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DISTRIBUTION OF BENTHIC FORAMINIFERA IN THE CORAL REEFS ECOSYSTEM OF PULAU BIDONG, TERENGGANU, SOUTHERN SOUTH CHINA SEA

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Abstract: A study on the distribution of benthic foraminiferal species in the surface sediments of coral reefs was carried out in *Pulau Bidong* in the southern South China Sea (SCS). Samples were collected at 12 sites around *Pulau Bidong* at water depths ranging from 5 m to 30 m. Live (rose bengal stained) and optimally preserved empty tests of benthic foraminifera were analysed based on their chamber and apertural characteristics observed under binocular microscope (Leica Zoom 2000). The results revealed that 32 genera of benthic foraminifera were found in the coral reefs sediments. *Amphistegina* was the most abundant genus with relative abundance of 68% and frequently recorded at depths of between 10-15 m and 25-30 m. Other common genera that were found were *Calcarina, Elphidium, Heterolepa, Heterostegina, Quinqueloculina, Peneroplis* and *Triloculina.* These genera showed depth distribution preference in the shallow water zone (5 m depth). The highest diversity index (2.3) and number of taxa (26 genera) were recorded at station W2, located at the western part of Pulau Bidong. The lowest diversity index (0.2) and number of taxa (seven genera) were recorded at station S3, located at the southern part of *Pulau Bidong*. The frequency distribution and diversity of benthic foraminifera in the study area were related to water depth.

Keywords: Benthic foraminifera, distribution, coral reefs, diversity, southern South China Sea.

Introduction

Coral reefs are distributed throughout the warm tropical and subtropical regions of the ocean. Coral reefs are one of the most biologically diverse ecosystems on earth, hosting many organisms, like sponges, pulpit, manta rays and dolphins. In *Pulau Bidong,* 66% of the reefs were in good health, 17% were in fair condition, while the remaining 17% were in poor shape (Reef Check Malaysia, 2017). Coral reefs are experiencing a decline due to genuine local effects, which is also occuring on a global scale, affecting the environment and climate, i.e., increased temperature and nutrient runoff, lowered water clarity and storm surge (Hallock *et al.,* 2004). Bryant *et al.* (1998) estimated that 58% of global coral reefs cover is endangered by human activities, e.g., sewage, industrial pollution, deforestation and overfishing.

Benthic foraminiferal assemblages in coral reefs were dominated by calcareous tests, which possess similar characteristics like the corals (Natsir & Subkhan, 2011). According and Natsir & Muchlisin (2012), many of the collected species from Tambelan Archipelago, Indonesia, were recognized as symbiont-bearing foraminifera (larger benthic foraminifera). The most common among them were *Assilina ammonoides* and *Amphistegina lessonii*. Larger foraminifera prefer to live in the euphotic zone of warm oligotrophic seas. All larger benthic foraminifera (LBF) are epifaunal microorganisms that prefer to live on hard substrates, like coral rubbles or other bioclasts. Endosymbionts in the LBF tests help in the calcification and production of food, just as zooxanthellae help corals (Hallock, 2000).

The distribution of benthic foraminifera is determined by depth, light intensity and hydrodynamics in the ocean (Hottinger, 1983, Hallock *et al.,* 1991; Hohenegger, 2005). Benthic foraminifera construct more robust tests in high-energy environments, while thin-walled tests dominate in quiet environments (Hohenegger, 2005). Miliolids with opaque porcelaneous test walls produce structures such as pores to allow the passage of light into the protoplasm (Hallock *et al.,* 1991). This study aims to determine the relative abundance and frequency distribution of benthic foraminifera in the surface sediments of coral reefs in *Pulau Bidong,* as well as to assess their community structure using diversity indices. Reef foraminifera have been studied as bioindicators of coral reefs health due to their similar characteristics to zooxanthellae, thus the present data may also be applied as a reconnaissance to the status of coral reefs health in tropical seas.

Methodology

Study area

Pulau Bidong, which is located at coordinate *5°37'*16" N, 103°03'41" E, is one of the many coral reef islands in the east coast of Peninsular Malaysia (Figure 1). It directly faces the southern South China Sea (SCS), surrounded by oligotrophic warm water that is inhabited by coral reefs and other marine organisms. The island is located 14 km from the mainland and the depth of the surrounding water can reach a maximum of 30 m. Two monsoon seasons influence the climate of the island; the northeast monsoon from November to March, and the southwest monsoon from April to August (Daryabor *et al.,* 2016).

Sample collection and processing

Samples were collected by SCUBA divers at 12 stations around the island (Figure 1) by placing 100 ml of surface sediments in plastic bottles. Three stations were located in the north (N1, N2 and N3), four stations in the west (W1, W2, W3 and W4), three stations in the south (S1, S2 and S3) and two stations in the east (E1 and E2). Samples were brought back to the laboratory within 24 hours of sampling, later preserved in 10% buffered formalin and rose bengal solution before any protoplasm decaying process could occur (Walton, 1952). Samples were washed gently in a 63 μm sieve to remove clay and silt before drying in the oven at 60°C for 24 hours. Foraminiferal specimens were picked out randomly using a fine artist brush in a Leica Zoom 2000 binocular microscope. About 300 foraminiferal specimens were picked out from each sample to represent the total assemblages (live and dead foraminifera). Specimens were identified based on their morphology, such as test shape, chamber shape, chamber numbers, test ornamentation and apertural position, following Loeblich and Tappan (1994).

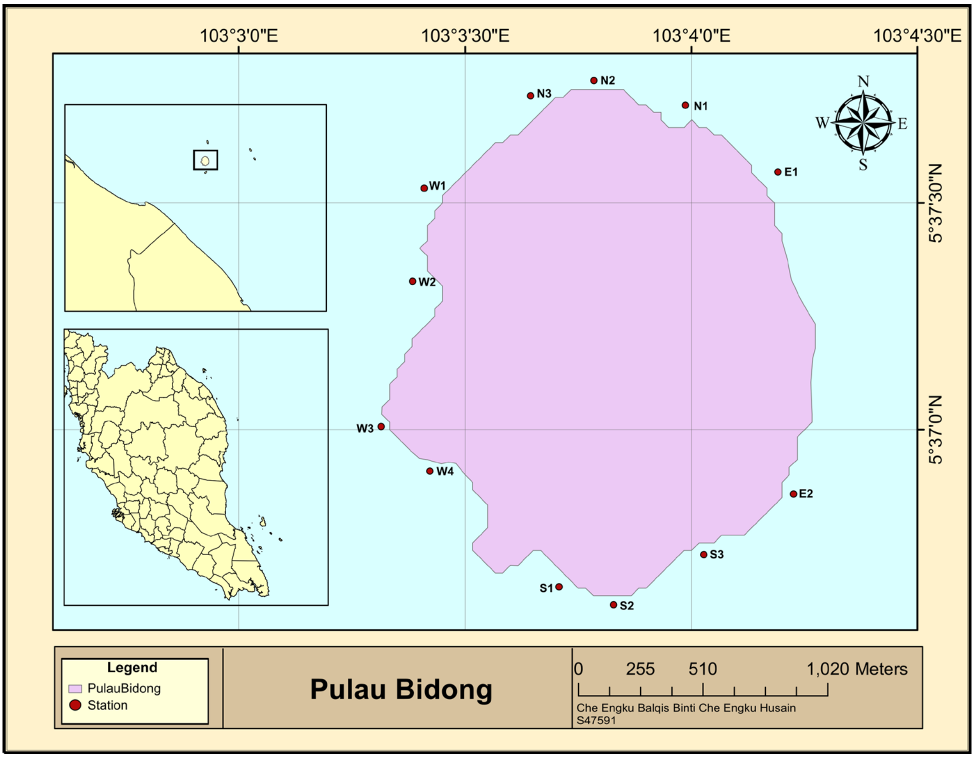

Figure 1: Map of Peninsular Malaysia showing the location of Pulau Bidong off the southern SCS as indicated by the small black box. Locations of sampling stations around the island were indicated by the small red circles in the enlarged map of Pulau Bidong

Data analysis

The relative abundance of each genus and frequency distribution at the different depth gradient were calculated using Microsoft Excel for Windows. Diversity indices, such as richness, evenness and diversity, were calculated using PAST 4 for Windows.

Results

Relative abundance

Altogether, there were 10,208 foraminiferal tests that were identified and counted from the 12 stations in Pulau Bidong. This data represented the total assemblages of live and dead foraminifera, which made up the 32 genera inhabiting the coral reefs sediments. Table 1 shows the relative abundance of each genus with *Amphistegina* spp. as the most dominant genus in the study area. More than half of the tests analysed in this study consisted of *Amphistegina* spp. The relative abundance of this genus was 68% with 6947 tests. The tests of *Amphistegina* spp. are hyaline, therefore it marked the dominance of hyaline tests in the reef sediments. Other common genera found in the study area were *Calcarina* spp. (hyaline tests) and *Quinqueloculina* spp. (porcelaneous tests) with a relative abundance value of 6% scored by each genus (Figures 2 and 3). Less common genera included *Peneroplis* spp. and *Triloculina* spp. with 3% relative abundance each. *Heterolepa* spp., *Textularia* spp. and *Elphidium* spp. all recorded 2% relative abundance each. The least common genera found in the area, which recorded a 1% relative abundance, were *Heterostegina, Miliolinella, Operculina, Pyrgo, Ammonia* and *Agglutinella*. There were also many rare genera recorded in the study area, i.e., *Neorotalia, Hauerina, Reusella, Planorbulinella, Sahulia, Pseudotriloculina, Siphonaperta, Pseudohauerina, Spiroloculina, Mikrobelodontos, Cibicides, Rosalina, Bolivina, Nonion, Discorbinella, Ammomassilina, Hanzawaia* and *Eponides*.

Table 1: Relative abundance of foraminiferal genera recorded at 12 sampling stations in Pulau Bidong

Genera/Station	N1	N2	N3	S1	S2	S3	E1	E2	W1	W2	W3	W4	Indv.	Relative Abundance (%)
Amphistegina	813	808	457	223	588	793	945	1062	290	309	292	367	6947	68
Calcarina	118	248	22	10	14	10	42	55	33	9	38	11	610	6
Quinqueloculina	66	43	17	55	7	2	8	42	56	79	87	114	576	6
Peneroplis	74	16	9	32	1	0	2	59	28	64	10	14	309	3
Triloculina	6	8	0	13	0	0	1	1	28	123	21	59	260	3
Heterolepa	5	0	1	24	8	0	3	14	42	91	25	20	233	2
Textularia	31	24	15	0	4	5	2	15	20	54	4	11	185	2
Elphidium	24	25	15	13	0	3	2	38	5	8	24	12	169	2
Heterostegina	29	17	8	3	3	14	10	34	2	0	5	0	125	1
Miliolinella	12	6	2	9	0	0	0	6	8	6	14	19	82	1
Operculina	9	0	2	3	1	0	4	15	1	1	2	41	79	1
Pyrgo	26	9	5	6	0	0	1	13	1	12	3	3	79	1
Ammonia	6	0	0	0	8	0	0	4	25	21	9	2	75	1
Agglutinella	0	6	3	0	1	0	0	1	17	23	0	4	55	1
Neorotalia	1	2	1	3	10	1	1	7	10	0	4	10	50	0
Hauerina	21	0	2	4	0	0	2	4	1	4	11	0	49	0
Reusella	0	0	0	1	0	0	0	0	3	18	16	6	44	0
Planorbulinella	0	0	7	1	0	0	0	5	8	5	12	0	38	0
Sahulia	4	0	0	0	1	0	0	9	2	5	0	9	30	0
Pseudotriloculina	0	0	0	0	0	0	0	0	1	3	0	23	27	0
Siphonaperta	0	1	0	2	0	0	0	8	1	15	0	0	27	0
Pseudohauerina	11	3	1	1	1	0	0	3	0	0	3	1	24	0
Spiroloculina	6	1	0	2	0	0	1	8	0	4	0	0	22	0
Mikrobelodontos	2	6	0	1	0	0	0	5	1	1	0	5	21	0
Cibicides	0	0	0	0	0	0	0	0	2	16	1	0	19	0
Rosalina	1	0	1	0	0	0	0	0	6	7	0	1	16	0
Bolivina	1	0	1	1	0	0	0	0	6	5	0	1	15	0
Nonion	0	0	0	4	0	0	0	0	0	0	0	7	11	0
Discorbinella	4	1	0	1	0	0	0	0	0	0	2	1	9	0
Ammomassilina	0	0	0	1	0	0	0	7	0	0	0	0	8	0
Hanzawaia	4	0	1	0	0	0	0	0	0	2	1	0	8	0
Eponides	1	2	1	0	0	0	0	0	1	0	0	1	6	0

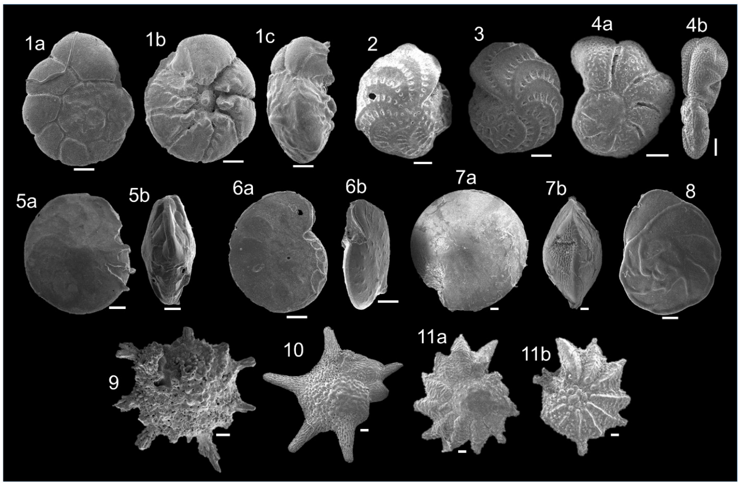

Figure 2: Scanning electron microscope images of selected foraminiferal species (Order Rotaliida) from Pulau Bidong. Scale bars = 100 µm. **1** *Ammonia parkinsoniana* a) dorsal b) ventral c) lateral; **2** *Elphidium fichtelianum*; **3** *Elphidium* sp.; **4** *Cibicides* sp. a) dorsal b) lateral; **5** *Heterostegina depressa* a) dorsal b) lateral; **6** *Operculina ammonoides* a) dorsal b) lateral; **7** *Amphistegina lessonii* a) dorsal b) lateral; **8** *Eponides repandus*; **9** *Calcarina hispida*; **10** *Calcarina mayori*; **11** *Neorotalia calcar* a) dorsal b) ventral

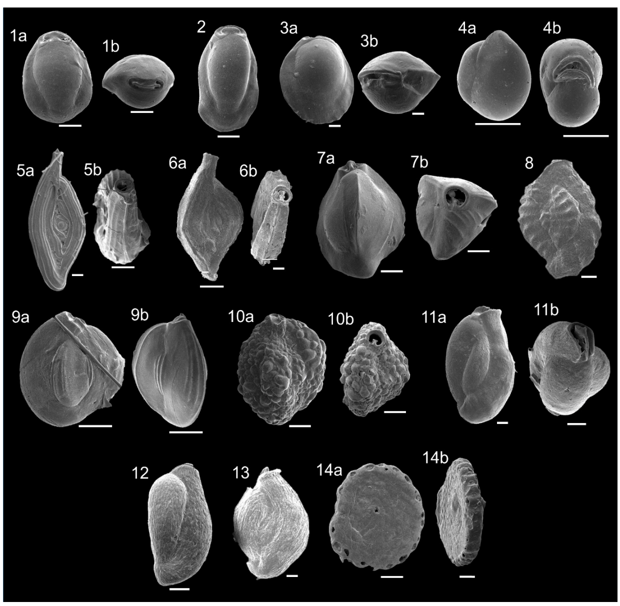

Figure 3: Scanning electron microscope images of selected foraminiferal species (Order Miliolida) from the Pulau Bidong. Scale bars = 100 µm. **1** *Pyrgo williamsoni* a) dorsal b) aperture; **2** *Pyrgo compressioblonga*; **3** *Pyrgo denticulata* a) dorsal b) aperture; **4** *Miliolinella circularis* a) dorsal b) aperture; **5** *Spiroloculina* cf. *S. corrugata* a) dorsal b) aperture; **6** *Spiroloculina* cf. *S. manifesta* a) dorsal b) aperture; **7** *Triloculina tricarinata* a) dorsal b) aperture; **8** *Quinqueloculina parkeri*; **9** *Quinqueloculina* cf. *Q. bicarinata* a) dorsal b) ventral; **10** *Agglutinella agglutinans* a) dorsal b) aperture; **11** *Triloculina* sp. 1 a) dorsal b) aperture; **12** *Quinqueloculina* sp. 1; **13** *Quinqueloculina* sp. 2**;** **14** *Sorites orbiculus* a) dorsal b) lateral

Frequency distribution

The frequency distribution of the common genera showed the depth distribution of the foraminifera (Figure 4). Samples were collected from the shallowest area at a depth of about 5 m until the deepest area at a depth of 30 m. The most dominant genus *Amphistegina* spp. was distributed between depths of 10-15 m and 25-30 m, and their tests were not found at depths of 5 m and 20 m. The test shape of *Amphistegina* spp. could not withstand the high energy wave dissipating zone of the shallowest water region. The rest of the common genera, i.e., *Calcarina* spp., *Heterolepa* spp., *Peneroplis* spp., *Quinqueloculina* spp., *Triloculina* spp., *Textularia* spp. and *Elphidium* spp., had their highest frequency distributions at the shallowest depth of 5 m, showing that these genera are able to withstand the high energy wave dissipating zone of the shallowest water region. The distribution of *Heterolepa* spp., *Triloculina* spp., *Textularia* spp. and *Elphidium* spp. in the study area was confined only at the shallowest water region, while at the deeper area their tests became extremely rare. Even though the highest frequency distributions of *Calcarina* spp., *Peneroplis* spp. and *Quinqueloculina* spp. were recorded at the shallowest water depth, their tests were still present at deeper water columns at depths of between 10m and 30m.

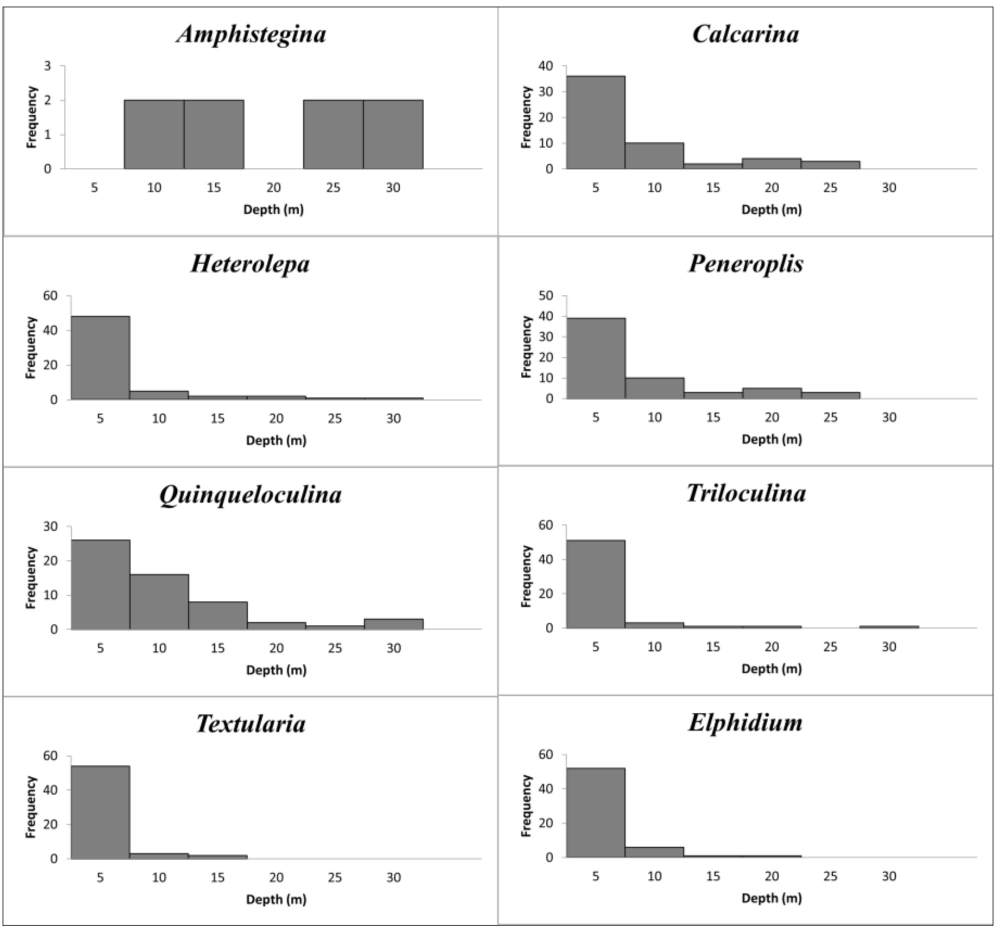

Figure 4: The frequency distribution of common benthic foraminiferal genera in Pulau Bidong. The depth distribution of *Amphistegina* spp., *Calcarina* spp., *Heterolepa* spp., *Peneroplis* spp., *Quinqueloculina* spp., *Triloculina* spp., *Textularia* spp. and *Elphidium* spp. at depths of between 5 m and 30 m

Diversity

The diversity of the benthic foraminiferal community was analysed in the PAST statistical software version 4 for Windows and is presented in Table 2. The highest number of taxa was recorded at station W1, which was in the western part of the island (Table 2), with 26 genera. The lowest number of taxa was recorded at station S3, which was located at the southern part of the island, with only seven genera. Only three stations were consistently showing low numbers of taxa, S2 and S3 in the south and E1 in the east, which directly faced the open sea. The highest number of foraminiferal individuals were recorded at station E2 with 1415 tests and the lowest at station S1 with 413 tests. The stations that consistently recorded the highest number of tests (> 1000 tests) were N1 and N2 at the northern part of the island and E1 and E2 at the eastern part of the island. Those stations directly faced the open sea. Margalef's Richness Index (S) was the lowest at station S3 (0.9) and the highest at station W1 (3.9), which coincided with the lowest and highest number of taxa, 7 and 26, respectively. Shannon's Diversity Index (H) was the lowest at station S3 (0.2), which confirmed the lowest number of taxa and value of S. The highest H value was recorded at station W2 (2.3) and not W1 (2.0), even though station W1 showed the highest number of taxa and S value, but station W2 recorded more foraminiferal tests than station W1. However, Fisher's Alpha Diversity Index (a) showed the highest value at station W1 (5.5), unlike the highest H value at station W2 because station W1 recorded more taxa than station W2. Pielou's Evenness Index (J) was the lowest at station S3 (0.1) and highest at station W2 (0.7), thus confirming that the lowest number of taxa at station S3 represented a high test abundance, while at station W2 a high number of taxa clearly represented a similar high abundance of tests.

Table 2: Diversity indices representing the structure of the benthic foraminiferal community in the surface sediments of coral reefs in Pulau Bidong. Indices of Margalef's Richness (S), Shannon's Diversity (H), Pielou's Evenness (J) and Fisher's Alpha (a)

Stn.	Taxa	Individuals	Margalef's Richness (S)	Shannon's Diversity (H)	Pielou's Evenness (J)	Fisher's Alpha (a)
N1	24	1275	3.2	1.5	0.5	4.2
N2	18	1226	2.4	1.2	0.4	3.0
N3	20	571	3.0	1.0	0.3	4.0
S1	23	413	3.7	1.8	0.6	5.3
S2	13	647	1.9	0.5	0.2	2.3
S3	7	828	0.9	0.2	0.1	1.0
E1	14	1024	1.9	0.4	0.2	2.3
E2	23	1415	3.0	1.2	0.4	3.9
W1	26	598	3.9	2.0	0.6	5.5
W2	25	885	3.5	2.3	0.7	4.8
W3	21	584	3.1	1.9	0.6	4.3
W4	24	742	3.5	1.9	0.6	4.7

Discussion

The results indicated that there were 32 genera of benthic foraminifera inhabiting the reef sediments of Pulau Bidong. Benthic foraminifera has been proven as excellent environmental indicators (Hallock *et al.* 2003), thus indicating that the data from this study can also be used to investigate the health status of coral reefs in Pulau Bidong. A'ziz *et al.* (2020) and Natsir and Subkhan (2011) investigated tropical reef foraminifera in Malaysia and Indonesia, respectively. They found that reef foraminifera can be used as bioindicators of the health of tropical coral reefs.

Amphistegina spp. was the most dominant genus, where it was found in almost every station in Pulau Bidong. During an investigation of benthic foraminifera in the coral reefs of Sesoko Island, Okinawa, Japan, it was found out that this genus was also dominant (Hohenegger, 1994). There were about five species of *Amphistegina* spp., i.e., *A. lobifera, A. lessonii, A. bicirculata, A. radiata* and *A. papillosa*. The foraminifera of this genus are diversified in terms of test size, but the shape is similar, which is lenticular. *Amphistegina* spp. is among the most abundant genus in warm tropical seas with epifaunal life positions. *Amphistegina* spp. hosts diatom endosymbionts, showing similar characteristics to zooxhanthellate corals, thus making it as an excellent reef health indicator (Ross & Hallock, 2019). The test abundance of *Amphistegina* spp. in the reef sediments also marked the dominance of hyaline tests in the coral reefs. Hyaline foraminifera have shown dominance in the sediments of coral reefs, as shown by Chang and Yoon (1995) and Hohenegger (1994).

The highest species richness was recorded in the western part of the island at station W1. The east stations (E1 and E2) and north stations (N1 and N2) of *Pulau Bidong* showed high foraminiferal abundance, while the southern part of the island (S3 and S1) recorded the lowest species richness and foraminiferal abundance. Species richness and abundance of benthic foraminifera in a tropical island setting may have been influenced by sediment transport (Hohenegger & Yordanova, 2001). The topography of the coral reefs is determined by the downslope transport of sediments with two main interplaying factors influencing the rate of transport, i.e., hydrodynamics and slope inclination (Hohenegger & Yordanova, 2001). Sediment transport, which is caused by tidal or wind-induced currents in fair-weather conditions, is confined in the shallow slope of coral reefs. Sediment grains in coral reefs are composed of carbonate skeletons produced by stony corals, coralline and green algae, bryozoans, molluscs and larger foraminifera; with larger foraminifera as one the primary carbonate producers (Hohenegger, 2006; Langer, 2008). The hydrodynamics condition of the island is influenced by the physical properties and dynamics of the SCS. There are two monsoon seasons influencing the hydrodynamics of the SCS; the northeast monsoon (November to March) and southwest monsoon (April to August). Wind and tides are the two major factors controlling the speed of the currents in *Pulau Bidong* (Daud & Akhir, 2015), thus suggesting that wind and tidal-induced currents around Pulau Bidong are the major cause of foraminiferal test displacement in the sampling stations.

The frequency distribution of the most common genera showed that the distribution along the depth gradient of *Pulau Bidong* was composed of three LBF genera, *Amphistegina* spp., *Calcarina* spp. and *Peneroplis* spp., while the rest were all smaller benthic foraminiferal genera (SBF). *Amphistegina* spp. was able to occupy the shallow and deep euphotic zones (Hohenegger *et al.,* 1999). The distribution of *Calcarina* spp. was confined in the shallow water regions, confirming that this genus was restricted in the shallow zone. *Peneroplis* spp. are able to tolerate a wide range of water column, from shallow to deep euphotic zones. The depth distribution of LBF taxa is influenced by hydrodynamics and illumination (Hohenegger, 1994). The downslope transport of the tests will also influence the depth distribution of these LBF taxa (Hohenegger & Yordanova, 2001). The *Amphistegina* spp. found by Hohenegger (1994) includes *A. lessonii, A. bicirculata, A. radiata, A. lobifera* and *A. papillosa*. The distribution of *A. lessonii* was restricted in the upper fore reef zone, with optimal distribution of living individuals at 20 m with a lower limit of 70 m, which could be influenced by the low buoyancies of the thick-lenticular test shape (Hallock, 1984; Hohenegger, 1994; Hohenegger *et al.,* 1999). The upper limit of the depth distribution of living *A. bicirculata* was located at a depth of 30 m and the lower limit was below 100 m (Hohenegger, 1994), which might be related to the high buoyancies of the thin-lenticular test shape. *Calcarina* spp. attained its niche optimum in the shallow euphotic zone due to the low test buoyancies (Hohenegger, 2006).

The rest of the SBF taxa were showing depth distribution in the shallow and deeper euphotic zones of the study area in *Pulau Bidong*, e.g., *Heterolepa* spp., *Triloculina* spp., *Textularia* spp. and *Elphidium* spp. These genera were mostly distributed in the shallowest water region, while in the deeper areas, their tests became extremely rare. *Quinqueloculina* spp. are able to tolerate a wide depth distribution range, from shallow until deeper euphotic zones, similar to *Peneroplis* spp. Factors influencing the depth distribution of SBF taxa could be related to sediment type, availability of organic matter as a source of food and test buoyancies (Saelan & Hohenegger, 2018). Benthic foraminifera are ubiquitous, therefore its distribution is not confined to a specific environment. Benthic foraminiferal distribution is influenced by a variety of chemical and physical factors, with depth being the composite factor (Hohenegger, *et al.,* 1999).

The distribution of modern benthic foraminiferal species is significant to paleoecological analysis. Environmental factors, or also called as gradients, could not be directly measured in paleoecological studies, but can be estimated based on species proportion in the modern environment using the transfer function technique (Hohenegger, 1995). Paleoclimatic reconstruction was mainly conducted using planktonic foraminifera, where temperature is the gradient that was being measured. Benthic foraminifera were used to reconstruct paleoecological analysis with water depth acting as the main gradient, which is related to seafloor topography, illumination intensity, water energy and hydrostatic pressure.

Conclusion

Foraminiferal assemblages in the coral reefs of *Pulau Bidong* were dominated by *Amphistegina* spp., distributed at depths of between 10-15 m and 25-30 m, and their tests were not found at depths of 5 m and 20 m. The Test shape of *Amphistegina* spp. could not withstand the high energy wave dissipating zone of the shallowest water region, therefore the tests were not found at a depth of 5 m. *Calcarina* spp., *Heterolepa* spp., *Peneroplis* spp., *Quinqueloculina* spp., *Triloculina* spp., *Textularia* spp. and *Elphidium* spp. had the highest frequency distribution at the shallowest depth of 5 m, indicating that these species can tolerate a high energy wave dissipating zone. This study will provide the data needed in the assessment of the health of coral reefs, as well as establishing paleodepth for biostratigraphy and paleoenvironmental reconstruction of southern South China Sea.

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