38. MID-TERTIARY *BRAARUDOSPHAERA*-RICH SEDIMENTS ON THE EXMOUTH PLATEAU[1]

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ABSTRACT

Nannofossil assemblages enriched in *Braarudosphaera* occur in lower Oligocene to lower Miocene sediments at Ocean Drilling Program Sites 762 and 763 on the central Exmouth Plateau. Braarudosphaerids appear here rather abruptly in the lower Oligocene (in Zone NP21). They reach their greatest numbers in the lower Oligocene (in Zones NP22 and NP23), where they comprise up to 10% of some samples. *Braarudosphaera bigelowii* is the overwhelmingly dominant species, occurring together with rare specimens of *B. discula* and *Micrantholithus pinguis*. The holococcoliths *Peritrachelina joidesa* and *Lanternithus minutus* are also associated with the *Braarudosphaera* enrichment. There are two populations of *B. bigelowii:* one of normal size (10–14 μm) and one of large specimens (20–22 μm). The larger braarudosphaerids are more common than the smaller forms. *Braarudosphaera*-rich sediments are absent at Wombat Plateau sites during the same time interval. We attribute this to latitudinal control, because the Wombat sites are about 4° north of the central Exmouth Plateau sites. We believe that the occurrence of braarudosphaerids is related to an Oligocene to early Miocene oceanographic event on the Exmouth Plateau. We suspect that mid-ocean upwelling of cool, low-salinity, nutrient-rich water along a divergent zone created the *Braarudosphaera*-rich sediments in the South Atlantic and Indian oceans.

INTRODUCTION

A prominent occurrence of *Braarudosphaera*-rich sediments was discovered during Ocean Drilling Program (ODP) Leg 122 drilling on the Exmouth Plateau (Fig. 1). *Braarudosphaera*-rich oceanic sediments have previously been reported from scattered areas and various time intervals but are known chiefly from a transoceanic belt across the South Atlantic. The reason for these prolific Atlantic blooms of *Braarudosphaera* remains unexplained. The recovery of *Braarudosphaera*-rich sediments in the Oligocene and lower Miocene on the Exmouth Plateau is the first published report of this phenomenon in sediments of the eastern Indian Ocean.

The purpose of this paper is to describe these *Braarudosphaera*-rich sediments, to comment on their possible relationship to the South Atlantic occurrences, and to suggest an explanation for both occurrences. Stable isotope and trace element analyses of the Leg 122 braarudosphaerid sediments provide clues to the oceanographic conditions that existed at the time of deposition.

PREVIOUS STUDIES

In today's oceans, *B. bigelowii* prefers low-salinity, nearshore waters and is rarely found in the open ocean (Bukry, 1974). In fossil assemblages, *B. bigelowii* and its relatives are also most common in sediments deposited in nearshore environments. It is tacitly assumed that the environmental control (salinity?) influencing the modern distribution also controlled the abundance of this species in the past.

Thus, it has been difficult to explain the occurrence of the Oligocene "*Braarudosphaera* Chalk" deposited under apparently open-ocean conditions recovered during Deep Sea Drilling Project (DSDP) drilling in the South Atlantic (in Zone NP23, Maxwell, von Herzen, et al., 1970, Leg 3; in Zones NP22–NP25, Supko, Perch-Nielsen, et al., 1978, Leg 39; in Zones NP22–NP24, Bolli, Ryan, et al., 1978, Leg 40; in Zone NP23, Hsü, LaBrecque, et al., 1984, Leg 74). Other studies discussing the South Atlantic occurrences include Wise and Hsü (1971), Wise and Kelts (1972), Bukry (1974), Wise (1977), Bukry (1978, 1981), LaBrecque et al. (1983), and others.

Briefly, the "*Braarudosphaera* Chalk" occurs today in a belt traversing the South Atlantic between approximately 20°S and 35°S. Many but not all of the *Braarudosphaera* beds are true "chalks"; some are "oozes," and frequently *Braarudosphaera* ooze units alternate with *Braarudosphaera* chalk units. Some of these beds are only a few centimeters thick, whereas others are up to 1.5 m thick.

Members of the Braarudosphaeracea family may compose over 90% of the sediment in the South Atlantic deposits. Reports in the literature show that *B. bigelowii* is the most common species found, followed by *B. rosa* and *B. discula*. *Micrantholithus* spp. and *Pemma* spp. are recorded in small numbers in the same sediments. Small but significant numbers of holococcoliths such as *Peritrachelina joidesa* and *Lanternithus minutus* are also recorded from many *Braarudosphaera*-rich sediments (Parker et al., 1985).

Similar occurrences of *Braarudosphaera*-rich sediments are now known from the North Atlantic and Gulf of Mexico (Zones NP20–NP25, Lang and Watkins, 1984, Leg 77; Zones NP21–NP23, Parker et al., 1985, Leg 82; and Zone NP23, Bukry, 1978, Oceanographer Canyon). These sites occur only in the central and western North Atlantic between about 24°N and 40°N.

To date there have been no reports of *Braarudosphaera*-rich sediments from the Pacific Ocean or the eastern Indian Ocean. A western Indian Ocean occurrence was reported by Roth (1974, Leg 24), who found *Braarudosphaera*-rich sediments in the upper Paleocene, the lower and middle Eocene, the lower and upper Oligocene, and (rarely) in the upper Miocene. Geographically, the western Indian Ocean sites lie between about 3°S and 12°S. The North Atlantic/Gulf of Mexico and western Indian Ocean occurrences are not as
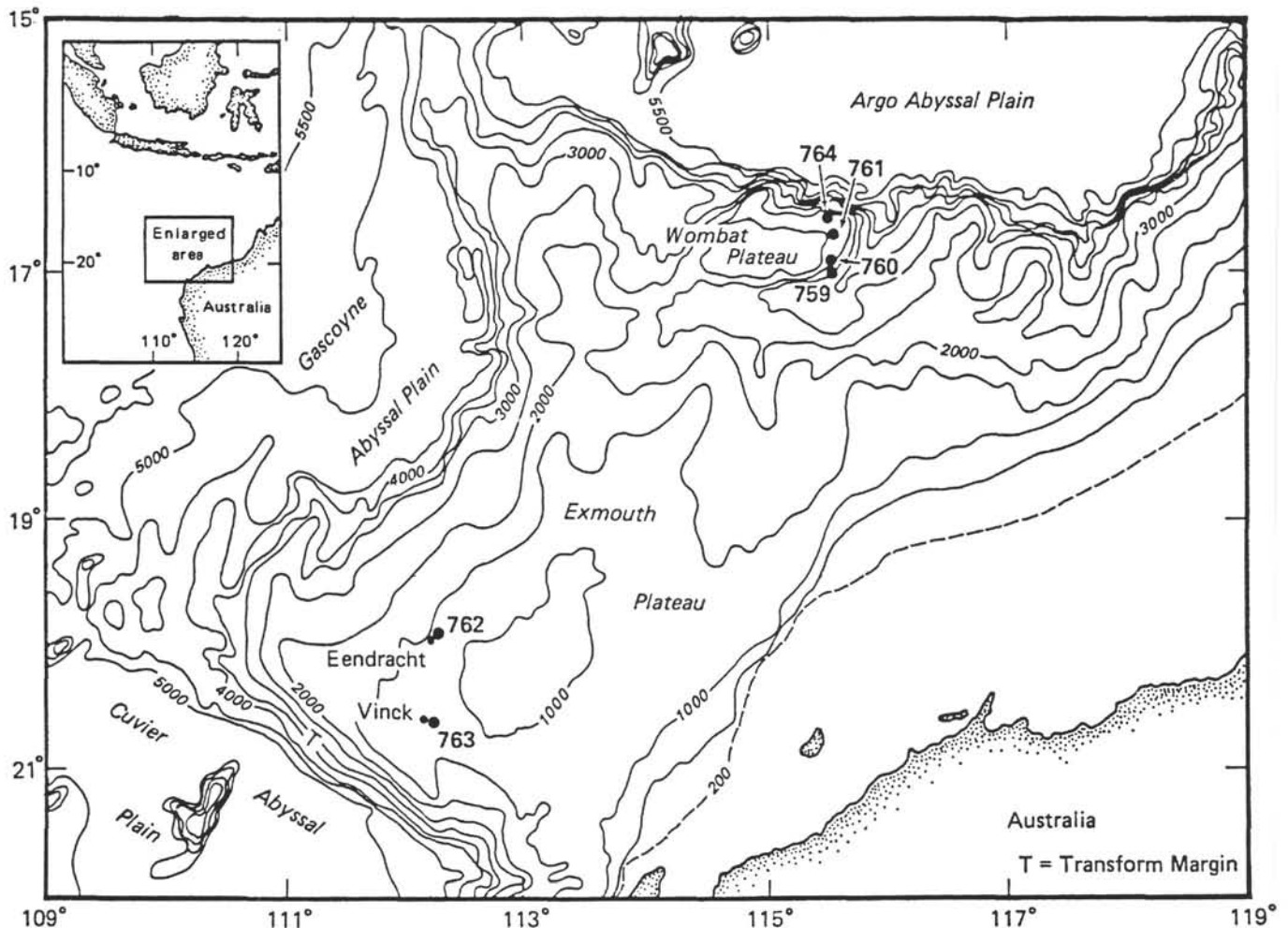
Figure 1. Location map showing Leg 122 drill sites on the central Exmouth Plateau (Sites 762 and 763) and on the Wombat Plateau (Sites 759, 760, 761, and 764). Contours are in meters below sea level. Map is from Haq et al. (1988).

widespread, or as rich in braarudosphaerid specimens, as the South Atlantic occurrences.

GEOLOGIC SETTING

The Exmouth Plateau is a deeply subsided fragment of rifted continental crust lying off the coast of northwestern Australia (Fig. 1). The present configuration of the plateau began to take shape during the Late Triassic, when rifting began between northwestern Australia, Greater India, and other East Gondwanan fragments (Haq et al., 1988). Breakup and separation occurred during the Jurassic/Early Cretaceous, after which 1–2 km of marine sediments accumulated over the plateau. The *JOIDES Resolution* drilled at six sites on the Exmouth and Wombat plateaus (the latter being a marginal spur of the former) during July-August 1988. *Braarudosphaera*-rich sediments were found in the lower Oligocene to lower Miocene interval at both Sites 762 and 763 on the central Exmouth Plateau, but not at any site on the Wombat Plateau (Siesser and Bralower, this volume). Three holes were drilled at Site 762 (Holes 762A, 762B, and 762C) in a water depth of 1340 m. Hole 762A recovered a single core of Quaternary age. Hole 762B was cored using the advanced piston corer (APC) down to a depth of 175.4 meters below seafloor (mbsf) (lower Oligocene), and obtained a core recovery of 99.7%. The extended core barrel (XCB) was used for coring below 175.4 mbsf (Hole 762C). The Cretaceous/Tertiary (K/T) boundary

was crossed at 554.5 mbsf in Hole 762C. Physical disturbance and a marked color change suggest that the boundary is incomplete here. Hole 762C reached its total depth at 940.0 mbsf in Berriasian-age sediments.

Drilling at Site 762 encountered a thick, almost continuous sequence of nannofossil ooze and chalk ranging in age from Quaternary to Maestrichtian. The only parts of the Cenozoic missing are short intervals in the Miocene (viz., Martini's (1971) nannofossil Zones NN3, NN8, and NN10).

Three holes were also drilled at Site 763 (Holes 763A, 763B, and 763C). Site 763 is located 84 km south of Site 762, in a water depth of 1368 m. The APC was used for coring down to a depth of 195.0 mbsf, and the XCB below that depth. A relatively complete sequence of Quaternary to middle Eocene nannofossil-foraminifer ooze and chalk was cored from the seafloor down to about 250 mbsf, where an unconformity separates middle Eocene sediments from upper Campanian. Hole 763C bottomed in middle to upper Berriasian sediments, at a depth of 1037 mbsf.

BRAARUDOSPHAERA OCCURRENCES ON THE EXMOUTH PLATEAU

On the Exmouth Plateau we found *Braarudosphaera*-rich sediments in the lower and upper Oligocene and in the lower Miocene at Sites 762 and 763. The braarudosphaerid-bearing units are nannofossil oozes at Site 762 and nannofossil chalks

at Site 763. Braarudosphaerids range from "rare" to "common" in the stratigraphic interval where they are found (see range charts in Siesser and Bralower, this volume). Notations of relative abundance are as follows: "common" = 1 to 10 specimens of a single species per field of view at a magnification of 1000×; "few" = one specimen per 2–10 fields; "rare" = one specimen per 11–100 fields; "very rare" = one specimen per 101–1000 fields. Where *Braarudosphaera* is listed as "common," it makes up an estimated 5%–10% of the sediment. A few scattered specimens of *B. bigelowii* (small forms) and *M. pinguis* were noted in the lower Eocene at Site 762.

The first sediments consistently rich in braarudosphaerids occur in Section 122-762C-3X-CC (lower Oligocene, Zone NP21) and disappear in Section 122-762B-15H-4 (lower Miocene, Zone NN4/5). Relative abundance of braarudosphaerids fluctuates uphole. Specimens are rare but consistently present in the core sections immediately after their first appearance in mid-Zone NP21. They are mostly few to common in the upper part of Zone NP21, and in Zones NP22 and NP23. Overall, braarudosphaerids are most common in Zone NP22. Abundances are rare to few in combined Zones NP24/25 and NN1/2. The species becomes common again just before and just after the lower Miocene hiatus (Zone NN3). Braarudosphaerids disappear shortly above the hiatus in Section 122-762B-15H-2. The last braarudosphaerid sample is in the combined nannofossil Zone NN4/5, which spans the lower-middle Miocene boundary. Shipboard foraminifer studies date this sample as lower Miocene.

At Site 763, *B. bigelowii* makes its first appearance (rare) in Section 122-763A-21H-CC (lower Oligocene, Zone NP21). Abundances continue to be rare and occurrences are sporadic until Section 122-763A-17H-2 (early Miocene, Zone NN3), when specimens become common. Specimens are also common in the lowest sample in Zone NN4/5 (Section 122-763A-16H-CC), which we consider to be the last braarudosphaerid occurrence at Site 763 (again, probably lower Miocene). A rare to very rare occurrence in Section 122-763A-16H-3 is probably caused by reworking.

In summary, *Braarudosphaera*-rich sediments occur in the same time interval at both Sites 762 and 763 (Zones NP21–NN4/5; lower Oligocene–lower Miocene). Their presence tends to be more consistent and abundances considerably greater in cores from the site farther offshore (Site 762).

The "braarudosphaerids" in these sediments are overwhelmingly dominated by *B. bigelowii*. Very large specimens of *B. bigelowii* (up to 22 μm) coexist with *B. bigelowii* specimens of a more "normal" (10–14 μm) size. Larger specimens in the 20- to 22-μm range are always more abundant than the smaller forms.

We found a few rare *Micrantholithus pinguis*, but only in the samples where *B. bigelowii* is most common. We also recorded a few specimens of *B. discula* (as very rare). Holococcoliths of *Peritrachelina joidesa* and *Lanternithus minutus* are present in significant numbers in the Oligocene, co-occurring with the braarudosphaerids (Siesser and Bralower, this volume).

Preservation of braarudosphaerids appears to be moderately good when viewed with the light microscope (Figs. 2 and 3) but scanning electron micrographs (Figs. 4 and 5) show calcite overgrowths on all specimens. Larger specimens seem to have accrued more calcite than smaller specimens. "*Braarudosphaera rosa*" is often recorded with or without *B. bigelowii* in *Braarudosphaera* chalks. *B. rosa* was originally described from the middle Oligocene of Alabama by Levin and Joerger (1967). They described *B. rosa* as small forms (10 μm), "with their segments broadly rounded at the periphery so as to present a lobate outline." Levin and Joerger (1967)
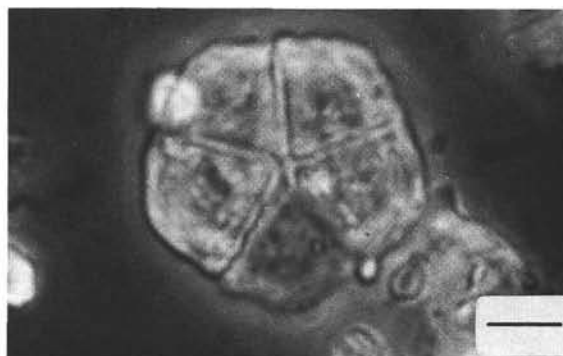

Figure 2. Light micrograph of *Braarudosphaera bigelowii*. Sample 122-762B-18H-CC; phase-contrast illumination. Scale bar = 6 μm.
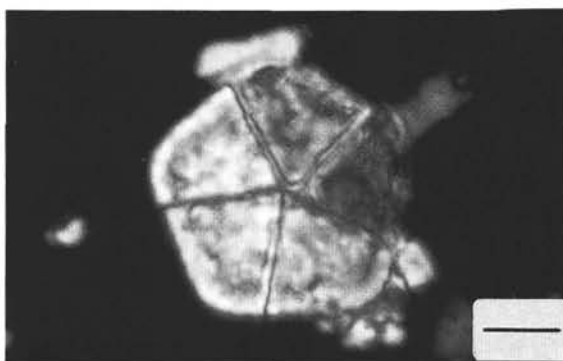

Figure 3. Light micrograph of large *Braarudosphaera bigelowii* with rounded pentalith corners. Sample 122-762B-18H-CC; crossed nicols. Scale bar = 6 μm.

found *B. rosa* occurring in rare numbers and only where *B. bigelowii* was frequent.

Our survey of the literature suggests some degree of latitude in subsequent usage of the name "*B. rosa*" Some illustrations of *B. rosa* in the secondary literature are similar to what we are calling *B. bigelowii*. None of the specimens we found on the Exmouth Plateau, however, matches the description or the illustrations presented by Levin and Joerger (1967). Many of the larger braarudosphaerid specimens in our samples have pentaliths with rounded peripheries but none has the distinctive lobate projection of the pentaliths shown by Levin and Joerger (1967). We believe, moreover, that the "rounding" of pentalith peripheries is caused by calcite overgrowths (Figs. 4 and 5). We saw this rounding mostly in the larger braarudosphaerid specimens. A spectrum of *B. bigelowii* forms can be seen, grading from those with fairly sharp corners at the periphery of the pentalith, to those with broadly rounded peripheries (but still lacking extended lobes).

PALEOENVIRONMENT

Stable isotope and trace element analyses were performed on selected braarudosphaerid-bearing samples, as well as on samples lacking braarudosphaerids, in order to determine if any paleoenvironmental information could be obtained. Analyses were made on the size fraction composed of approximately 3- to 44-μm material. This size fraction was separated by first sieving, then settling and decanting the sediment. Smear slides prepared from each separated sample confirmed
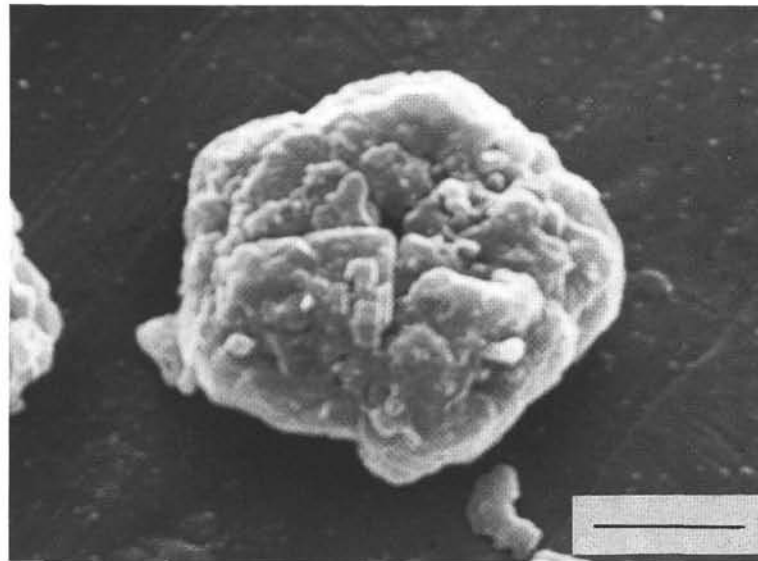
Figure 4. Scanning electron micrograph of *Braarudosphaera bigelowii* with calcite overgrowths. Sample 122-762B-17H-6. Scale bar = 7 μm.
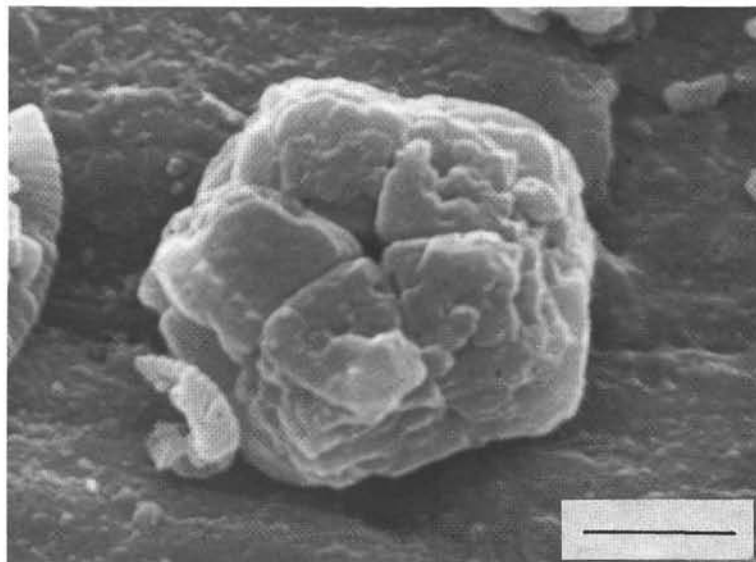

Figure 5. Scanning electron micrograph of *Braarudosphaera bigelowii* with calcite overgrowths. Sample 122-762B-17H-6. Scale bar = 6 μm.

that the 3- to 44-μm residues were composed of >90% calcareous nannofossil remains.

Stable Isotopes

Stable isotope analyses were performed by Dr. P. Swart of the Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, using a Finnigan-MAT mass spectrometer. Isotopic results are reported here in per mil deviations from the PDB-1 standard.

Samples analyzed are listed in Table 1. Braarudosphaerid-bearing samples ranging in age from earliest Oligocene (Zone NP21) to early Miocene (Zone NN1) were analyzed. Two older samples (late Eocene combined Zones NP19/20, and middle Eocene Zone NP17) and two younger samples (early to middle Miocene combined Zones NN4/5, and middle Miocene Zone NN11) were also analyzed.

The $\delta^{13}C$ results (Table 1 and Fig. 6) show no significant differences or trends corresponding to either the presence or absence of braarudosphaerids. The $\delta^{18}O$ values, on the other hand, show definite differences (Table 1 and Fig. 7). $\delta^{18}O$ values across the lower Oligocene to lower Miocene braarudosphaerid-rich interval are consistently and markedly higher (average of 1.28‰) than in the Eocene (average of 0.25‰) or younger Miocene (average 0.11‰). Both temperature and salinity will affect $\delta^{18}O$ values. Salinity and $\delta^{18}O$ concentration in seawater normally vary directly. High-salinity water has an increased evaporation rate and would thus be enriched in $\delta^{18}O$, and vice versa. Temperature fluctuations in seawater are

Table 1. Carbon and oxygen stable isotopes.

| Core, section, interval (cm)	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)	*Braarudosphaera* abundance	Series	Zone
122-762B-					
12H-4, 139–141	0.94	0.60	Absent	upper Miocene	NN11
15H-1, 88–90	1.58	−0.38	Absent	lower Miocene	NN4/5
15H-5, 88–90	1.12	1.67	Common	lower Miocene	NN1
17H-1, 100–102	0.99	1.02	Rare	upper Oligocene	NP25
17H-6, 100–102	0.44	1.50	Common	lower Oligocene	NP23
19H-3, 100–102	1.91	1.12	Few–Common	lower Oligocene	NP22
122-762C-					
3X-1, 100–102	2.35	1.11	Few–Common	lower Oligocene	NP21
5X-2, 36–38	1.55	0.24	Absent	upper Eocene	NP19/20
11X-5, 99–100	2.28	0.26	Absent	middle Eocene	NP17
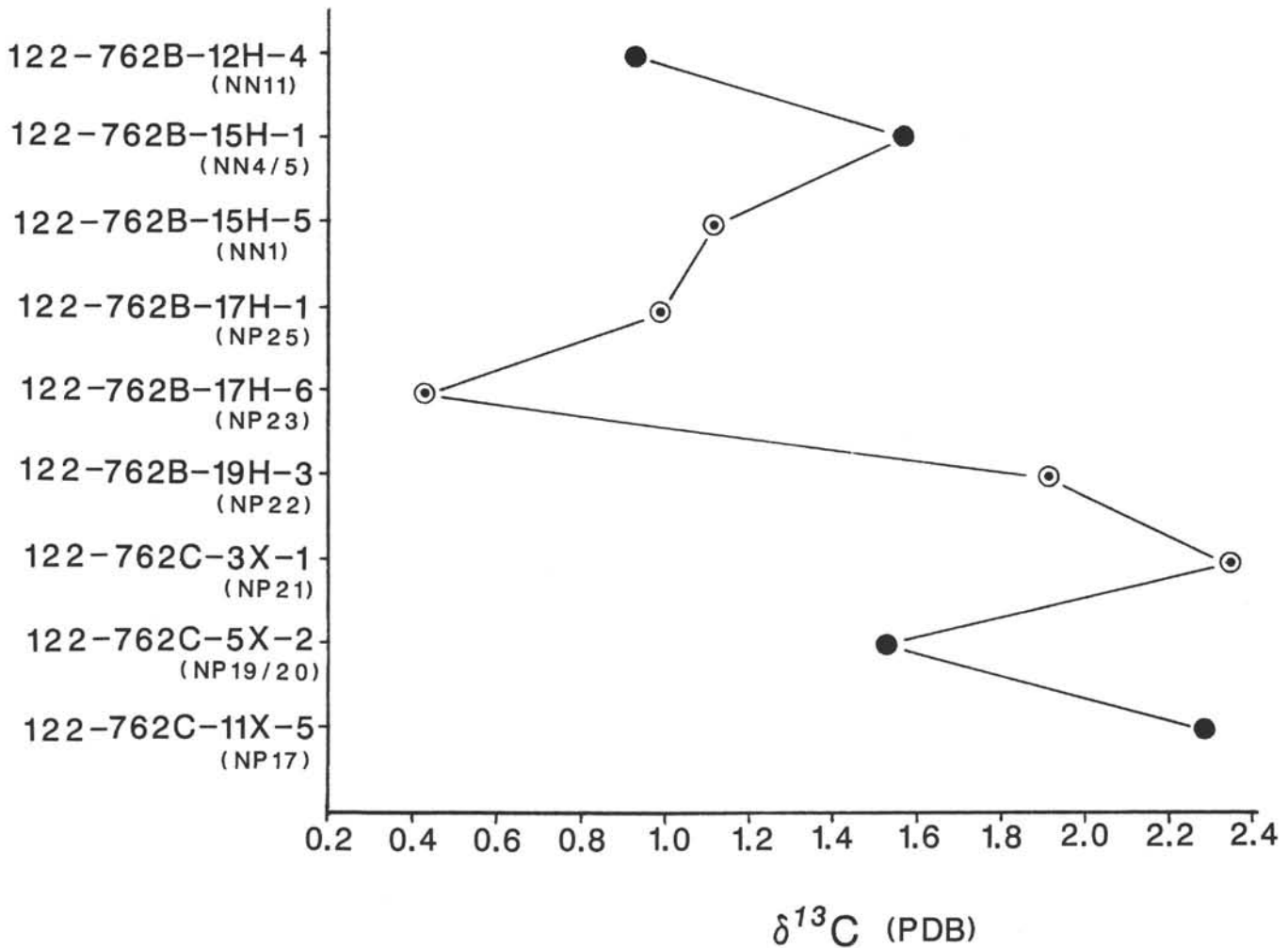
Figure 6. $\delta^{13}C$ concentrations in *Braarudosphaera*-rich samples (Sections 122-762C-3X-1 to 122-762B-15H-5) and adjacent samples on the Exmouth Plateau. Sample intervals are the same as in Table 1. Solid circles represent samples in which braarudosphaerids are absent.

almost always larger than salinity changes, however, and thus oxygen isotope fractionation related to temperature is considered to be a more important influence on $\delta^{18}O$ concentrations than salinity (Kennett, 1982). Temperature and $\delta^{18}O$ concentration vary inversely; as temperature decreases, the $\delta^{18}O$ concentration increases.

It is well known that Pleistocene enrichment in $\delta^{18}O$ reflects both increased continental ice volume (which alters seawater composition) and decreased water temperatures. The Pleistocene $\delta^{18}O$ signal is considered to be about two-thirds dependent on continental ice volume and one-third dependent on temperature (Kennett, 1982). In the Oligocene–early Miocene, intervals of increased ice volume have been inferred (e.g., Mead et al., 1986), although major covering of continental ice is generally not believed to have occurred until the middle Miocene (Shackleton and Kennett, 1975). We
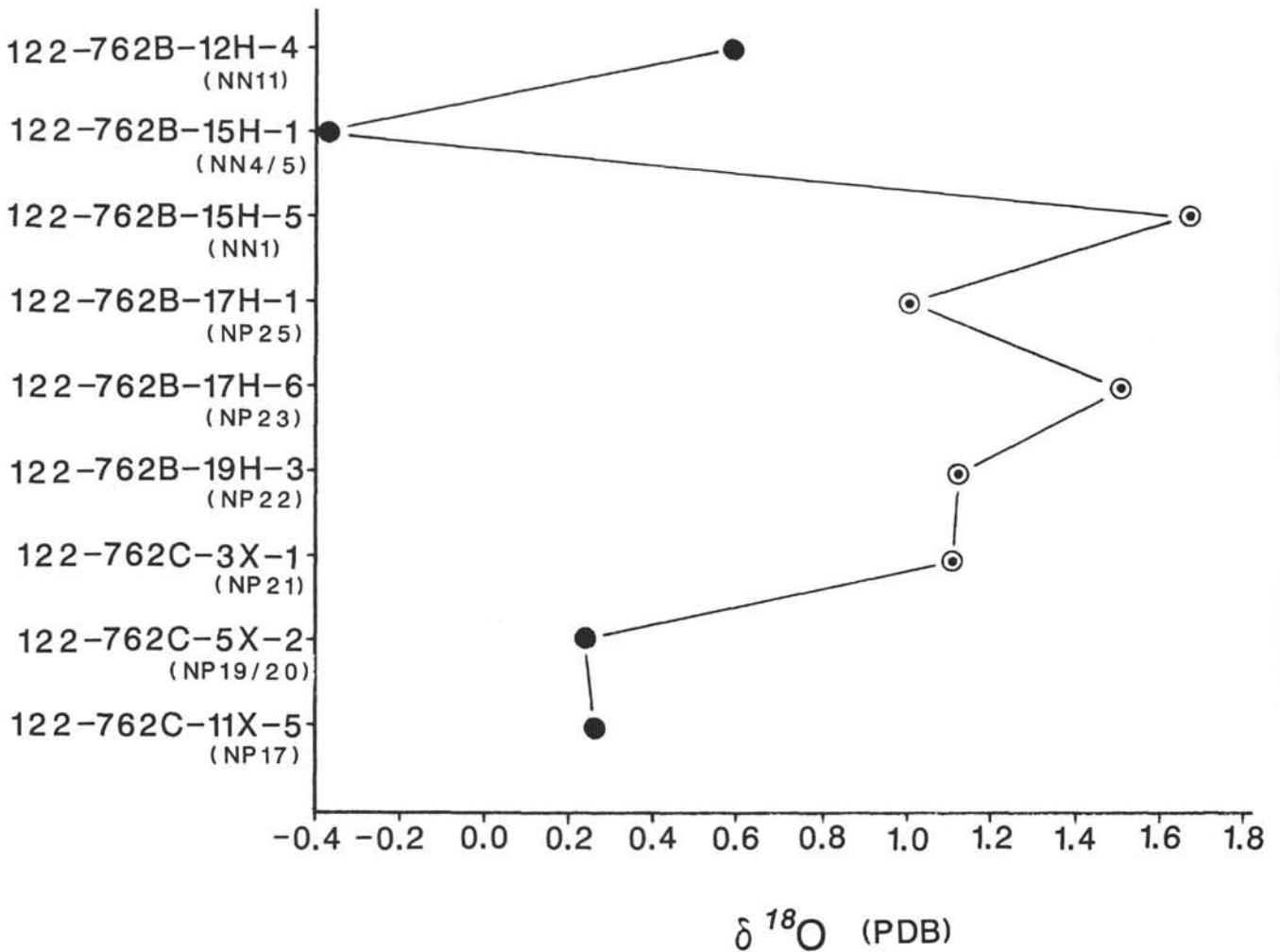
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Figure 7. $\delta^{18}O$ concentrations in *Braarudosphaera*-rich samples (Sections 122-762C-3X-1 to 122-762B-15H-5) and adjacent samples on the Exmouth Plateau. Sample intervals are the same as in Table 1. Solid circles represent samples in which braarudosphaerids are absent.

therefore assume that temperature was the cause of most of the enrichment in $\delta^{18}O$ during the Oligocene. The dramatic enrichment in $\delta^{18}O$ values across the braarudosphaerid interval suggests some environmental perturbation–in all likelihood a significant cooling of the surface waters–over the Exmouth Plateau during the time of the braarudosphaerid bloom.

We have not attempted to calculate actual temperatures from our oxygen isotope results. "Vital effects" within the polyspecific nannofossil population in the samples, syn- or post-depositional diagenesis, and varying assumptions as to the isotopic composition of Oligocene–early Miocene seawater are some of the factors complicating temperature calculations (e.g., see Paull and Thierstein, 1987).

For example, overgrowths on the braarudosphaerid specimens (Figs. 4 and 5) formed while the fossils were part of the seafloor sediment. We do not know the depth of burial when diagenesis produced the overgrowths and thus cannot estimate the temperature of the interstitial waters. Assuming the "worst-case scenario" (i.e., that the waters from which the overgrowth calcite was precipitated were colder than the surface waters), then the overgrowth calcite would add to the enrichment in $\delta^{18}O$ during the Oligocene–early Miocene interval. Braarudosphaerid specimens seem to be much more

susceptible to accruing overgrowths than most other taxa in these sediments (discoasters are a notable exception). In samples both where *Braarudosphaera* is present and where it is absent, taxa other than the braarudosphaerids and discoasters show only minor diagenetic overgrowths. Even in the samples where braarudosphaerids were concentrated by sieving and settling, they still make up only about 25%–30% of the sediment. The potential effect in diagenetically enriching the samples in $\delta^{18}O$ would, in fact, be even less than 25%–30%, since most of the calcite in a specimen is original skeletal calcite, deposited while the organism was living and in equilibrium with the ambient surface waters. A smaller amount of the calcite making up an individual specimen is overgrowth calcite precipitated by bottom waters.

Diagenesis would, nevertheless, still have some effect on temperature calculations, as would vital effects, salinity, and other controls. Any temperature calculation would therefore only be an approximation, and we prefer to use our results merely to show relative temperature values and trends in temperature changes.

Trace Elements

The same samples used for isotope analyses were analyzed for a selection of trace elements. Calcium carbonate in the

Table 2. Trace elements in parts per million.

Section	Cu	Fe	Mn	Ni	P	Zn	Mg	Sr	Ba	Li	*Braarudosphaera* abundance	Series	Zone
122-762B-12H-4	28.9	65.3	166	4.15	18.8	16.2	1.80	1.52	0.117	1.76	Absent	upper Miocene	NN11
122-762B-15H-1	310	2.63	446	6.12	53.9	92.78	1.69	1.24	0.069	1.86	Absent	lower Miocene	NN4/5
122-762B-15H-5	925	32.70	157	7.44	104	59.4	2.85	0.682	0.050	1.94	Common	lower Miocene	NN1
122-762B-17H-1	30.8	1.39	258	1.94	50.9	26.4	1.82	0.975	0.092	1.26	Rare	upper Oligocene	NP25
122-762B-17H-6	38.5	1.14	131	0.68	47.9	17.0	1.51	0.810	0.202	1.46	Common	lower Oligocene	NP23
122-762B-19H-3	42.5	3.32	310	1.56	47.5	15.4	2.09	1.08	0.071	0.84	Few–Common	lower Oligocene	NP22
122-762C-3X-1	19.4	263	278	0.72	6.3	17.0	1.92	1.25	0.064	1.4	Few–Common	lower Oligocene	NP21
122-762C-5X-2	17.5	54.8	192	0.80	12.9	10.1	1.30	1.29	0.112	1.21	Absent	upper Eocene	NP19/20
122-762C-11X-5	14.3	28.1	257	0.37	19.2	12.0	0.88	1.23	0.244	0.79	Absent	middle Eocene	NP17

Table 3. Interelement correlation matrix.

	Cu	Fe	Mn	Ni	P	Zn	Mg	Sr	Ba	Li
Cu	1.000									
Fe	−.159	1.000								
Mn	−.090	−.012	1.000							
Ni	.837	−.236	.151	1.000						
P	.853	−.508	−.058	.717	1.000					
Zn	.661	−.250	.550	.824	.614	1.000				
Mg	.737	.083	−.102	.670	.718	.395	1.000			
Sr	−.583	.334	.290	−.210	−.802	−.221	−.499	1.000		
Ba	−.437	−.257	−.322	−.546	−.349	−.457	−.774	.063	1.000	
Li	.627	.060	−.079	.811	.461	.674	.546	−.136	−.455	1.000

samples was removed by leaching in a 0.5-M acetic acid solution, after which the leach liquor was analyzed using a Leeman Labs PS1 inductively coupled plasma spectrometer. This method of dissolution may also leach trace elements from the surfaces of clays and other minerals present. The samples used were, however, concentrates consisting of >90% nannofossils, and we do not believe any extraneous trace elements leached from the remaining sediment fraction will significantly affect the interpretations based on the elemental concentrations reported here.

Table 2 shows the concentration (in ppm) of each of the 10 elements analyzed; Table 3 gives an interelement correlation matrix. Copper, nickel, phosphorus, and zinc all show progressive enrichment with time, increasing their concentrations from the Eocene to the Miocene (Fig. 8). Copper shows the most dramatic change, increasing from a low of 14.3 ppm in Section 122-762B-11H-5 (middle Eocene) to 925 ppm in Section 122-762B-11H-5 (lower Miocene). Nickel increases from 0.37 to 7.44 ppm, phosphorus from 19.2 to 104 ppm, and zinc from 12.0 to 59.4 ppm in the same samples. It is tempting to suggest that the braarudosphaerid bloom that began in the early Oligocene did so because these elements, and perhaps others, served as nutrients that finally reached concentration levels high enough to allow the braarudosphaerid family to reproduce in enormous numbers. It is well known that dissolved nutrients are essential for phytoplankton growth, but relatively little is known about which trace elements phytoplankton need as part of their nutrient requirements and in what concentrations. Martin and Gordon (1988), for example, described the effect of a little-studied oceanic nutrient, iron. They examined the phytoplankton demand for iron and the effect of iron on productivity in upwelling environments. They concluded that a lack of this nutrient would limit phytoplankton growth.

Concentrations of copper, nickel, and phosphorus all peak in Section 122-762B-15H-5, then decrease progressively in the next two younger sections examined, 122-762B-15H-1 and 122-762B-12H-4 (zinc peaks in Section 122-762B-15H-l) (Table 2). Braarudosphaerids, which are common in Section 122-762B-15H-5, are absent in Sections 122-762B-15H-1 and

122-762B-12H-4. One difficulty with a cause-and-effect hypothesis relating the Exmouth Plateau braarudosphaerid enrichment to the large concentrations of copper, nickel, phosphorus, and zinc is that Sections 122-762B-15H-5 and 122-762B-12H-4, although lower in these elements than their peak amounts, still contain concentrations higher than those existing during the early part of the enrichment (Table 2). It may be that some other influence (low-salinity water?) must act with the nutrient cocktail to produce an enrichment. Take away one influence (e.g., the low-salinity water) and, although nutrient levels remain high, no bloom will occur. By the same argument, braarudosphaerids might not bloom in low-salinity water if it contained insufficient concentrations of selected nutrients.

OCEANOGRAPHIC IMPLICATIONS AND DISCUSSION

Several questions need to be considered. The first is, do the Exmouth Plateau braarudosphaerid occurrences have any relationship in time or space to the Atlantic or western Indian Ocean occurrences?

It might be suggested that the Exmouth Plateau occurrence is a local phenomenon, perhaps caused by lowered salinity owing to freshwater runoff from the adjacent Australian mainland. Sites 762 and 763 are now between 190 and 240 km offshore and are far removed from the influence of Australian coastal runoff. Mid-Tertiary sea-level fluctuations (Haq et al., 1987) would not have pushed the western Australian coastline out far enough for normal runoff to affect the salinity at Sites 762 and 763.

The Exmouth Plateau sites are located at 19°53′S (Site 762) and 20°35′S (Site 763). This is just within the latitudinal limits of the extensive South Atlantic *Braarudosphaera* belt. South Polar stereographic projections by Smith and Briden (1977) show that the South Atlantic and Exmouth Plateau occurrences had approximately the same latitudinal relationship to each other from late Eocene to early Miocene. The co-occurrence in time also seems more than simply coincidental. LaBrecque et al. (1983) and others have shown that the most prominent South Atlantic *Braarudosphaera* occurrences are
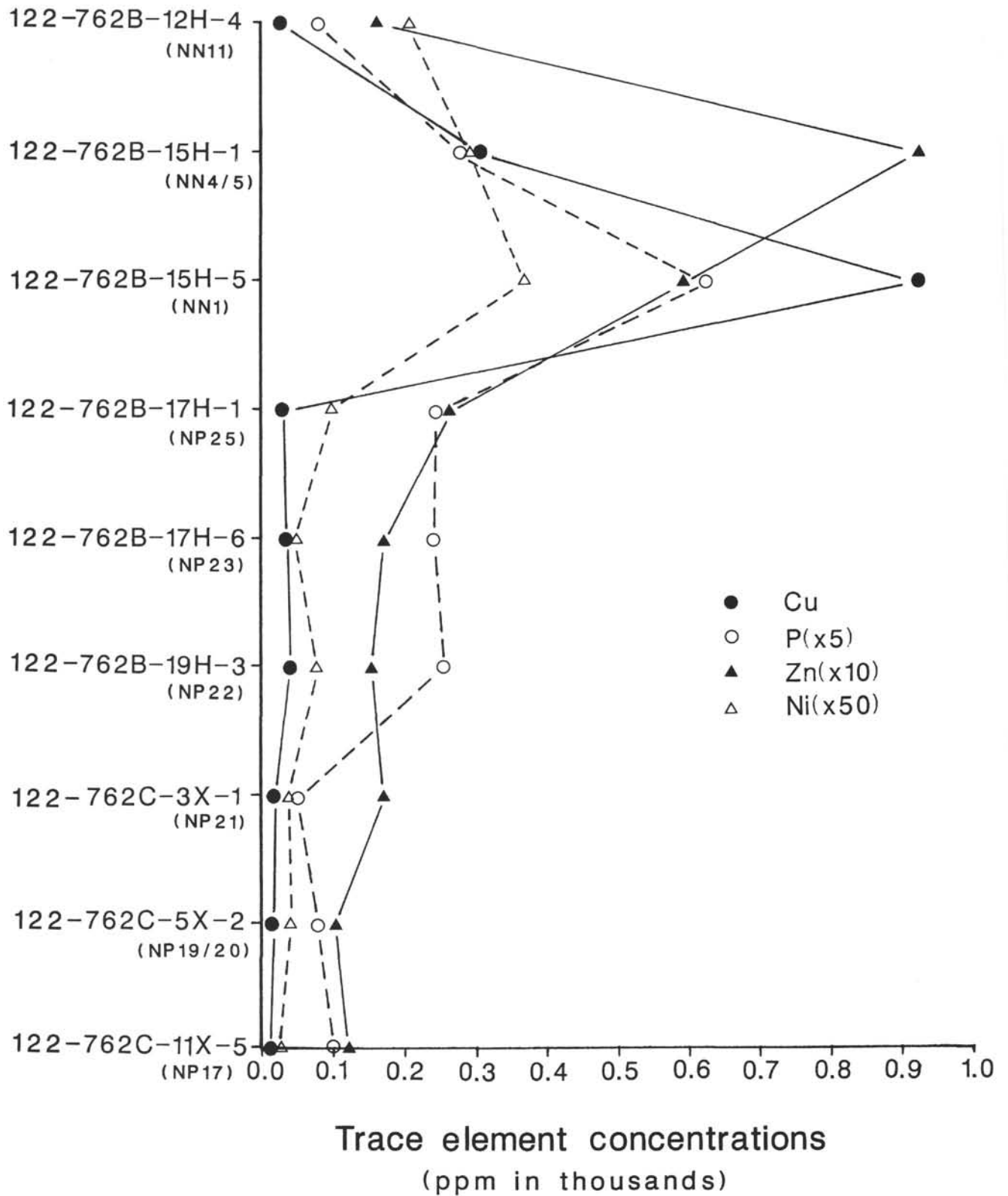
Figure 8. Concentrations of Cu, P, Zn, and Ni in *Braarudospaera*-rich samples (Sections 122-762C-3X-1 to 122-762B-15H-5) and adjacent samples on the Exmouth Plateau. Sample intervals are the same as in Table 1.

inthe lower Oligocene (Zones NP22 and NP23). This is also the interval when the most abundant *Braarudosphaera* bloom occurs at Site 762. The spatial and temporal similarity between the two occurrences seems more than just coincidental, and we believe there may be a common explanation. The Exmouth Plateau occurrences differ from those in the South Atlantic in that they are not as rich in braarudosphaerids. In that respect, the Exmouth occurrences are more similar to the North Atlantic occurrences (Parker et al., 1985), which also contain 5%–10% braarudosphaerids. The western Indian Ocean occurrences reported by Roth (1974) are not geographically similar to either the Atlantic occurrences or those reported here. They also span a longer time interval (Paleocene, Eocene, Oligocene, and, rarely, into the late Miocene). The relationship, if any, of the western Indian Ocean occurrences to those in the South Atlantic or to those on the Exmouth Plateau is uncertain.

A second question that needs to be considered is, why does the Oligocene–lower Miocene interval on the central Exmouth Plateau contain *Braarudosphaera*-rich sediments, but not the same time interval on the Wombat Plateau?

Most of the same *Braarudosphaera*-rich time intervals occurring at Sites 762 and 763 also occur on the Wombat Plateau. The lower Oligocene is partly missing at Site 760 and entirely missing at Sites 761 and 764, but the upper Oligocene–lower Miocene interval is complete at all the Wombat sites. Yet braarudosphaerids are absent from all Oligocene–lower Miocene samples on the Wombat Plateau.

A simple explanation for this may be that whatever is controlling the latitudinal limits in the South Atlantic is also at work here. Sites 762 and 763 are located at about 20°S, whereas the Wombat sites are at 16°S. The Wombat Plateau sites are seemingly outside the latitudinal boundaries of whatever dictates production of braarudosphaerid blooms. Suggestions as to what these controls may be are discussed in the following paragraphs.

Before leaving this question we should mention depth as a possible reason for the lack of braarudosphaerids on the Wombat Plateau. Sites 762 and 763 are 1379 m and 1371 m, respectively, below sea level. The Wombat sites range from 1981 m to 2701 m in depth. Bukry (1971) and Wise (1977) have noted that *B. bigelowii* is more susceptible to solution than are many nannofossil species, and, conceivably, a difference of 600 m or more in depth could selectively remove braarudosphaerids from the Wombat sites. Parker et al. (1985) concluded, however, that braarudosphaerids would readily accumulate at depths shallower than about 2700 m.

A third question is, can we gain any new information from the Exmouth Plateau which might bear on the causes, global or otherwise, of open-ocean *Braarudosphaera*-rich sediments? The enormous blooms of braarudosphaerids that have created these peculiar oozes/chalks in the Atlantic and Indian oceans must be related to unusual oceanographic conditions that are favorable to almost monogeneric productivity. The difficult questions are, what are these favorable conditions and what causes them?

As mentioned earlier, living *B. bigelowii* prefer coastal waters. Studies in the Bay of Fundy and the Gulf of Maine (Gran and Braarud, 1935) and the Gulf of Panama (fide Bukry, 1974) found large populations of this species ranging up to 1500 cells per liter. Conversely, *B. bigelowii* is very rare in open-ocean waters, if present at all. *B. bigelowii* was absent from almost all of the 20 lists of open-ocean phytoplankton we examined during preparation of this paper. These lists were published between 1959 and 1988, and include stations located over a broad spectrum of latitudes in the Atlantic, Pacific, and Indian oceans. Although these are certainly not all the phyto-

plankton lists published during those years, we believe they are a representative sampling. The only counts of *B. bigelowii* we found were made by Hulbert (1962) and Hulbert and Rodman (1963) from the North Atlantic. Hulbert (1962) found 2 cells per liter at two North Atlantic stations (but absent at 17 other stations), and Hulbert and Rodman (1963) found *B. bigelowii* at one station near Bermuda (34 cells per liter) but absent at seven other stations. Okada and McIntyre (1977) noted *B. bigelowii* was "rare" at several Pacific and North Atlantic stations, but did not list it among the counted species at the stations (Okada and Honjo, 1973). Nishida (1979, 1986) also noted *B. bigelowii* as present at several Pacific stations but did not list it among the counted assemblage, presumably because of its rare occurrence.

This distribution has led various authors (e.g., Bukry, 1974) to suggest that *B. bigelowii*, and (largely by association) fossil members of its family, prefer waters of lower-than-normal salinity. Rivers emptying freshwater into coastal bays and onto the inner continental shelf would be the chief cause of lowered salinity. The hypothesis is strengthened by the presence of *B. bigelowii* in the Black Sea, where surface waters have an average salinity of 17‰ to 18‰ and the absence of this species in the high-salinity water of the Red Sea (Bukry, 1974). Roth (1974) has noted a single occurrence of *B. bigelowii* associated with higher-than-normal salinity. That occurrence was in Holocene sediments (not in the water itself) of the Persian Gulf, where surface waters have salinities between 34‰ and 40‰. Low-salinity events in the open ocean during the Oligocene have been suggested, calling upon increased regional rainfall (Bukry, 1974) or increased meltwater from the Antarctic ice cap (Bukry, 1978).

Blooms of braarudosphaerids have also been reported in sediments deposited immediately after the K/T boundary extinctions (see Perch-Nielsen, 1985). The impression given is that of a survivor–an opportunistic taxon able to tolerate more stressful environmental conditions than most other nannoplankton.

To explain the mid-ocean South Atlantic braarudosphaerid occurrences, Wise and Kelts (1972) suggested that unusual current conditions might have generated profuse blooms of braarudosphaerids to the extent that the carbonate compensation depth (CCD) would have been lowered, and therefore the preservation of the braarudosphaerids enhanced. Another appealing suggestion is mid-ocean upwelling (Berger, 1979; LaBrecque et al., 1983). Upwelling of cold, nutrient-rich waters is a well-known coastal phenomenon. Mid-ocean upwelling is less common. Two areas where mid-ocean upwelling occurs today are along the equator (the Tropical Divergence) and surrounding Antarctica (the Antarctic Divergence). Less well known is the Subtropical Divergence (Tasman Front), a more regionally localized divergence zone located east of Australia at about 30°S (Knox, 1970). Elmstrom and Kennett (1986) and Kennett and von der Borch (1986) have shown that localized upwelling along this zone occurred during the Neogene. Productivity of calcareous microfossils was greater than that of siliceous microfossils along the Subtropical Divergence, but species diversity appears normal for a mid-ocean site.

Regional divergent upwelling might be the explanation for mid-ocean braarudosphaerid blooms. Divergent-zone upwelling is likely to be roughly linear across a broad front, and would thus explain the apparent latitudinal constraints. We suggest that other regional divergence zones may have developed in the oceans during the past. The Subtropical Divergence just described may be a model for this type of regional mid-ocean upwelling, but it does not lend actual evidence to the occurrence of braarudosphaerid-rich sediments, since no

braarudosphaerids were found at sites drilled beneath the divergence zones (Lohman, 1986).

Upwelled waters are cold and markedly lower in salinity than normal surface waters. As examples, the Benguela Upwelling System has salinities in the 34.6‰–34.9‰ range (Mitchell-Innes and Winter, 1987), offshore California areas range down to 33.7‰ (Martin and Gordon, 1988), and some parts of the equatorial region have even lower values (less than 33.5‰; Kennett, 1982).

B. bigelowii has shown its preference for low-salinity waters. We suspect that particularly intense divergent upwelling bringing up cold, excessively low-salinity water might be necessary to generate the profuse braarudosphaerid blooms found in the Oligocene. Enriched $\delta^{18}O$ levels during the Oligocene (Table 1) provide evidence of colder surface waters over the Exmouth Plateau during this time.

Low-salinity waters may be only part of the explanation for open-ocean braarudosphaerid-rich sediments. Upwelling water also brings up dissolved nutrients that are necessary for phytoplankton growth. Perhaps the presence (or absence?) of some nutrient combination helped launch the prolific blooms of braarudosphaerids. Braarudosphaerids have not yet been cultured in the laboratory, and almost nothing is known about their physiology. So with only the meager evidence from our elemental analyses (Table 2), we venture to suggest that nutrient concentrations may influence the blooms of braarudosphaerids. Perhaps upwelling is the ultimate cause of the blooms, but it may not be entirely the associated low salinity that causes the increased production of braarudosphaerids. The Oligocene was not an epoch of particularly high productivity. An Oligocene mid-ocean upwelling event may, however, have carried a high enough concentration of a single nutrient or nutrient mixture that, together with low salinity water, created conditions so favorable to the reproduction of braarudosphaerids that the family bloomed in enormous numbers and produced very large (at least on the Exmouth Plateau) braarudosphaerids.

SUMMARY

Sites 762 and 763 contain Oligocene–lower Miocene sediments that are unusually rich in braarudosphaerids. Braarudosphaerids comprise up to 10% of the sediments in some samples from the lower Oligocene, the interval where they are most abundant. Members of the Braarudosphaeraceae family present include *B. bigelowii* (overwhelmingly dominant), *B. discula* (rare), and *M. pinguis* (rare). The sediments are enriched in $\delta^{18}O$ across the braarudosphaerid-rich interval, suggesting cooler waters during that time. Concentrations of copper, nickel, phosphorus, and zinc are also high in the calcium carbonate fraction of the sediment within the braarudosphaerid interval. Oceanographic conditions of an unusual nature led to extremely high productivity of braarudosphaerids. We suggest mid-ocean upwelling along a latitudinally restricted divergent zone as the driving force. This upwelling brought cool, unusually hyposaline water and abundant concentrations of necessary trace element nutrients to the surface, which triggered enormous blooms of *Braarudosphaera*.

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