

Braarudosphaera bigelowii morphotypes in the surface sediments of the southwestern South China Sea

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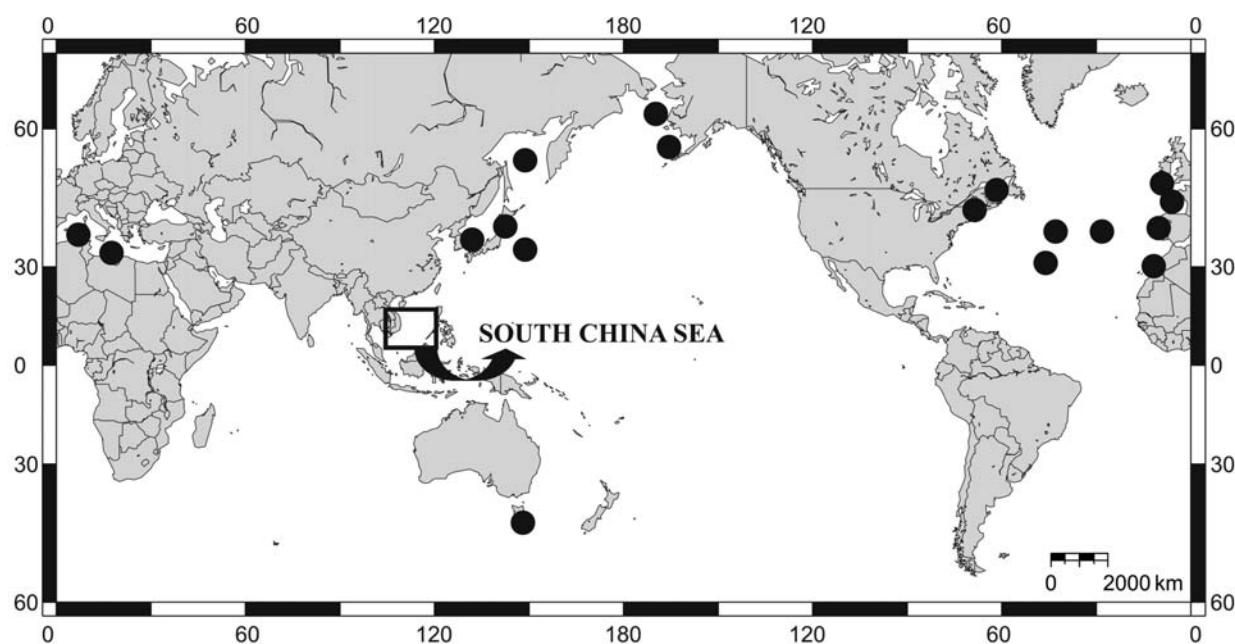
ABSTRACT: The present study reports on the distribution and occurrence of *Braarudosphaera bigelowii* in the surface sediments of the western part of the South China Sea (SCS), along the coast of Vietnam. This part of the SCS is a known upwelling region, characterized by low salinity conditions due to high annual rainfall and river run-off, confirming the results of earlier studies regarding the occurrence of *B. bigelowii* in shallow bays, nearshore, low salinity marine waters and upwelling areas. Morphometric analysis of *B. bigelowii* pentaliths in the western SCS revealed the presence of the 3 morphotypes proposed by Takano et al. (2006) based on the pentalith side lengths from coccospheres encountered in surface water samples. This paper also reports the occurrence of a new *B. bigelowii* morphotype in the SCS, corresponding to specimens with a pentalith side length of 3.5–4.0 µm. An attempt to relate the distribution of these morphotypes with temperature and salinity proved to be inconclusive, suggesting the possibility that other factors could be influencing the occurrence of the morphotypes in the study area.

Keywords: *Braarudosphaera bigelowii*, calcareous nannofossils, morphotypes, South China Sea (SCS), surface sediments

INTRODUCTION

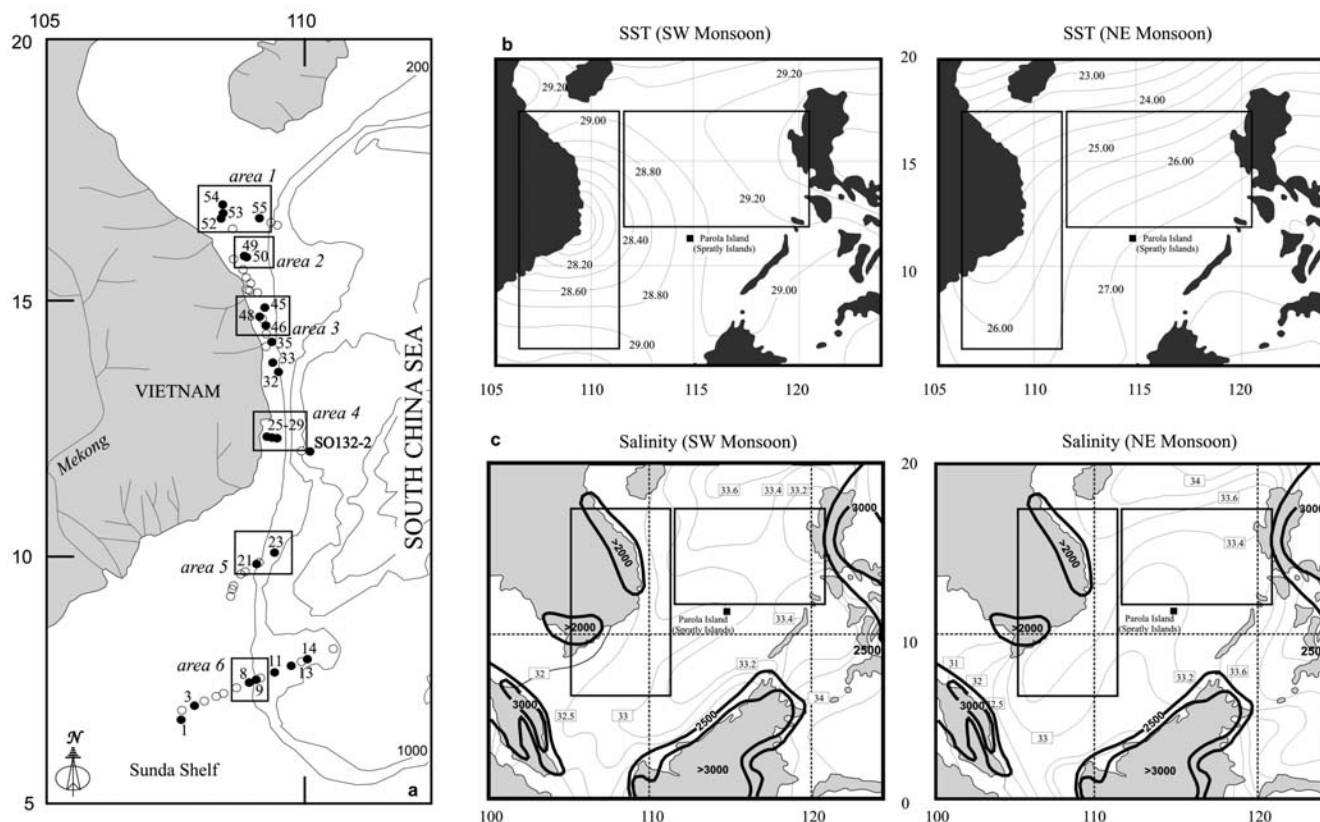
The coccolithophorid *Braarudosphaera bigelowii* has a long fossil record that goes back to the Late Cretaceous Period, and is probably the oldest of the extant calcareous nannoplankton taxa (Burnett et al. 1998). The living cell is enclosed by a theca of calcareous plates with five-fold symmetry, called pentaliths,

which form the typical dodecahedron-shaped “coccosphere” (Young et al. 2003). At present, *B. bigelowii* occurs sporadically in shelf environments, usually associated with low salinity conditions. However, in the past, it formed extensive blooms in the open ocean, for example, during the Oligocene in the South Atlantic (Peleo-Alampay et al. 1999) and after the Cretaceous/Tertiary (K/T) mass extinction (Lamolda et al. 2005).



TEXT-FIGURE 1

Location of the study area (South China Sea) and some of the locations where living *Braarudosphaera bigelowii* has been reported (data from Konno et al. 2007). In the South China Sea, *B. bigelowii* pentaliths/coccospheres are found in the surface sediments along the coast of Vietnam (see text-fig. 2a).



TEXT-FIGURE 2

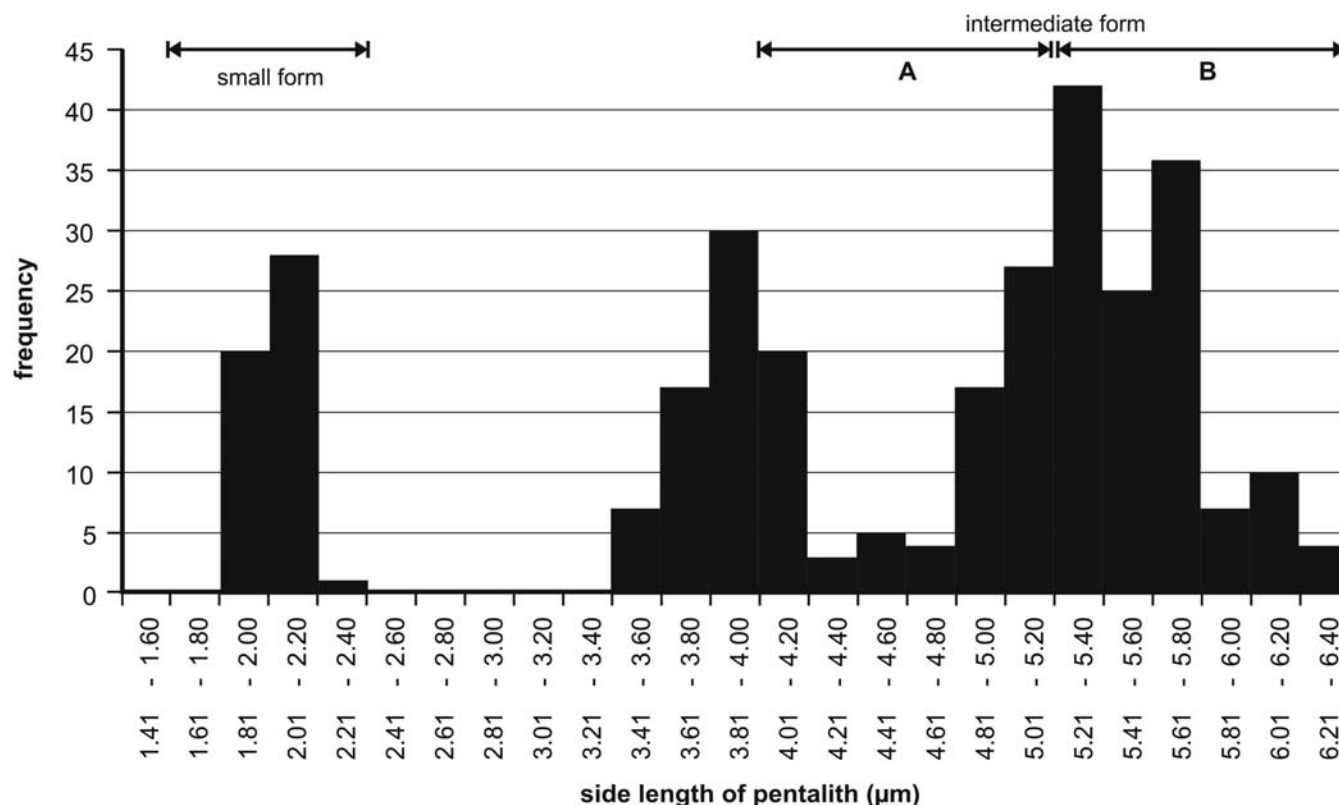
(a) Location of stations along the coast of Vietnam where pentacaliths of *B. bigelowii* were encountered (solid circles). Boxes correspond to the six areas that were chosen to illustrate the distribution of the morphotypes in the South China Sea. (b) Sea-surface temperature (from Wyrki 1961 and IGOSS 1999) and (c) sea surface salinity (thin contour lines; from Wyrki 1961) and average annual rainfall (in mm; thick contour lines) in the SCS during the SW and NE monsoons. (The solid squares in Text-figs. 2b and 2c show the location of the Spratly Islands)

Several studies have already reported the presence of *B. bigelowii* in surface sediments of shallow seas (e.g., Bukry 1974, Tanaka 1991, Okada 1992) and surface waters of the world's oceans (e.g., Duarte-Silva et al. 2004, Takano et al. 2006, Konno et al. 2007, Hagino et al. 2009; text-fig. 1). In the South China Sea (SCS), *B. bigelowii* pentacaliths were reported by Fernando et al. (2007) only in the western part, along the coast of Vietnam (text-fig. 2a), which is a known upwelling region (ODP Leg 184 Shipboard Scientific Party 2000, Kuo et al. 2000, Liu et al. 2002). This area represents one of the few places in the SCS where *B. bigelowii* can be found. Recently, Takano et al. (2006) subdivided *B. bigelowii* into three morphotypes (small form, Intermediate forms -A and -B) based on the pentacalith side lengths, and showed that the SSU rDNA sequences of a specimen of intermediate form-A and of a specimen of intermediate form-B are significantly different from each other. Hagino et al. (2009) studied the morphometric and genetic variation of *B. bigelowii* in the seas surrounding Japan, classified living *B. bigelowii* into four morphotypes and five SSU rDNA genotypes, and showed that the genotype is related to pentacalith size not sample locality. They concluded that *B. bigelowii* is a species complex consisting of multiple discrete species with different pentacalith size ranges, although the taxonomy of *B. bigelowii* has not yet been emended. These results indicate that the pentacalith size is a reliable criterion for the

classification of *B. bigelowii*. In the present study, a morphometric analysis of the pentacaliths encountered in the surface sediments was conducted to determine whether the morphotypes reported in the surface waters are also present in the sediments of the SCS, and to determine whether the spatial distribution of these morphotypes can be related to the unique oceanographic parameters in the western part of the SCS.

STUDY AREA

The surface water of the SCS is mainly influenced by the East Asian Monsoon System which consists of two seasonal monsoons: winter (NE) and summer (SW) monsoons (Wyrki 1961 as reproduced in Miao et al. 1994). Of particular interest in the present study is the occurrence of upwelling along the coast of Vietnam (on the Vietnam and Sunda Shelves) during the SW Monsoon as evidenced by lower sea surface temperatures (SSTs) and an elevated nutricline (text-fig. 2b; Wiesner et al. 1998, Villanoy et al. 1999; for nutricline data, refer to text-fig. 2d of Fernando et al. 2007). This is in contrast to the central and eastern parts of the SCS which are characterized by higher SSTs and deeper nutricline regardless of the prevailing monsoon (Wei et al. 1998, Wiesner et al. 1998, Liu et al. 2002). Surface salinity values in the western portion of the SCS are also significantly lower than the rest of the SCS (text-fig. 2c). This is attributed to



TEXT-FIGURE 3

Frequency distribution of all *B. bigelowii* morphotypes (defined by Takano et al. 2006) measured in the western South China Sea. Total number of specimens per morphotype is discussed in the paper.

the high rainfall throughout the region, particularly during the SW monsoon, and the proximity of the area to large rivers draining into the SCS, like the Mekong River (Miao et al. 1994).

METHODOLOGY

The surface sediment samples used in the present study were collected during the R/V Sonne cruise SO-140A in 1999 (Wiesner et al. 1999). The smear slides used by Fernando et al. (2007), to study the distribution of calcareous nannofossils in the surface sediments across the SCS, were also used in this study. Six areas, comprising a total of 16 samples, were chosen to illustrate the distribution of *B. bigelowii* in a north-south transect along the coast of Vietnam (text-fig. 2a).

Like Takano et al. (2006), the morphometric analysis of the *B. bigelowii* pentaliths involved measuring the pentalith side lengths. However, while Takano et al. (2006) measured the pentaliths with a scanning electron microscope (SEM), the present study measured the pentaliths using a Zeiss Axiophot polarizing light microscope (LM). The measurements were verified and refined by taking pictures and measuring the pentalith side lengths using the computer software CorelDRAW.

Pentaliths of *B. bigelowii* are rare to very few in the samples, comprising <1% of the total surface sediment nannofossil as-

semblage in 300 specimen counts (Fernando et al. 2007). Except for 3 samples, at least 15 *B. bigelowii* pentaliths were measured per sample and tabulated into size intervals of 0.2 μm, following the works of Takano et al. (2006) and Hagino et al. (2009). Histograms of the data at each area were constructed to determine and illustrate the morphotypes present in the surface sediments of the western SCS.

RESULTS AND DISCUSSION

Surface Sediment and Surface Water Distribution

In the study of Fernando et al. (2007), it was shown that *B. bigelowii* pentaliths are restricted to the western part of the SCS, off the coast of Vietnam (text-fig. 2a). Investigation of the oceanographic and climatic conditions in the area reveals the occurrence of low SSTs, due to the presence of a coastal upwelling system during the SW Monsoon and the prevalence of low-salinity surface waters due to high annual rainfall and river run-off. This low salinity zone could explain the occurrence of *B. bigelowii* pentaliths in the area, as the species is known to prefer shallow bays, nearshore areas, and low salinity marine waters (e.g., Gran and Braarud 1935), as well as being adapted to upwelling conditions (e.g., Duarte-Silva et al. 2004). Fernando et al. (2007) classified the nannofossils in this area (including *B. bigelowii*) as part of the upwelling (shelfal) assemblage.

TABLE 1

Comparison of the temperature, salinity, CaCO₃ % of the sediments and *B. bigelowii* pentalith measurements in the western SCS.

Area	Sample number	Water Depth (m)	Distance from coast (km)	Temperature (°C)	Salinity (ppt)	CaCO ₃ %	# of Pentaliths counted	Average side length (µm)	Smallest side length (µm)	Largest side length (µm)
1	SO-140-55	114.80	100.92	28.99	33.06	13.57	17	4.97	3.75	6.38
	SO-140-54	92.90	65.25	25.15	33.70	18.10	20	4.78	1.84	6.12
	SO-140-53	94.40	51.91	25.36	34.12	n/a	22	4.20	1.93	5.99
	SO-140-52	91.10	38.57	23.85	33.57	14.22	21	3.50	1.84	5.71
2	SO-140-50	84.50	37.12	25.37	33.86	n/a	15	5.13	3.99	6.03
	SO-140-49	82.50	37.12	25.37	33.86	31.02	41	3.95	1.84	6.12
3	SO-140-48	61.50	11.02	25.21	33.43	n/a	18	5.04	3.72	5.73
	SO-140-46	100.00	18.27	26.64	32.18	18.10	14	4.70	3.90	5.20
	SO-140-45	97.90	21.75	25.05	33.96	16.81	21	4.86	1.94	5.97
4	SO-140-28	103.60	21.75	27.07	33.94	7.76	18	4.13	1.91	5.83
	SO-140-26	59.30	16.82	27.46	31.60	6.02	19	4.50	1.99	5.74
	SO-140-25	45.50	11.60	25.57	31.76	7.11	19	4.61	1.91	6.12
5	SO-140-23	280.10	149.35	27.84	33.39	24.56	15	4.68	1.92	5.82
	SO-140-21	155.90	150.80	29.92	33.24	35.55	15	4.46	1.94	6.20
6	SO-140-09	213.90	377.00	27.70	33.43	n/a	12	4.10	2.02	6.25
	SO-140-08	149.70	374.01	28.94	33.14	9.70	14	4.96	1.85	7.58

Although *B. bigelowii* are rare to very few in occurrence, both small- and medium-sized pentaliths were observed in the surface sediment samples (Plate 1). However, aside from their small size, the former are more difficult to observe under the microscope because of their lower birefringence. *Braarudosphaera bigelowii* coccospheres were also observed in the surface sediment samples (Plate 1), although they have not been reported yet from Vietnam waters (e.g., Doan 2000). Coccospheres of *B. bigelowii* collapse easily, so it is very likely that those found in the sediments are autochthonous, rather than as a result of transport from elsewhere. A *B. bigelowii* coccosphere was also observed in a surface water sample collected near Parola Island (North Danger Reef) in the Spratly Islands during the 4th Joint Oceanographic and Marine Scientific Research Expedition (JOMSRE IV) in the SCS (unpublished data). This area, therefore, represents one of the few localities in the world where living *B. bigelowii* has been found (see text-figs. 1 and 2).

Morphometric Analysis of Pentaliths

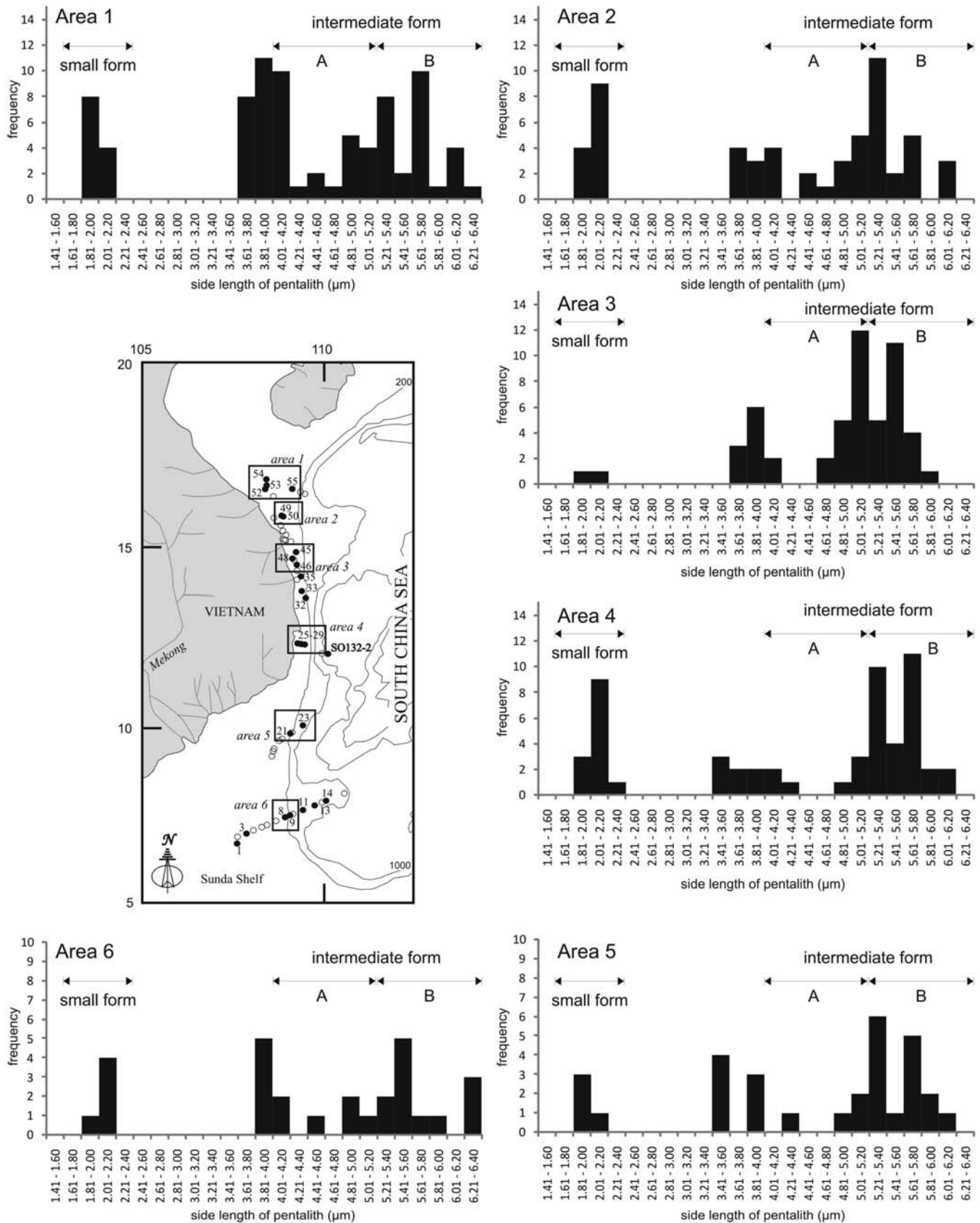
Of the 303 pentaliths measured in this study, 49, 76 and 124 specimens correspond to the small form (<2.4µm), intermediate form A (4.0-5.3µm) and intermediate form B (5.3-7.2µm), respectively, of Takano et al. (2006) and Hagino et al. (2009), but the remaining 54 specimens with pentalith side lengths of 3.5 to 4.0µm differed in size range from those of the previously reported morphotypes (Table 1; text-figs. 3 and 4). Similar to the previous morphometric studies of *B. bigelowii*, a clear separation exists between the small forms (<2.4µm) and the larger morphotypes in the SCS (text-figs. 3 and 4). The boundaries between the larger morphotypes, however, somewhat overlap. In Takano et al. (2006), the boundary between the populations of intermediate forms A and B is represented by a frequency minimum at 5.2-5.4µm. This frequency minimum is also recognized in the present study, albeit at a different size interval (5.4-5.6µm), which may be due to the different type of microscopy (LM vs SEM) used to calculate the measurements in the two studies. Despite this, the difference in frequency minimum using the two methods is only 0.2µm. In the present study, those specimens with a size range of 3.4 to 4.0µm could represent a new morphotype from the SCS (herein referred to as the small form B morphotype). The largest specimens of this small form B are identical in size (i.e., 4.0µm) to the smallest specimens of intermediate form A from the seas around Japan, but they differ in size range and frequency distribution. The pentalith side

length of intermediate form A ranges from 4.0-5.3µm with a frequency peak around 4.2-4.6µm and, so far, no specimens have been reported <4.0µm. On the other hand, the pentalith side lengths of small form B specimens are > 3.5µm with a frequency peak at 3.8-4.0µm. A frequency minimum that likely corresponds to the separation of the small form B and intermediate form A was found at around 4.2-4.4µm (text figs. 3 and 4). The frequency peak at around 3.8-4.0µm, therefore, strongly suggests that specimens <4µm actually exist in the SCS, and are not due to a technical error during measurement of the pentaliths in the LM. It should be noted that a specimen of *B. bigelowii* within this size range (3.6-3.8µm) was also observed by Konno et al. (2007) in their SEM-based morphometric studies of *B. bigelowii* from the Bering Sea. Currently there is no genetic data for the specimens of the small form B, however, a clear relationship between other size-morphotypes and SSU rDNA genotypes of *B. bigelowii* reported by previous studies (Takano et al. 2006, Hagino et al. 2009) indicate the possibility that the small form B is genetically different from other '*B. bigelowii*' populations at the species level. No specimen with a pentalith side length >7.4µm, which corresponds to the large form of Hagino et al. (2011), was found in samples from areas 1-6 (text-fig. 4). However, a pentalith observed on the Sunda Shelf had a side length of 7.58µm (Table 1), which is within the range of the morphotype referred to as "large form" by Hagino et al. (2009).

The different *B. bigelowii* morphotypes were all observed in the 6 areas along the coast of Vietnam. There is no apparent change in the trend, except for the less common occurrence of the small form morphotype in areas 3, 5 and 6 and the more common occurrence of the small form B morphotype in area 1 (text-fig. 4). Investigation of salinity and temperature values in these areas (Table 1) reveal that variations among samples are insufficient to explain the observed trend. The difference in the distribution of the morphotypes, therefore, may be just an artifact of the sediment record or due to differences in the number of pentaliths counted per area. Interestingly, Hagino et al. (2009) suggested that the size of *B. bigelowii* pentaliths, rather than being influenced by the environment, is genetically-controlled.

SUMMARY AND CONCLUSIONS

The study confirms the occurrence of *B. bigelowii* in nearshore, low salinity marine waters and upwelling areas, which charac-



TEXT-FIGURE 4
Frequency distribution and occurrence of *B. bigelowii* morphotypes in the 6 areas investigated along the coast of Vietnam. Forms slightly smaller than the “intermediate A” morphotype were consistently recorded in all the areas. These morphotypes are referred to as “small form B”.

terize the western part of the South China Sea (along the coast of Vietnam).

Morphometric analysis of *B. bigelowii* pentoliths in the surface sediments of the SCS revealed the presence of the 3 morphotypes originally described in surface water samples (Takano et al. 2006), and a new morphotype (3.5–4.0 µm), which is herein referred to as the “small form B”. This observation suggests that there could be greater diversity in the modern *B. bigelowii* complex, which has been already established in previous studies indicating genetic differences between the different morphotypes.

Based on available data, the distribution of the morphotypes does not seem to be influenced by temperature and salinity, supporting the result of a previous study suggesting that the size of the pentoliths are genetically-controlled and are not affected by the environment.

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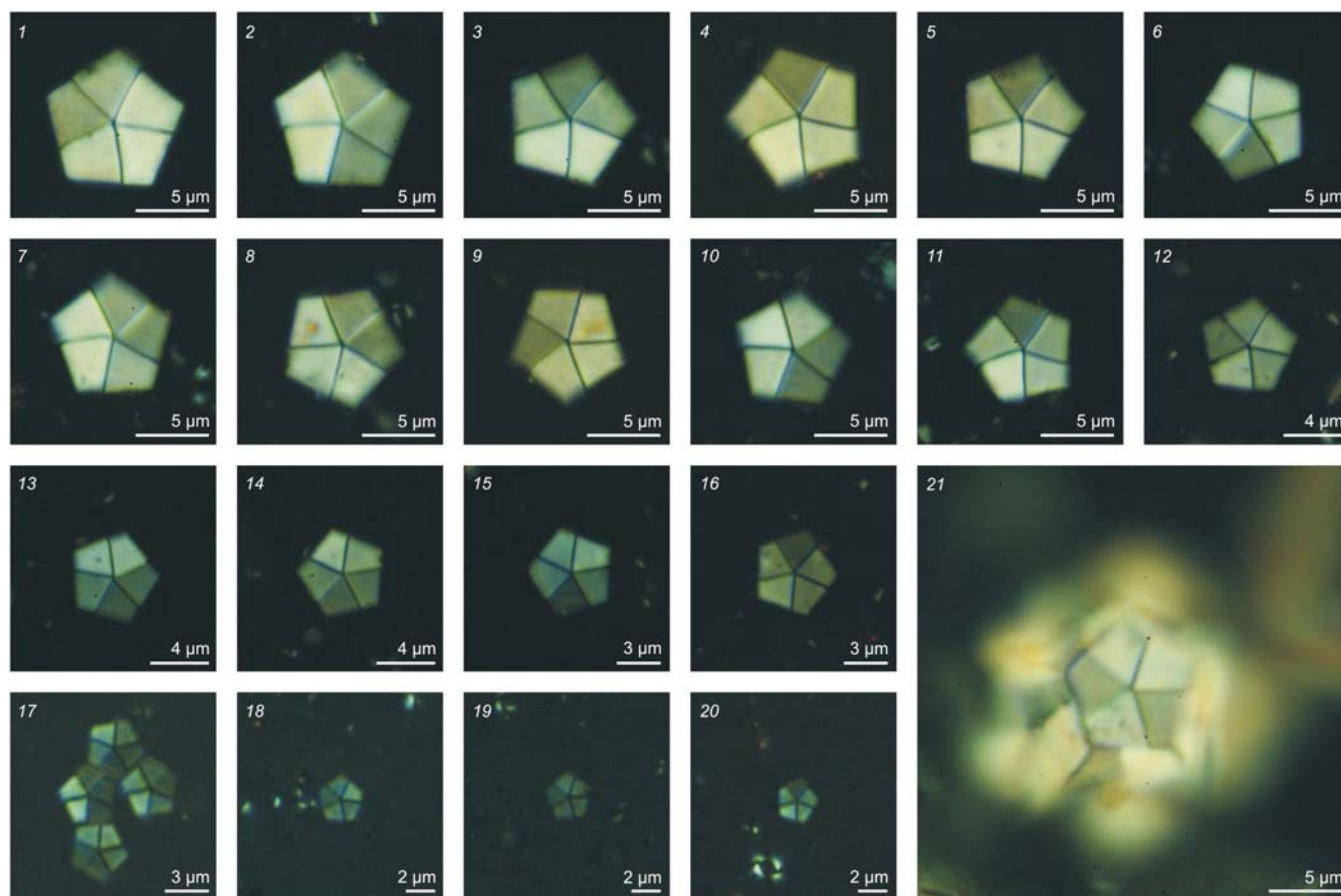


PLATE 1

Microphotographs of the different pentalith morphotypes of *B. bigelowii* and coccosphere from the surface sediments of the South China Sea.

1–4 *Braarudosphaera bigelowii* Intermediate form B (Takano et al. 2006)

- 1 SO-140-25
- 2 SO-140-52
- 3 SO-140-49
- 4 SO-140-09

5–12 *Braarudosphaera bigelowii* Intermediate form A (Takano et al. 2006)

- 5 SO-140-08
- 6 SO-140-21
- 7 SO-140-53
- 8 SO-140-53
- 9 SO-140-48
- 10 SO-140-08
- 11 SO-140-50
- 12 SO-140-49

13–16 *Braarudosphaera bigelowii* Small form B (This study)

- 13 SO-140-55
- 14 SO-140-26
- 15 SO-140-48
- 16 SO-140-28

17–20 *Braarudosphaera bigelowii* Small form (Takano et al. 2006)

- 17 SO-140-49
- 18 SO-140-45
- 19 SO-140-28
- 20 SO-140-54

21 *Braarudosphaera bigelowii* Intermediate form A (Takano et al. 2006) coccosphere; SO-140-53

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