to these
deposits. It is established that some of these off-
shore episodes deposited massive quantities of cal-
careous pentaliths on the seafloor that accumu-
lated into layers with nearly monospecific nanofloras (e.g. Bukry, 1978). Pelagic ‘blooms’ of Braarudosphaera are preserved also in sedi-
ments just above the Cretaceous/Tertiary (K/T)
boundary mass extinction (e.g. Fischer and Ar-
thur, 1977; Thierstein and Berger, 1978). Conse-
quently, many researchers consider braarudo-
sphaerids to be disaster forms adapted to survive
harsh environmental conditions. Thus, low nan-
oplankton diversities within lower Oligocene
Braarudosphaera chalks have sparked added inter-
est in the South Atlantic deposits.

Finally, drilling in both the western and eastern
sectors of the South Atlantic has confirmed the
presence of braarudosphaerid deposits in lower
Oligocene sections atop the Rio Grande Rise and Walvis Ridge (Maxwell et al., 1970a; Bolli
et al., 1978; Barker et al., 1983; Hsū et al.,
1984; Moore et al., 1984). This paleobiogeo-
draphic distribution suggests that the braarudo-
sphaerid depositional events were not mere local
oddities. Rather, it suggests that they were formed by recurrent ocean/climate change felt throughout the subtropics of the South Atlantic, making them paleoceano-graphic indicators of regional impor-
tance.

2. Biochronology, materials and methods

DSDP Site 363 was drilled in the southeastern
Atlantic Ocean (19°38.75'S, 09°02.80'E; 2248 m
water depth) atop an isolated basement high in
the Frio Ridge segment of the Walvis Ridge (Bolli
et al., 1978). Today, this region is strongly af-
fected by coastal upwelling and lies directly under
the path of the Benguela Current (Fig. 2). The
lower Oligocene section drilled at this site con-
tains numerous Braarudosphaera chalks/oozes
that are intercalated with foram/nannofossil chalks (Bukry, 1978). Two closely-spaced Braaru-
dosphaera layers recovered in core 4 (section 2)
were selected for study based on their well-pres-
served foraminiferal assemblages.

Despite having been cored discontinuously, the
Oligocene section recovered from Site 363 con-
tains a series of biostratigraphic datums that con-
forms to the planktonic foraminiferal biozonation
of Berggren et al. (1995). The presence of ‘Turbo-
rotalia’ ampliapertura (Plate I, fig. 1) in the lower-
most portion of core 5 indicates that this strat-
igraphic interval belongs to Zone P19. The Last
appearance Datum (LAD) of T. ampliapertura
(30.3 Ma) is recorded at 114.29 m below sea-
floor (bsf). Specimens from these assemblages exhibit
varying degrees of carbonate dissolution suggesting that the interval spanning the Zone P19/P20
transition is condensed (Fig. 3). The P20/P21a
zonal boundary (29.4 Ma) is defined by the First
Appearance Datum (FAD) of Globigerina anguli-
suturalis (Plate I, fig. 2). This datum is preserved
within the middle of core 5 at 111.29 mbsf. The
rapid succession from the T. ampliapertura LAD to the G. angulisuturalis FAD makes Zone P20

Fig. 2. Map showing DSDP sites from which braarudosphaerid layers have been recovered (open circles); study
area (DSDP Site 363) indicated by filled circle. Arrows de-
note flow of surface-water currents in modern South Atlantic
gyre.
only about 3 m thick (Fig. 3). In contrast, Subzone P21a is approximately 40 m thick as indicated by the concurrent ranges of *G. angulisuturalis* and *Chiloguembelina cubensis*. The top of Subzone P21a (28.5 Ma) is delimited by the Last ‘Common’ Occurrence (LCO) of *C. cubensis* (Plate I, fig. 3) and is placed near the top of core 3 at 70.83 mbsf. Thus, the two braarudosphaerid layers are preserved within Subzone P21a (29.4–28.5 Ma), which was deposited within a stratigraphically expanded interval (Fig. 3). Linear interpolation between the *G. angulisuturalis* FAD and *C. cubensis* LCO yields an impressive sedimentation rate of \( \sim 4.5 \text{ cm/k.y.} \) for the study section.

Smear slides for nannofossil assemblage counts were prepared from slurries of each sample. *Braarudosphaera* abundances were estimated by counting the number of trapezoidal elements; complete pentaliths were scored as 5 elements. Intact pentaliths often consist of multiple layers, so this approach likely underestimates the actual number of braarudosphaerid elements. A minimum of 300 nannofossils was counted in each sample (Table 1).

Stable isotope measurements were performed at

Plate I. Scanning electron micrographs of representative specimens of foraminiferal taxa from the lower Oligocene study section at Site 363. (1) *Turborotalia ampliapertura* – 114.29 mbsf; (2) *Globigerina angulisuturalis* – 110.76 mbsf; (3) *Chiloguembelina cubensis* – 90.43 mbsf; (4) *G. angulisuturalis* – 90.43 mbsf; (5) *Catusydrax unicavus* – 90.43 mbsf; (6) *Cibicidoides tuxpanensis* – 90.43 mbsf. Note that specimens (3)–(6) are from within the lower *Braarudosphaera* layer.
Woods Hole Oceanographic Institution (WHOI), MA, using a Finnigan MAT252 mass spectrometer equipped with a Kiel device. Analytical precision for this instrument is better than 0.08‰ for δ¹⁸O and 0.03‰ for δ¹³C, and stable isotope ratios are reported relative to Vienna-Pee Dee Belemnite (V-PDB; see Ostermann and Curry, 2000). The stable isotope records were constructed using a succession of 13 stratigraphic samples taken at 4–10-cm increments across the two braarudospheraid layers (Fig. 3). Bulk-sediment samples used for stable isotope analysis consisted of powdered residues (<63 μm) ground from original, pristine sediments. Parallel stable isotope records were generated using a suite of foraminiferal species. Size-specific planktonic foraminifera belonging to two shallow-dwelling species (Chiloguembelina cubensis and Globigerina angulisuturalis) were selected to monitor sea-surface conditions (Plate I, figs. 3 and 4), while a deep-dwelling species (Catasydrax unicavus) was used to monitor changes at depth within the thermocline (Plate I, fig. 5). The depth ecologies of these planktonic foraminiferal species have been well characterized using stable isotopes (e.g. Poore and Matthews, 1984). Size-specific specimens of a benthic foraminiferal species, Cibicidoides tuxpamensis, were also used to detect changes in bottom-water conditions (Plate I, fig. 6). Shell-size ranges and number of specimens picked for each foraminiferal sample varied as follows: C. cubensis (75–106 μm, 70 specimens), G. angulisuturalis (150–250 μm, 15–20 specimens), Catasydrax unicavus (300–355 μm, 8 specimens), and Cibicidoides tuxpamensis (150–250 μm, 3–4 specimens). All stable isotope data are reported in Table 1.

Bulk-sediment samples consisting of powdered residues (<63 μm) were used also to generate a wt% carbonate record for this set of samples (Table 1). An automated, carbonate-digestion devise with an analytical precision of ±1% (WHOI) was employed to measure the relative amount of calcium carbonate in each sample.

3. Results

Counts performed on the nannofossil assem-
blages confirm the presence of two distinct, but closely-spaced, layers that are enriched in braarudosphaerid remains. The base of the lower layer is marked by a sharp increase in the relative abundance of braarudosphaerid remains. Braarudosphaerid fragments represent nearly 70% of the nannofossil assemblage at 90.43 mbsf, exhibiting a gradual upsection decline to 36% at 90.39 mbsf and 2% at 90.33 mbsf (Fig. 4A). Immediately above this layer is a 15-cm-thick interval that contains relatively few braarudosphaerid remains. A second layer enriched with braarudosphaerid remains caps this depleted interval. Braarudosphaerid remains represent more than 50% of the nannofossil assemblage at 90.18 mbsf, declining steadily upsection to 23% at 90.14 mbsf and <1% at 90.07 mbsf (Fig. 4A). Braarudosphaerid remains consist largely of isolated, trapezoidal elements in both layers.

Each Braarudosphaera layer is associated with a modest increase in carbonate content that imparts a white color to the sediments (Fig. 4A). The moderate resolution at which the study section was sampled hinders precise determination of the layer thicknesses, but the sediment color record indicates that the lower Braarudosphaera layer is ~5 cm thick and the upper Braarudosphaera layer is ~10 cm thick (Fig. 4A).

The Braarudosphaera layers coincide with pronounced increases in the δ¹⁸O compositions of the bulk-sediment samples (Fig. 4B). Bulk-sediment samples within the lower layer (90.39, 90.43 mbsf) record the highest δ¹⁸O values (~2.3‰) of the study section, representing a striking increase of ~1.0‰. Bulk-sediment δ¹⁸O ratios exhibit a similar increase (~0.6‰) within the upper layer (90.14, 90.18 mbsf), again registering high δ¹⁸O values (~1.7‰). No consistent shifts are seen in the bulk-sediment δ¹³C values across the braarudosphaerid layers (Fig. 4C). Bulk-sediment samples taken from within the lower layer (90.39, 90.43 mbsf) record background δ¹³C values (~1.3‰), whereas the bulk-sediment samples taken from within the upper braarudosphaerid layer (90.14, 90.18 mbsf) record the lowest δ¹³C values of the study section (~0.9‰).

Benthic foraminiferal (Cibicidoides tuxpamensis)
$\delta^{18}$O values display two maxima. The first $\delta^{18}$O maximum (2.1‰) is less pronounced than the second and coincides with the base of the lower Braarudosphaera layer at 90.43 mbsf (Fig. 4B). This smaller $\delta^{18}$O maximum (90.43 mbsf) appears to be a minor inflexion upon a more protracted, larger increase that culminates in the second $\delta^{18}$O maximum (2.3‰) recorded just below the base of the upper Braarudosphaera layer at 90.23 mbsf (Fig. 4B). Benthic foraminiferal $\delta^{18}$O values then decline abruptly by $\sim 0.5$‰ immediately following this second, larger maximum.

The $\delta^{18}$O values for the thermocline-dwelling species of planktonic foraminifera, Catasydrix unicavus, increase sharply ($\sim 0.5$‰) at the base of the lower Braarudosphaera layer (90.43 mbsf), and remain relatively high ($> 1.5$‰) throughout the stratigraphic interval embracing both of the Braarudosphaera layers. It is not until the horizon immediately above (90.07 mbsf) the top of the uppermost Braarudosphaera layer that C. unicavus $\delta^{18}$O values return to lower levels, decreasing by $\sim 0.5$‰ (Fig. 4B).

The parallel $\delta^{18}$O records generated from the two shallow-dwelling species of planktonic foraminifera (Chiloguembelina cubensis and Globigerina angulisuturalis) exhibit divergent stratigraphic trends. Little variation is seen in the C. cubensis $\delta^{18}$O record throughout the entire study section, while the G. angulisuturalis $\delta^{18}$O record exhibits transient increases of $\sim 0.4$‰ across each Braarudosphaera layer (Fig. 4B).

Overall, the stratigraphic interval containing the two Braarudosphaera layers exhibits a general trend toward lower $\delta^{13}$C values (Fig. 4C). The secular $\delta^{13}$C decrease initiates within the lower Braarudosphaera layer and ends within the upper Braarudosphaera layer. This $\delta^{13}$C decline is seen in all five of the parallel records, and attains its minimum within the upper Braarudosphaera layer.

Fig. 4. Relative abundance of Braarudosphaera, wt% calcium carbonate, bulk-sediment and foraminiferal stable isotope records for the lower Oligocene (foram Subzone P21a, 28.5–29.4 Ma) study section from DSDP Site 363. (A) Relative abundance of isolated braarudosphaerid elements and wt% calcium carbonate in bulk-sediment. (B) Parallel oxygen isotope records for bulk-sediment and foraminiferal samples. (C) Parallel carbon isotope records for bulk-sediment and foraminiferal samples. Shaded areas denote stratigraphic intervals enriched with braarudosphaerid carbonate. Core photograph on left shows light-colored intervals enriched with braarudosphaerid carbonate.
Superimposed upon this general decline are two short-lived, negative excursions in the $\delta^{13}C$ records of the deep-dwelling (Catasydrax unicavus) and shallow-dwelling (Globigerina angulisuturalis) planktonic foraminifera (Fig. 4C). The first shift in the $C$. unicavus $\delta^{13}C$ record entails a $\sim 0.5\%$ decrease that coincides with the base of the lower Braarudosphaera layer (90.43 mbsf). This abrupt $\delta^{13}C$ decrease results in a marked reduction in the carbon isotopic gradient between the $C$. unicavus and benthic foraminiferal values (Fig. 4C). The benthic-to-thermocline $\delta^{13}C$ gradient is subsequently reestablished above the lower Braarudosphaera layer, although it is less pronounced than in the lowermost part of the study section. A second decrease of comparable magnitude ($\sim 0.5\%$) is seen in the $C$. unicavus $\delta^{13}C$ record within the upper Braarudosphaera layer (90.14 mbsf). At this horizon, $\delta^{13}C$ values for $C$. unicavus converge upon those recorded by the benthic foraminiferal species, temporarily eliminating the $\delta^{13}C$ gradient between these two species (Fig. 4C). The benthic-to-thermocline $\delta^{13}C$ gradient is reestablished once again just above the upper Braarudosphaera layer (90.07 mbsf) as $C$. unicavus values increase by $\sim 0.5\%$.

Much like their $\delta^{18}O$ records, the $\delta^{13}C$ records of the two shallow-dwelling species (Chiloguembe-lina cubensis and Globigerina angulisuturalis) exhibit divergent stratigraphic trends. In general, the $C$. cubensis $\delta^{13}C$ record displays no consistent pattern of change across the Braarudosphaera layers; it simply parallels the overall $\delta^{13}C$ decline seen in the bulk-sediment and benthic foraminiferal records (Fig. 4C). The $\delta^{13}C$ record of $G$. angulisuturalis, on the other hand, exhibits transient decreases of $\sim 0.3\%$ within both of the Braarudosphaera layers (Fig. 4C). The $\delta^{13}C$ record for $G$. angulisuturalis is similar to that of deep-dwelling Catasydrax unicavus, although the $\delta^{13}C$ minima for these two species appear to be slightly out of phase.

4. Discussion

The most striking feature of the Site 363 stable isotope records is the transient, bulk-sediment $\delta^{18}O$ increases that coincide with the Braarudosphaera-enriched intervals (Fig. 4B). Similar bulk-sediment $^{18}O$-enrichments have been measured from other Braarudosphaera chalks (Lloyd and Hsu, 1972; Hsu et al., 1984; Siesser et al., 1992; Peleo-Alampay et al., 1999). Bulk-sediment samples taken from two Oligocene Braarudosphaera layers at DSDP Site 522 in the southeastern Atlantic registered $\delta^{18}O$ values that were on the order of 0.7–1.0% higher than background values (Hsu et al., 1984). Thus, a hallmark signature of Braarudosphaera chalks is high, bulk-sediment $\delta^{18}O$ values.

The anomalous magnitudes of these bulk-sediment $\delta^{18}O$ increases become more evident when compared to the foraminiferal $\delta^{18}O$ data. In general, the $\delta^{18}O$ record of shallow-dwelling Globigerina angulisuturalis parallels that of the bulk-sediment samples, displaying positive shifts across the braarudosphaerid-enriched intervals (Fig. 4B). However, the $\delta^{18}O$ increases in the $G$. angulisuturalis record are only about half the magnitude of those seen in the bulk-sediment curve, indicating that some factor other than environmental change has imprinted the bulk-sediment $\delta^{18}O$ values. It could be argued that the magnitudes of the bulk-sediment $\delta^{18}O$ increases were amplified by a pronounced ice volume effect on the $\delta^{18}O$ composition of seawater. This explanation is rejected because the maximum value (2.3%) seen in the benthic foraminiferal $\delta^{18}O$ record does not coincide with either of the Braarudosphaera layers.

Within the two Braarudosphaera layers, the bulk-sediment $\delta^{18}O$ increases give rise to a range of values (1.5–2.3%) that converge upon those recorded by the benthic foraminifera. This $\delta^{18}O$ convergence is unexpected since most of the bulk-sediment is composed of fine-fraction carbonate grown by coccolithophorids and braarudosphaerids in the warm, euphotic zone of surface waters. Indeed, scanning electron microscopy has shown that braarudosphaerid pentaliths commonly exhibit secondary overgrowths (e.g. Wise and Hsu, 1971; Wise...
and Kelts, 1972), yet unusually high $\delta^{18}O$ values ($\sim 2.2\%$) are registered also by fine-fraction ($< 63 \mu m$) samples enriched ($\sim 95\%$) with braarudosphaerids that exhibit no post-burial overgrowths (Peleo-Alampay et al., 1999).

The stratigraphic difference between the bulk-sediment and foraminiferal stable isotope records is inconsistent with diagenetic overprinting as a cause for the $^{18}O$-enriched signatures of the two *Braarudosphaera* layers. Specifically, benthic foraminiferal $\delta^{18}O$ values decrease by $\sim 0.5\%$ across the base of the upper braarudosphaerid layer (Fig. 4B), while bulk-sediment $\delta^{18}O$ values display a coeval increase of $\sim 0.4\%$ (Fig. 4B). A similar asymmetry exists between the bulk-sediment $\delta^{18}O$ values and those recorded by the planktonic foraminiferal species *Chiloguembelina cubensis*. The $C. cubensis$ $\delta^{18}O$ values display no significant change across the base of the lower braarudosphaerid layer (Fig. 4B), whereas those recorded by the bulk-sediment samples exhibit a $\sim 1.0\%$ increase (Fig. 4B). One would not expect such marked differences between the bulk-sediment and foraminiferal $\delta^{18}O$ records if recrystallization and isotopic reequilibration had been pervasive within these samples. The same line of reasoning holds true for the stable isotopic offsets seen between the various foraminiferal species. For example, the $\delta^{18}O$ records for the two shallow-dwelling species, *C. cubensis* and *Globigerina angulisuturalis*, display divergent patterns of stratigraphic change (Fig. 4B). As noted above, the *C. cubensis* $\delta^{18}O$ record exhibits no significant variation, while the *G. angulisuturalis* $\delta^{18}O$ record displays transient increases across both the braarudosphaerid layers. In short, the interspecific differences seen in the foraminiferal isotope data attest to the well-preserved state of these microfossil assemblages and are an expression of the shallow burial depths of the study section throughout its geologic history.

We therefore favor the interpretation that the $^{18}O$-enriched signatures of braarudosphaerid-laden sediments are largely a product of strong isotopic disequilibria during *Braarudosphaera* calcification. Stable isotopic studies performed on monospecific cultures of coccolithophorids grown under controlled conditions in the laboratory have demonstrated that many modern species exhibit strong biological fractionations (‘vital effects’) during calcification (Dudley et al., 1986; Dudley and Nelson, 1994). Likewise, stable isotopic analysis of deep-sea nannofossil ($< 38 \mu m$) samples has provided additional evidence for isotopic disequilibria during coccolithophorid calcification (Paull and Thierstein, 1987). The lines of evidence cited above suggest that biologically-induced fractionation effects have exerted a strong influence on the stable isotopic composition of braarudosphaerid calcite, a process that has confounded paleoceanographic interpretation in previous studies.

### 4.1. Foraminiferal stable isotope data: an independent line of geochemical evidence

Early stable isotope investigations of South Atlantic braarudosphaerid deposits focused on bulk and fine-fraction ($< 63 \mu m$) carbonate samples (e.g. Lloyd and Hsu‘, 1972; Hsu‘ et al., 1984; Siesser et al., 1992). This approach is understandable in the sense that it measures the stable isotopic composition of *Braarudosphaera* carbonate, but unsatisfactory from a paleoceanographic standpoint due to the likelihood that the stable isotopic composition of *Braarudosphaera* carbonate is strongly affected by vital effects. To date, only one other study (Peleo-Alampay et al., 1999) has used foraminiferal stable isotopes to investigate Lower Oligocene *Braarudosphaera* deposits in the South Atlantic. Here, we reutilize this approach to generate stable isotope data measured from a suite of well-preserved, foraminiferal species that occupied a wide range of depth-habitats in order to reconstruct the paleoceanographic conditions that fostered the Early Oligocene *Braarudosphaera* blooms.

Numerous paleoceanographic models have been proposed to explain the presence of *Braarudosphaera*-enriched sediments in the Lower Oligocene sections of the subtropical South Atlantic. Wise and Hsu‘ (1971) considered the possibility that braarudosphaerids were concentrated in sediments through the selective dissolution of other calcareous nannofossil taxa. However, such a preservational bias is rejected on the grounds that braarudosphaerid deposits are associated
with the increased carbonate content of deep-sea sediments (e.g. Wise and Kelts, 1972). This observation is corroborated by the fact that peak Braarudosphaera abundances coincide with the two stratigraphic intervals that record the highest carbonate contents for the study section (Fig. 4A). Furthermore, the shells of planktonic foraminifera collected from within the two Braarudosphaera layers exhibit no signs of dissolution (Plate I, figs. 3–6). Thus, the scarcity of other nannofossil taxa within Braarudosphaera chalks is most likely a dilution effect caused by the prodigious production of braarudosphaerid blooms, not a preservational bias.

Many of the models devised to explain the formation of Braarudosphaera chalks and oozes are predicated upon the assumption that Oligocene forms preferred low-salinity, coastal waters. Several of these hypotheses call upon redepositional mechanisms to transport ‘coastal’ braarudosphaerids out into the open ocean. Maxwell et al. (1970b) proposed that Braarudosphaera-enriched sediments were originally deposited in coastal environments and subsequently transported downslope to their present locations via submarine slumps. The presence of braarudosphaerid layers atop topographic highs along the seafloor is inconsistent with downslope transport (e.g. Wise and Kelts, 1972). Moreover, there is no sedimentological evidence (graded bedding, cross-bedding) to support such a redepositional process (sensu Lloyd and Hsu, 1972). Another of these transport/redepositional models envisions strong surface currents sweeping coastal blooms of braarudosphaerids out to sea (Maxwell et al., 1970a). The coherent structure of the foraminiferal δ18O and δ13C shifts across the braarudosphaerid layers precludes such a taphonomic mechanism (Fig. 4B,C).

An offshoot of the low-salinity hypothesis invokes increases in regional rainfall and/or riverine runoff as a means of diluting sea-surface salinity to trigger massive braarudosphaerid blooms (e.g. Bukry, 1974; Siesser, 1978; Bolli et al., 1978). One version of this theme is that sea-surface salinities were reduced by large discharges of fresh, deglacial meltwater (Bukry, 1978). The δ18O records for the shallow-dwelling planktonic foraminifera are clearly at odds with such a reduction in sea-surface salinity. Specifically, the δ18O compositions of Chiloguembelina cubensis and Globigerina angulisuturalis do not exhibit significant decreases across either of the braarudosphaerid layers (Fig. 4B).

It has also been speculated that braarudosphaerid blooms were fostered by increased surface-water fertility fueled by the upwelling of cool, nutrient-rich intermediate waters (e.g. Siesser, 1978; Labrecque and Hsü, 1983; Peleo-Alampay et al., 1999). The foraminiferal stable isotope data support this model. The extended interval of high Catasydrax unicavus δ18O values (> 1.5‰) that embraces both of the Braarudosphaera layers indicates cooling at thermoclinal depths, and effectively binds the braarudosphaerid layers (Fig. 4B). Hence, these two deposits may be bundled with a more prolonged (~ 6.7 k.y.) episode of ocean/climate change. Moreover, the δ18O and δ13C gradients separating the benthic (Cibicidoides tuxpamensis) and thermocline (C. unicavus) species are reduced markedly within both of the braarudosphaerid layers. The diminished benthic-to-thermocline δ13C and δ18O gradients reflect strong mixing of the oceanic water column during the braarudosphaerid blooms (Fig. 4B,C).

Another possible indication that these two braarudosphaerid blooms are coupled can be seen in the benthic foraminiferal δ18O record. The benthic foraminiferal δ18O record exhibits a ‘saw-tooth’ signal that is reminiscent of Quaternary glacials (e.g., Emiliani, 1978), with braarudosphaerid layers straddling either side of the peak value (Fig. 4B). Thus, braarudosphaerid blooms may have been fostered by paleoceanographic conditions that pre- and postdate Early Oligocene glacials. Others have proposed that braarudosphaerid depositional events may be related to fluctuations in Antarctic ice volume (LaBrecque and Hsü, 1983; Emery and Uchupi, 1984); however, such a causal relationship is not straightforward since the expected 18O-enrichments are not apparent in either of the shallow-dwelling planktonic foraminiferal δ18O records (Fig. 4B). Namely, the δ18O values for Chiloguembelina cubensis do not display any significant variation throughout the study section (sensu Zachos
embedded within the prolonged (6.7 k.y.) episode of thermocline cooling are two short-lived δ\(^{18}\)O increases in the shallow-dwelling *Globigerina angulisuturalis* record, each associated with a braarudosphaerid layer (Fig. 4B). If the full magnitude of these δ\(^{18}\)O increases is attributed solely to temperature change, then the transient increases in the *G. angulisuturalis* record represent episodic cooling (∼2 °C) of the oceanic mixed layer. Furthermore, the *G. angulisuturalis* δ\(^{13}\)C record displays transient decreases that parallel the δ\(^{18}\)O increases across the braarudosphaerid layers (Fig. 4C). These negative δ\(^{13}\)C shifts corroborate the notion that upwelling of nutrient-laden, 12C-enriched intermediate water fostered both of the braarudosphaerid blooms.

Striking differences are seen between the stable isotope stratigraphies for the two shallow-dwelling species of planktonic foraminifera. The δ\(^{18}\)O record for *Chiloguembelina cubensis* displays little variation throughout the entire study section, even across stratigraphic intervals enriched in braarudosphaerid remains (Fig. 4B). This lack of variation contrasts with the transient δ\(^{18}\)O increases seen in the *Globigerina angulisuturalis* record (Fig. 4B). The short-lived increases in the *G. angulisuturalis* values result in short-lived δ\(^{18}\)O offsets of ∼0.5‰ between these two species. One possible explanation for these transient, interspecies δ\(^{18}\)O offsets is that *G. angulisuturalis* occupied a slightly deeper depth-habitat than *C. cubensis*. This being the case, braarudosphaerid layers may represent ‘subsurface blooms’ that occurred within the deeper parts of the euphotic zone.

Alternatively, the transient δ\(^{18}\)O offsets between *Chiloguembelina cubensis* and *Globigerina angulisuturalis* may indicate that these two mixed-layer dwellers calcified their shells during different times of the year. Under this seasonal scenario, *C. cubensis* would have calcified its shells in warm summer waters, while *G. angulisuturalis* grew its shells in cooler winter/spring waters brought to the surface by intense upwelling. Seasonal changes in hydrographic conditions exert a strong influence on both the faunal composition and stable isotopic variation of modern planktonic foraminifera (e.g. Williams et al., 1979; Reynolds and Thunell, 1985). Thus, the coincidence of braarudosphaerid deposits with transient δ\(^{18}\)O offsets between *C. cubensis* and *G. angulisuturalis* may reflect periods of pronounced seasonality. Sediment-mixing processes would smooth such a seasonal signal, giving rise to a time-averaged stratigraphic record like that of Site 363.

### 4.2. Temporal and spatial patterns

Despite stratigraphic complications stemming from discontinuous coring and poor recovery, a total of 15 separate *Braarudosphaera* layers were recovered from the lower Oligocene section drilled at Site 363 (Bolli et al., 1978). The thickness of these *Braarudosphaera* layers varies considerably from a minimum of only about 5 cm to a maximum of roughly 65 cm. We attribute this variability to differences in the duration and intensity of *Braarudosphaera* blooms and/or vagaries associated with sedimentary processes on the seafloor. Thus, the two *Braarudosphaera* layers investigated herein are relatively thin, and are believed to have been deposited on short geological time-scales; ∼1.1 k.y. for the lower layer and ∼2.2 k.y. for the upper layer. It is important to note that these durations are but crude approximations based upon a linear sedimentation model, and may represent maximal values since sedimentation rates probably increased under the upwelling cells that fostered the deposition of the two layers. Conversely, the two *Braarudosphaera* layers appear to be bundled within a more prolonged (∼6.7 k.y.) phase of thermocline cooling. It is therefore possible that the two *Braarudosphaera* layers are actually a ‘split signal’ of a single, more prolonged period of enhanced upwelling. The estimated duration of ∼6.7 k.y. for this period of intensified upwelling is comparable to previous estimates (6–19 k.y.) derived from non-linear sedimentation models (Peleo-Alampay et al., 1999).

The recurrence of *Braarudosphaera* layers in lower Oligocene sequences on both sides of the South Atlantic implicates a large-scale circulation feature, although the deposits at Site 363...
are believed to reflect the initiation of local upwelling cells related to a prototype of the Benguela Current (e.g. Bolli et al., 1978). Geographically, these deposits are concentrated atop submarine, topographic highs that underlie both the eastern and western retroflexions of the South Atlantic gyre (Fig. 2). It is in these areas that the South Atlantic gyre sweeps surface waters offshore, permitting the upwelling of nutrient-rich, intermediate waters. We therefore postulate that the genesis of *Braarudosphaera* deposits was governed, in part, by rhythmic changes in the vigor and configuration of South Atlantic gyre circulation.

The overall temporal distribution of the *Braarudosphaera* layers is focused within a critical period in the tectonic evolution of the South Atlantic sector of the Southern Ocean, and several researchers have alluded to the possibility that the opening of the Drake Passage triggered the *Braarudosphaera* blooms (e.g. Peleo-Alampay et al., 1999). However, Barker and Burrell (1977) provide paleomagnetic evidence showing that coherent spreading of the Drake Passage did not initiate until magnetostratigraphic Chron C8 (~26–27 Ma), which is roughly correlated with the gradual termination of braarudosphaerid depositional events near the Early/Late Oligocene boundary. Thus, it appears that the gradual cessation, as opposed to the initiation, of *Braarudosphaera* blooms in the South Atlantic may be correlatable with opening of the Drake Passage. Determination of the precise nature of this paleoceanographic change is beyond the scope of our limited data set, and we note only the temporal relationship between this tectonic event and the lower Oligocene *Braarudosphaera* blooms.

5. Conclusions

Stable isotope data generated from bulk-sediment and foraminiferal samples are employed to develop a better understanding of the paleoceanographic conditions that fostered the formation of lower Oligocene *Braarudosphaera* chalks in the South Atlantic Ocean. Bulk-sediment samples enriched in *Braarudosphaera* remain invariably yield exceptionally high $\delta^{18}O$ ratios. This telltale $\delta^{18}O$ signature is largely the product of an isotopic disequilibrium caused by strong vital effects, a process that has hampered paleoceanographic interpretation in past studies.

Foraminiferal stable isotope records across two, closely-spaced braarudosphaerid layers exhibit reduced benthic-to-thermocline $\delta^{13}C$ and $\delta^{18}O$ gradients, a pattern of isotopic variation consistent with intensified upwelling. The two layers straddle a single maximum in the benthic foraminiferal $\delta^{18}O$ record indicating that braarudosphaerid depositional events may have been paced by paleoceanographic change that recurverd over glacial/interglacial timescales. Moreover, the pair of braarudosphaerid layers occurs as a couplet bundled with a prolonged period (~6.7 k.y.) of thermocline cooling. In this particular case, the two layers appear to represent a split signal for a single paleoceanographic event.

Short-lived offsets in the $\delta^{18}O$ records of two mixed-layer species of planktonic foraminifera coincide with the braarudosphaerid layers, one species (*Globigerina angulisuturalis*) displays transient $\delta^{18}O$ increases whereas the other (*Chiloguembelina cubensis*) shows no significant variation. These transient $\delta^{18}O$ offsets may reflect subtle differences in the depth ecologies of the two species. If so, then the braarudosphaerid layers may have been formed by ‘subsurface’ blooms that occurred at deeper depths within the euphotic zone. Alternatively, the transient $\delta^{18}O$ offsets may reflect short periods (1.1–2.2 k.y.) of enhanced seasonality with braarudosphaerid blooms having been fueled by strong spring upwelling.

The presence of *Braarudosphaera* layers in lower Oligocene sequences from both the western and eastern sectors of the South Atlantic implicates a large regional-scale mechanism. We therefore postulate that the recurrence of these unusual nannofossil assemblages reflects rhythmic fluctuations in the vigor and configuration of the South Atlantic gyre. It is also speculated that the gradual cessation of these exotic blooms near the end of the Early Oligocene signifies an important shift in the character of South Atlantic circulation that is likely related to the crossing of a critical, tectonic threshold in the opening of the Drake Passage.
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