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Abstract

The Great Australian Bight is a large carbonate cold water environment located on the central and western portions of the southern Australia. Seagrasses (Posidonia sp.) and macroalgae benthic habitats are widely distributed in the shallow water environment of southern Australia, contributing to the carbonate factory. This study investigated the distribution of modern benthic foraminiferal assemblages in the microtidal wave-dominated inner-shelf of Esperance Bay (southwestern Australia), that lies on the western margin of the Great Australian Bight. Benthic foraminifera were taxonomically identified and biotic parameters (species richness, density, Fisher-α index, Shannon-Weaver index, dominance) were calculated. Multivariate analyses (Hierarchical Cluster Analysis, Principal Component Analysis) were performed to understand foraminiferal distribution in the context of environmental conditions. Four main foraminiferal assemblages have been recognized: (I) a nearshore assemblage of dense seagrass meadow, dominated by Lamellodiscorbis dimidiatus, Elphidium craticulatum, Elphidium crispum, Cibicides lobatulus, II) a second assemblage associated with unvegetated seabed (approximately 30 m depth) with Lamellodiscorbis dimidiatus, Elphidium crispum, Quinqueloculina disparilis, III) a third assemblage in the central sector of the bay, characterized by a discontinuous and mixed seagrass-algae coverage with Lamellodiscorbis dimidiatus, Elphidium crispum, Elphidium macellum, Cibicides refulgens, and Quinqueloculina poeyana, and IV) an epiphytic assemblage of transitional zone from the coastline to the upper limit of a mixed seagrass-algae meadow, dominated by Elphidium crispum, Chrysalidinella dimorpha, Planulinoides biconcava, Planoglabratella opercularis, Rugobolivinella elegans. The spatial distribution of the four assemblages appears closely related to sediment texture, seagrass cover and depth, but it is also influenced by the shoreface morphology and the hydrodynamic energy. The understanding of the ecological parameters that influence benthic foraminiferal distribution, composition and assemblage structure within seagrass meadows is useful for paleoecological and paleoenvironmental interpretations.

Keywords	benthic foraminifera; seagrass; epiphytes; coastal zone; south-western Australia.

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Highlights:

- Distribution of benthic foraminifera in a shallow environment was investigated
- Epiphytic foraminifera dominated the assemblages
- Four foraminiferal biotopes were recognized
- *Lamellodiscorbis dimidiatus* was the most abundant species

Foraminiferal biotopes in a shallow continental shelf environment: Esperance Bay (southwestern Australia)

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The Great Australian Bight is a large carbonate cold water environment located on the central and western portions of the southern Australia. Seagrasses (*Posidonia* sp.) and macroalgae benthic habitats are widely distributed in the shallow water environment of southern Australia, contributing to the carbonate factory. This study investigated the distribution of modern benthic foraminiferal assemblages in the microtidal wave-dominated inner-shelf of Esperance Bay (southwestern Australia), that lies on the western margin of the Great Australian Bight.

Benthic foraminifera were taxonomically identified and biotic parameters (species richness, density, Fisher-α index, Shannon-Weaver index, dominance) were calculated. Multivariate analyses (Hierarchical Cluster Analysis, Principal Component Analysis) were performed to understand foraminiferal distribution in the context of environmental conditions. Four main foraminiferal assemblages have been recognized: (I) a nearshore assemblage of dense seagrass meadow, dominated by *Lamellodiscorbis dimidiatus*, *Elphidium craticulatum*, *Elphidium crispum*, *Cibicides lobatulus*, II) a second assemblage associated with unvegetated seabed (approximately 30 m depth) with *Lamellodiscorbis dimidiatus, Elphidium crispum*, *Quinqueloculina disparilis*, III) a third assemblage in the central sector of the bay, characterized by a discontinuous and mixed seagrass-algae coverage with *Lamellodiscorbis dimidiatus*, *Elphidium crispum*, *Elphidium macellum*, *Cibicides refulgens*, and *Quinqueloculina poeyana*, and IV) an epiphytic assemblage of transitional zone from the coastline to the upper limit of a mixed seagrass-algae meadow, dominated by *Elphidium crispum*, *Chrysalidinella dimorpha*, *Planulinoides biconcava*, *Planoglabratella opercularis*, *Rugobolivinella elegans*. The spatial distribution of the four assemblages appears closely related to sediment texture, seagrass cover and depth, but it is also influenced by the

shoreface morphology and the hydrodynamic energy. The understanding of the ecological parameters that influence benthic foraminiferal distribution, composition and assemblage structure within seagrass meadows is useful for paleoecological and paleoenvironmental interpretations.

Keywords: Benthic foraminifera, Seagrass, Epiphytes, Coastal zone, South-western Australia

Introduction

Benthic foraminiferal assemblages are useful as (paleo)ecological proxies for characterization of specific environments in coastal systems (Murray, 2006) because they possess several key characteristics that make them excellent environmental indicators (Scott et al., 2001). In fact, foraminifera constitute the most diverse and widespread group of shelled microorganisms in modern oceans (e.g., Debenay et al., 1996; Murray, 2006), they have relatively short life-cycles and many specimens can be retrieved from a relatively small sediment sample. In addition, benthic foraminifera can indicate both short- and long-term changes in most marine and transitional environments because their life-cycle is related to several parameters such as sediment texture (Buosi et al., 2013a,b; Celia Magno et al., 2012), seabed morphology (Corbí et al., 2016; Schröder-Adams et al., 2008), bathymetry (Avnaim-Katav et al., 2015; García-Sanz et al., 2018), water currents (Buosi et al., 2012; Schönfeld, 2002a,b), seagrass ecosystem (Frezza et al., 2011; Mateu-Vicens et al., 2014; Trabelsi et al., 2018), temperature (Lei et al., 2019; Titelboim et al., 2019), organic content (Armynot du Châtelet et al., 2009; Di Bella et al., 2019; Martins et al., 2015), dissolved oxygen, salinity, light (Charrieau et al., 2018; Lee et al., 2016a; LeKieffre et al., 2017), and pollutants (e.g., Ferraro et al., 2006; Schintu et al., 2016). Reasons for the growing interest in these studies are multiples but are mainly linked to two principal aspects: data on modern distributions allow the interpretation of past environments and provide baseline information for monitoring of future environmental changes, induced by natural or anthropogenic forcing (Quilty and Hosie, 2006).

Benthic foraminiferal studies of the northern Hemisphere are numerous, and they have focused on the distribution and ecology of assemblages in natural and contaminated coastal areas (e.g., Alve and Murray, 1999; Celia Magno et al., 2012; Debenay et al., 2001; Di Bella et al., 2016; Diz and Francés, 2008; Goineau, et al., 2011; Jorissen 1987; Jorissen et al., 1992; Mendes et al., 2004; Milker et al., 2009; Mojtahid et al., 2009; Panieri et al., 2005; Pascual et al., 2008; Salvi et al., 2015; Sgarrella and Moncharmont Zei, 1993). However, the equivalent body of literature for Australia is scarce (Dean and De Deckker, 2013). The clear majority of these studies deals with the distribution of large benthic foraminifera like *Amphistegina* spp. and *Marginopora vertebralis* (e.g., Doo et al., 2017; Lee et al., 2016b; Prazeres et al., 2017) or investigates the importance of large benthic foraminifera to reef sediment budget and dynamics of the Great Barrier Reef (e.g., Dawson et al., 2014; Renema et al., 2013). Despite these studies, the investigations of the benthic foraminifera assemblages and associated physical and biological parameters that influenced their distribution in the nearshore environments of southern Australia are very limited (Cann et al., 1993; Dean and De Deckker, 2013; Li et al., 1996; Nash et al., 2010; Quilty and Hosie, 2006; Schröder-Adams et al., 2014).

In coastal areas characterized by the presence of seagrass or macroalgae communities, foraminiferal assemblages differ significantly from one type of substrate to another (Benedetti and Frezza, 2016; Langer, 1993; Mateu-Vicens et al., 2014). In particular, along the southern Australia coast, *Posidonia* sp. meadow represents the main habitat for many epiphytal foraminifera, including permanent and temporarily attached species. The presence of this seagrass outlines similar benthic habitats between the coastal areas of South Australia and Mediterranean basin, as temperate water carbonate sedimentation dominates the inner shelf at these locations. The similarities are mainly related to analogous processes regulating seagrass distribution and the capacity of meadows to physically retain sediments deposited at shallower depths (Buosi et al., 2017; De Muro et al., 2018; Tecchiato et al., 2016, 2019).

The main objectives of this study were to: 1) identify the foraminiferal biotopes in the nearshore sediments of a microtidal, wave-dominated coastal area of southern Australia (Esperance Bay; Figure 1); 2) assess the influence of depth and sedimentary parameters on the benthic foraminiferal distribution; and 3) determine the effect of seagrass and macroalgae on foraminiferal community.

Regional Setting

Esperance Bay is a ~10 km long southwest facing embayment in the Archipelago Recherche in southwestern Australia (Figure 1), approximately 700 km south-east of Perth. This area lies on the western margin of the Great Australian Bight, the largest carbonate cold water environment in the world (James et al., 2001). Esperance Bay is bordered by two rocky headlands, Dempster Head to the SW and Wylie Head to the E, and sandy barriers. Several small islands are visible in the bay, and represent outcrops of Middle Proterozoic granites, gneisses and migmatites (Ryan et al., 2007) that protrude through mainly flat lying Cenozoic limestones (Cann and Clarke, 1993). Limestone outcrops dominate in <100 m water depth (James et al., 2001).

Human population is concentrated on the western foreshores of the bay in the town of Esperance. Esperance is a growing urban and industrial centre but is also a tourist destination. The local port is located on the South-western side and represents an important exporting hub which is accessed by large bulk carriers through a dredged channel. The Bandy Creek stream in the central sector of the bay supplies sediment from the hills and coastal dunes to the coastline. The eastern sector is characterized by a wide dune system (about 25 km^2).

Esperance bay is a microtidal wave-dominated embayment, exposed to the most extreme wave energy of the entire Australian coastline (Hemer, 2006; Ryan et al., 2007). The seabed is relatively smooth inshore, and slopes at approximately 0.3° towards the southwest (Ryan et al., 2008). As detailed below, carbonate sediments are common in this area and their origin is mostly associated with seagrass meadows (mainly *Posidonia* sp.) and subordinately also by macroalgal communities (Ryan et al., 2007; Tecchiato et al., 2019).

Southwestern Australia is characterised by a semi-arid Mediterranean climate, featuring a mean annual rainfall of 619 mm, 50% of which occurs in the austral winter. This region is influenced by the warm, low salinity and oligotrophic Leeuwin Current (Ryan et al., 2008). The current rounds Cape Leeuwin on the South-West corner of western Australia and then flows eastward. As the current progresses South and then East, the temperature decreases, and the salinity increases due to mixing with local waters (Cresswell and Peterson, 1993). The Leeuwin Current flow results stronger during the winter months (April–September) as a consequence of the seasonal differences in wind stress along the West coast. Sea temperatures range from 21.2 °C in summer to a spring minimum of 16.0 °C (mean 18.9 °C), whereas salinity ranges from 35.2 to 36.0 (Ryan et al., 2008). The warm Leeuwin Current allows the presence of sub-tropical to tropical taxa such as the calcareous alga *Halimeda*, and the benthic foraminifera *Marginopora vertebralis* (Cann and Clarke, 1993).

Previous Studies

The study area was previously investigated by several authors. Tecchiato et al. (2019) investigated the relationships between morpho-sedimentary features and distribution of seagrass meadows through an integrated analysis of geomorphology, sediments and benthic habitat structure. The results demonstrated that seagrass distribution is related to gradients in sediment texture and composition, hydrodynamics and human impact. In fact, according to Tecchiato et al. (2019), dense seagrass meadows occurred in more sheltered regions of the bay, whereas sparser vegetation was found in areas of higher wave energy and artificial activities (like ship anchoring and dredging activities). In addition, carbonate sediment resulted transported onshore from the seagrass meadow supplying the beach system. De Muro et al. (2018) and Tecchiato et al. (2016) characterized the nearshore system using geomorphological, sedimentological and ecological data. These authors reported a similarity between the coastal areas of South-western Australia and South Sardinia (Italy, western Mediterranean Sea), as temperate water carbonate sedimentation dominates the inner shelf at these locations. According to the authors, the seagrass carbonate factory regulates the deposition and the distribution of modern bioclasts in these areas, producing significantly comparable sediment facies.

Previously, the inner shelf of Esperance Bay was examined by Ryan et al. (2007, 2008) in order to better identify the relationships between seabed geomorphology and the distribution of benthic habitats and the processes of carbonate sedimentation and preservation. Based on surficial sediments, video traverses, multibeam sonar data, cores and shallow seismic data, the marine environment of the Recherche Archipelago was divided in several sediment facies, including a shallow, cool-water biogenic carbonate assemblage with a significant warm-water component. Ryan et al. (2008) reported episodic accumulation of a prograding sediment wedge, with substantially thicker deposits located on the lee side of topographic highs such as the islands of the Recerche Arcipelago. According to these authors (Ryan et al., 2008), modern sediment accumulation was largely restricted to the inner and middle shelves, whereas storm events played an important role in the onshore sediment transport, in the reworking of particles and periodic removal of sediment, and in the formation of a mostly bare 'shaved' middle and outer shelf. In addition, Ryan et al. (2007) reported that also the seagrass distribution in Esperance Bay appeared primarily related to wave exposure rather than sediment type, whereas the Rhodolith habitat seemed influenced by exposure to moderate wave energy.

Previous foraminiferal study in the region was carried out by Cann and Clarke (1993) who described shallow-water benthic assemblages from surficial sediments collected along a transect (up to 16 m depth and 90 m from the coastline) adjacent to Woody Island. They found mostly bioclastic carbonates sediments in which the tests of benthic foraminifera were a major constituent. In particular, *Marginopora vertebralis* was abundant in relatively protected areas of algal turf and seagrasses. According to the authors, this abundance at southern latitudes could be attributed to the Leeuwin Current, which brings warm waters from the tropics to southwestern Australia, and then eastwards, past Esperance into the Great Australian Bight. Moreover, the benthic foraminiferal assemblages were dominated by *Nubecularia lucifuga* and *Lamellodiscorbis dimidiatus* (reported as *Discorbis dimidiatus*), with fewer specimens of *Textularia* spp., *Peneroplis planatus*, *Epistomaroides polystomelloides*, *Planorbulina rubra* and *Elphidium crispum* within the grain size fractions 1.00-0.50 mm and 0.50-0.25 mm. However, the detailed structure of foraminiferal distribution (like diversity and abundance) and its relationship to depth, sedimentological parameters and benthic habitat of the Esperance Bay inner shelf remain largely unknown because of lack of comprehensive studies.

Materials and Methods

Thirty-five stations in Esperance Bay were collected using a steel pipe dredge of 10 cm diameter on March 2017 at depths ranging from 3 to 35 m (Figure 1, Table 1). The steel pipe dredge was dragged on the seabed to collect surficial sand, as the compact substrate made sampling with a Van Veen grab difficult. Two subsamples were collected at each site—one for foraminifera and the other for grain-size and carbonate content analyses. The top centimetre of each sample (0–3 cm) was used for the analyses.

Sediments for grain-size analysis were washed with distilled water and air-dried, and subsequently representative bulk samples were isolated using the cone and quartering method. The fine fraction of the sediment (<63 µm) was separated from the sand and gravel fraction through a 63 µm mesh seave (wet seaving). Then, the fraction greater than 63 µm was dry-separated by sieves spaced at ¼ phi (ø) per unit (dry seaving the coarser fraction). Textural classification was calculated following the Folk and Ward (1957) protocols, with median, mean diameter and sorting as descriptive parameters. Dried samples were powdered, and carbonate content was determined using the Dietrich-Fruhling calcimeter in order to better characterize the sedimentological type.

Samples for foraminiferal investigation were preserved in ethyl alcohol and treated with Rose Bengal (Walton, 1952) to distinguish living and dead specimens. In the laboratory, for each sediment sample, a constant volume of approximately 50 cm^3 was washed with water through a 4 □ (63-µm) sieve, dried at 60°C and then weighed. When possible, 300 benthic foraminiferal specimens were selected from each sample and identified following the generic classifications of Loeblich and Tappan (1987) and of other taxonomic works (e.g., Cimerman and Langer, 1991; Debenay, 2012; Hottinger et al., 1993; Yassini and Jones, 1995; WoRMS, 2019).

As the number of living foraminifera was very low (see Appendix 1), the quantitative analysis was carried out on the total assemblage (living+dead). All broken and discolored tests and test fragments were interpreted as transported and not included in the count. Only relatively well-preserved tests were considered to be autochthonous. Our analyses are based on the assumption that the total assemblage represents a timeaverage of its species richness (Debenay et al., 2003, 2006). The dissimilarity between living and dead benthic foraminiferal assemblages in the shallow coastal area of Esperance Bay could be attributed to processes of sedimentary dynamic and the instability of physicochemical parameters that are unfavorable factors for the development of large living foraminiferal communities. The relationship between dead and living assemblages has not been fully understood yet, due to the small number of investigations (Dimiza et al., 2016; Martins et al., 2016, 2018, 2019a).

Foraminiferal species diversity was quantified by Species Richness (S, the number of species in a sample), Foraminiferal Density (FD, the number of specimens per 1 cm^3 of dry sediment), the Shannon-Weaver index or information function (H) ($H = -\Sigma pi \ln pi$, where pi is the proportion (n/N) of specimens of one particular species found (n) divided by the total number of specimens found (N); Shannon and Weaver, 1963), Fisher-α (Fα, extracted from the formula $S = a*\ln(1 + n/a)$ (where S is the number of taxa, n is the number of specimens and a is the Fisher-α) and Dominance (D), calculated using the PAST statistical software (Hammer et al., 2001).

The ecological relationship between foraminifera and phytal substrate was evaluated using the relative abundance of epiphytic foraminifers espressed as E_P index (number of epiphytic/total foraminifers; Mateu-Vicens et al., 2014). In addition, in order to provide an evaluation of the state of meadow, the morphotype classification was used to the aim of calculating the FORAM' (Foraminifera in Reef Assessment and Monitoring) Index (FI') following the formula proposed by Mateu-Vicens et al. (2014). This classification represents a starting point for monitoring of future changes in foraminiferal composition and seagrass ecological status in a coastal area affected by intense urbanization. Consequently, when possible, benthic foraminiferal species were assigned to different morphotypes following the criteria adopted by Langer (1993) and then modified by Mateu-Vicens et al. (2014), based on their shape, structure, and behavior. According to Langer (1993), Morphotype A includes sessile, flat, encrusting taxa with long life spans (about 1 year); Morphotype B comprises temporarily motile species with life spans of 2–5 months; Morphotype C encompasses permanently motile species, and morphotype D represents permanently motile taxa with a short life span. Mateu-Vicens et al. (2014) recognizeda fifth group composed by motile photosymbiotic foraminifera and suggested to assign all the symbiont-bearing species to the new morphotype SB. Consequently, the classification proposed by Mateu-Vicens et al. (2014) includes 5 categories where Morphotypes B and C are the same of Langer (1993), Morphotype A* corresponds to the encrusting and sessile forms of Langer's Morphotype A without symbiont-bearing taxa, Morphotype D* consist of Langer's Morphotype D opportunistic forms without symbiont-bearing species and, Morphotype SB encompasses symbiont-bearing species. The morpothype classification was used to highlight the relationship between foraminiferal distribution and meadow cover.

Multivariate statistical techniques of Q-mode Hierarchical Cluster Analysis (HCA) and Principal Component Analysis (PCA) were performed using the PAST statistical software (Hammer et al., 2001). Only the 35 species more abundant than 3% in at least one sample were considered for the statistical analysis. Species relative abundances were normalized and a logarithmic transformation log(X+1) was performed to reduce the influence of abundant taxa. The HCA was based on Euclidean-distance correlation coefficients in order to measure similarities, whereas on the Ward's linkage method to arrange pairs and groups into hierarchic dendrograms. The PCA was carried out to determine which species were influencing the formation of clusters. Six samples (FS3, FS12, FS13, SS12, SS13 and SS20) were not considered in the statistical analysis due to the low number of benthic foraminiferal specimens therein.

Results

Sediment grain-size and carbonate content

Sandy sediments characterized ~98% of the sampling sites (Table 1). The median (D50) values ranged between -0.03 □ (SS23) and 2.92 □ (FS15) (Table 1). The mean grain size corresponded to fine sand (2.03 □), that was found from the shoreline to ~20 m depth (FS2, FS5, FS8, FS11, FS14, FS15, SS11, SS15, SS18, SS20, SS26), and in the central area of Esperance bay (FS6, FS7, FS13, SS2, SS4, SS9, SS10, SS21 samples). Coarse sand was found in a sample located in the leeward side of Limpet Rock (SS23 in Figure 1) and medium sand was widespread in the bay and represented by the remaining (FS1, FS3, FS10, FS12, SS1, SS5, SS6, SS7, SS12, SS13, SS14, SS16, SS19, SS24, SS25) sediment samples (Table 1). The sediments ranged from very well to very poorly sorted [0.31 (FS5) to 1.57 (SS1)], the mean value was 0.62 (moderately well sorted) indicating that selective transport processes contribute to sediment sorting in <30 m depths (Table 1).

The carbonate content ranged from 0.2% (FS3) to 67.1% (SS6), with a mean value of 25.4% (Table 1). At Esperance, carbonate content decreased moving from onshore (up to 60%) to offshore with 0-15% sediment carbonate content within the meadow between 10 and 30 m depth. At depths greater than 30 m to the maximum investigated depth of 40 m, sediment carbonate content increased again to ~55%.

Benthic Foraminifera

The benthic foraminiferal assemblages in the Esperance Bay included a total of 56 genera and 92 species (Appendix 1). The characteristics of the assemblages varied across the study area (Table 2). Species richness ranged from 2 (SS12) to 39 (FS14), foraminiferal density from 0.06 (FS3) to 1183.33 (SS15) specimens per 1 cm^3, and Fisher-α diversity from 0 (FS3) to 12.43 (FS14). The Shannon-Weaver (H) index had a mean value of 1.70 [min 0.20 (SS12), and max 2.64 (FS14)]. Dominance values ranged from 0.14 (FS14) to 0.90 (SS12).

Agglutinated foraminifera were poorly present, except in samples SS23 (31.05%), SS14 (17.44%), SS5 (14.99%) and FS7 (8.22%). Porcelaneous tests showed the highest percentages (from 20 to 30%) in FS10, SS5, SS6 and SS25, whereas hyaline foraminifera accounted for the larger part (55–99 %) of the remaining samples (Figure 2).

Thirty-five species showed a relative abundance higher than 3% in at least one sample (Table 3), whereas only the frequency of *Cibicides refulgens*, *Elphidium craticulatum*, *Elphidium crispum*, *Elphidium macellum*, *Quinqueloculina disparilis*, *Textularia pseudogramen* and *Lamellodiscorbis dimidiatus* was greater than 10% in at least one sample. The benthic foraminiferal assemblage was dominated by *L. dimidiatus* (12.41–89.04%) and *E. crispum* (0–50.26%), followed by *E. macellum* (0–27.72%), *C. refulgens* (0–17.81%), *T. pseudogramen* (0–30.77%), *E. craticulatum* (0–29.34%), *Q. disparilis* (0–10.34%).

The benthic foraminiferal assemblage included no less than 82% of epiphytic foraminifera, as revealed by the E_P index, ranging from 0.82 to 1.00 (Table 4). Table 4 reports the categorization of epiphytic morphotypes proposed by Langer (1993) and by Mateu-Vicens et al. (2014). The benthic foraminiferal assemblage of Esperance Bay was mainly dominated by morphotype B species (temporary motile taxa), followed by morphotype C (motile) and D (permanently motile). There were not significative differences between the Langer's categorization and the new classification proposed by Mateu-Vicens et al. (2014). The permanently attached forms belonging to the morphotype A and A* were poorly represented in all the investigated samples (Table 4). Morphotype B ranged from 20.72 to 91.10% (Table 4). Morphotype C varied between 6.13 and 77.98% and it was mostly represented by keeled elphidiids such as *E. crispum*, *E. macellum* and *E. aculeatum*. The relative abundance of small miliolids belonging to morphotype D and D* ranged from 0.68 and 39%. The symbiont-bearing peneroplids (SB) showed a very low relative abundance (from 0 to 3.33%). The FI' index shows values <2 for the examined sediment samples (Table 4).

Q-mode cluster analysis

The resulting dendrogram of Q-mode HCA (Figure 3) represents the grouping of samples according to the relative abundance of benthic foraminiferal species. The dendrogram singled out four main clusters (I, II, III and IV) at the phenon line drawn at the Euclidean distance of 4.0.

Cluster I (Figure 3) was comprised of 8 samples and it is found in a depth ranging from 5 to 30 m. The sediment was constituted of medium sand (95.48%, Mz 1.67 □ on average) with a low percentage of gravel 4.34%. The sediment was moderately sorted (0.82 on average; Table 5). Carbonate content ranged from 0.4% to 66.2% (17.3% on average), with four samples (FS6, FS7, SS16, SS19*)* showing a carbonate content <10%. *Lamellodiscorbis dimidiatus* was the most frequent species with the variable percentages between 27.63% and 89.04%. *Elphidium crispum* (0–24.14%), *T. pseudogramen* (0–30.77%), *C. refulgens* (0–17.81%) and *E. macellum* (0–12.60%) were other species of this assemblage. *Elphidium craticulatum* showed a high percentage (29.34%) only in a sample (SS23). Species Richness ranged from 5 to 24, Shannon-Weaver index from 0.45 to 2.10, Fisher-α index between 1.00 and 6.02 (the average value was 3.63), whereas the dominance showed values between 0.20 and 0.80 (on the average 0.49; Table 5). The foraminiferal density varied between 1.46 and 212.67 specimens/1 cm^3 of dry sediment (mean 65.78). The analysis of morphotypes revealed a dominance of the B type (27.63–91.10%, mean 73.35%) followed by groups C (6.13–29.34%, mean 13.41%) and D (0.68–34.47%, mean 9.69%). The morphotypes SB, A* and A were very rare (<4%).

Cluster II (Figure 3) was found between 30 and 35 m water depth and comprised of 3 samples. Medium sand or slightly gravelly medium sand characterised the sediment cover (Mz 1.24 □ on average). The sediment was moderately well sorted (0.57 on average). The average value of carbonate content was 49.07% (from 28.00% to 67.10%; Table 5). Lithoclasts (sedimentary clasts composed of pre-existing rock types) were abundant in two samples (SS5 and SS6). *Lamellodiscorbis dimidiatus* (40.33–43.50%), *E. crispum* (12.81–16.71%), *Q. disparilis* (0.28–10.34%), *T. pseudogramen* (0–7.56%), *Triloculina trigonula* (0.80–7.27%), *Rosalina australis* (1.91–6.10%) and *Textularia truncata* (1.59–5.18%) were the most abundant species (Table 5). Species Richness ranged from 22 to 30, H index from 1.99 to 2.24, F-α index values between 5.10 and 7.73 (the average value is 6.34), whereas dominance showed values between 0.20 and 0.24. The foraminiferal density varied between

10.49 and 38.22 specimens/1 cm^3 of dry sediment (mean 26.71). The morphotype B (temporary motile species) characterized this cluster, ranging from 20.80 to 53.58%. The permanently-attached forms of morphotype A were infrequent (0–4.74%, mean 1.58%), whereas groups D (17.15–38.96%, mean 27.63%) and C (12.81–41.61%, mean 23.80%) were common. The permanently attached forms A* was absent and SB ranged from 0 to 1.09% (mean 0.36%).

Cluster III (Figure 3) groups 8 samples, between 5 and 34 m water depth. Sediments were generally composed of fine sand (Mz 2.12 □ on average), but medium sand content was relevant in some sampling stations (FS10, SS1, SS25). The sediment was moderately well sorted, whereas the average value of carbonate content was 17.71%, with four samples characterized by a percentage <10%. *Elphidium crispum* was the most frequent species with the variable percentages between 16.04% and 50.26%, followed by *L. dimidiatus* (17.36–38.56%), *E. macellum* (2.78–27.72%), *C. refulgens* (0–14.75%), *Bolivina pseudoplicata* (0–9.43%), *Neoconorbina terquemi* (0–8.68%), *Quinqueloculina poeyana* (0–7.84%), *Q. seminula* (0–7.55%) and *Miliolinella subrotunda* (0–6.94%; Table 5). The Species Richness values (Fig. 3A) ranged between 9 and 29 (mean, 19.38), whereas the H was relatively high (1.22–2.35), with an average value of 1.93. The F-α index ranged from 1.65 to 8.04 (5.19 on average) and dominance from 0.16 to 0.36 (Table 5). The FD did not show very elevated values, ranging between 1.65 and 142.96 specimens/1 cm^3 of dry sediment (mean 60.00; Table 5). The morphotype analysis revealed the prevalence of temporary motile forms of morphotype B (20.72–55.48%, mean 43.59%), followed by morphotypes C (22.22–77.98%, mean 38.82%) and D (1.04–30.72%, mean 13.49%). The permanently-attached forms (A) were rare (0–3.43%, mean 0.59%). The difference of this cluster with respect to II is mainly related to the lower value of the relative abundance of the morphotype D linking to a relative decreasing in smaller porcelaneous species.

Cluster IV (Figure 3) includes 10 samples located in the shoreface from the coastline to -5 m, except for SS2 collected at 31 m depth (Table 5). The sediment was constituted of well sorted, fine sand (99.90%, Mz 2.56 □ on average). Carbonate content ranged from 29.2% to 58.1% (44.73% on average). *Lamellodiscorbis dimidiatus* was the most frequent species with the variable percentages between 12.41% and 46.31%. *Elphidium crispum* (22.76–40.84%), *C. refulgens* (0–9.12%), *Chrysalidinella dimorpha* (0–7.51%), *M. subrotunda* (1.04–6.76%), *E. macellum* (0–6.57%) and *Rugobolivinella elegans* (0–6.57%; Table 5) were other species of this assemblage. Species Richness ranged from 16 to 39, H from 1.63 to 2.64, Fisher-α index values between 3.45 and 12.43 (the average value was 6.90), whereas the dominance showed values between 0.14 and 0.31. The foraminiferal density varied between 67.00 and 1183.33 specimens/1 cm^3 of dry sediment (mean 420.72; Table 5). The analysis of morphotypes revealed a dominance of the B type (20.80–54.26%, mean 40.37%) followed by groups C (26.42–43.66%, mean 34.11%) and D (6.23–17.15%, mean 11.75%). The morphotypes A ranged from 1.14 to 5.37% (mean 2.86%), whereas SB and A* were very rare (<3%).

In PCA, 31.6% of the data variance can be explained by the first two principal components (Figure 4A), and 30.7% of it by the first and third principal components (Figure 4B). The eigenvalues of components 1, 2 and 3 were 6.5, 4.5 and 4.2 respectively (Figure 4C). The percentages of *C. dimorpha*, *Planulinoides biconcava*, *R. elegans*, *Planoglabratella opercularis* and *T. pseudogramen* were the predominant elements in the first component, while the major contributions in the second component were from *M. subrotunda*, *T. truncata*, *Triloculina striatogonula*, and *Siphonaperta dilatata.* In the third component the predominant elements were *E. aculeatum*, *B. pseudoplicata*, *Q. seminula*, *Miliolinella elongata* and *Cibicidoides pachyderma*.

PCA analysis placed the stations in approximately the same groups as obtained with Q-mode cluster analysis. Accordingly, those sites on the right part of the diagram (component 1 vs component 2; Figure 4A), belonging to Cluster IV and III (except FS10, SS9, SS21, SS25; Figure 4A) can be assumed to contain sediment with high values of *P. biconcava*, *C. dimorpha*, *R. elegans*, *E. crispum* whereas those on the left part (Cluster II and two samples of Cluster III) are characterized by high relative abundance of *T. pseudogramen, Agglutinella arenata*, *S. dilatata* and *T. truncata* (Figure 4A), whereas samples of Cluster I appear characterized by higher percentages of *L. dimidiatus*, *E. craticulatum* and *Cibicidoides lobatulus* (Figure 4A).

PCA analysis (component 1 vs component 3; Figure 4B) grouped the sampling sites (Cluster IV and III) with high percentages *P. biconcava*, *C. dimorpha*, *R. elegans*, *P. opercularis* and *E. crispum* at right on the diagram, while the stations with high values of *T. pseudogramen*, *A. arenata*, *T. truncata* and *Q. disparilis* (samples of Cluster I and II; Figure 4B) are at the bottom left. The samples that contained important relative abundance of *E. aculeatum*, *B. pseudoplicata*, *Q. seminula*, *M. elongata* (SS21, SS25, FS7, FS10) are at the upper-central part (Figure 4B).

Discussion

Benthic foraminiferal assemblages represent a prominent component in the benthic community of Esperance Bay. Our results show a strong correlation between the phytal substrate and the benthic foraminifera structure and distribution, in fact, at Esperance Bay, benthic foraminiferal assemblage includes no less than 82% of epiphytic foraminifera.

The Q-mode HCA indicates a zonation of the Esperance Bay into four clusters corresponding to four foraminiferal assemblages that can be interpreted as biotopes reflecting different ecological conditions of the seabed (Scott et al., 2001). These biotopes indicate a transitional zone from the coastline to the upper limit of a mixed seagrass-algae meadow and sediment cover (Cluster IV), a nearshore environment with a continuous seagrass meadow (Cluster I), a central sector characterized by a discontinuous and mixed seagrass-algae coverage (Cluster III) and by unvegetated seabed at approximately 30 m depth (Cluster II). Figure 5 shows the geographic distributions of these four benthic foraminiferal clusters.

<u>Transitional zone from the coastline to the upper limit of the mixed seagrass-algae meadow</u> (Cluster IV: *Elphidium crispum* assemblage - additional common species: *C. dimorpha*, *P. biconcava*, *P. opercularis, R. elegans*, *L. dimidiatus*).

This assemblage dominates the shoreface between the coastline up to 10 m depth. The only exception is SS2 sample located in the central part of the Bay (around 30 m depth), approximately a kilometre West of Limpet Rock, that could be interpreted as a dumping site with the accumulation of dredging disposal ground, regularly undertaken within the harbours of Esperance at West and Bandy Creek in the central part of the Bay (De Muro et al., 2018). The transitional zone is characterized by fine sediments with a discrete amount of carbonate content and a mixed seagrass meadow. In this mixed siliciclastic-carbonatic sediment, high foraminiferal density (FD>300 specimens per 1 cm^3 of dry sediment) was mainly recorded in the shoreface zone from the coastline to 10 m depth. This area was characterized by the highest values of species richness and other biotic indices. *Elphidium crispum* dominated this assemblage associated to *C. dimorpha*, *P. biconcava*, *P. opercularis, R. elegans*, *L. dimidiatus*. The high relative abundance of *E. crispum* is typical of sandy or sandy-mud infralittoral/circalittoral bottoms, well-oxygenated environment with a vegetation meadow present in areas nearby (Buosi et al., 2012; 2013a; Milker et al., 2009). This species is also well-documented in the Mediterranean basin where lives as epiphytic form within the *Posidonia oceanica* meadow (Frezza et al., 2011; Langer, 1993; Mateu-Vicens et al., 2010). This sector is also characterized by a moderate energy originated by longshore littoral currents and waves. The presence of *C. dimorpha* that was found in the coastal environment of Exmouth Gulf characterized by spring-tide velocities about 0.5 m s^{-1} in deep areas, 1 m s^{-1} on shallow open flats, and several metres per second in tidal channels (Brown, 1988), may substantiate this hypothesis. The other species (*L. dimidiatus, P. biconcava, P. opercularis*) that characterized this environment are very common in the shallow coastal waters of Australia (Collins, 1974) and New Zealand (Hayward, 1982).

<u>Nearshore environment with a continuous seagrass meadow</u> (Cluster I: *Lamellodiscorbis dimidiatus* assemblage - additional common species: *E. craticulatum*, *E. crispum*, *C. lobatulus*, *T. pseudogramen*, *R. australis*)

This biotope includes sampling sites located in the nearshore zone around from 5 to 20 m depth. The only exceptions are samples SS23 located in leeward side of Limpet Rock at about 25 m depth and FS7 that was collected in the central area of the Bay at about 30 m depth. The marine environment was characterized by medium sand and the presence of a continuous seagrass meadow with typical epiphytic foraminifera (*L. dimidiatus, E. crispum*, *C. lobatulus*, *R. australis*). The higher relative percentages of epiphytic species can be attributed to the presence of continuous seagrass beds that provide a sheltered environment with a diversity of nichness in terms of food supply and physical habitats for fixed and mobile foraminifera (Langer, 1993). Furthermore, seagrass rhizomes act as sediment traps and the leaves are often colonized by sessile foraminifera, filamentous algae, bryozoans, hydrozoa, and sponges, and may also be encrusted by coralline red algae (Vénec-Peyré, 1984). *Lamellodiscorbis dimidiatus* was the most abundant species, however the presence of *E. craticulatum* and *T. pseudogramen* reached relevant percentages (around 30%) in the sediment gathered in the leeward side of Limpet Rock. These sectors can be interpreted as the most sheltered areas of the embayment from ocean swell waves, where seagrasses form denser and more continuous meadows. This is indicated by the highest relative abundance of epiphytic encrusting species, symbiontic-bearing taxa and the presence of *E. craticulatum*. Indeed, in literature, this species is reported as mixotrophic, chloroplast-retaining taxa, capable to support highly variable nutrient conditions, hypo-salinity, high-turbidity, low oxygen, low water energy and reduced water circulation, occurring in habitats at the upper limits of symbiont-bearing species (Narayan and Pandolfi, 2010; Palmieri, 1976; Renema, 2008). *Textularia pseudogramen, E.*

crispum, *C. lobatulus* and *R. australis* are cosmopolitan species, typical of tropical/temperate shallow-water (Collins, 1974; Montaggioni and Vénec-Peyré, 1993; Quilty and Hosie, 2006).

<u>Central sector of the Bay with a discontinuous and mixed seagrass-algae coverage </u>(Cluster III: *Lamellodiscorbis dimidiatus-Elphidium crispum* assemblage - additional common species *E. macellum*, *C. refulgens*, *Q. poeyana*, *Q. seminula*)

This biotope includes sampling sites located in the central area of the Bay at around 20 to 35 m depth. Only sample FS15 was collected near to the entrance of Esperance Harbour at about 5 m depth. The seabed is characterized by fine-medium sand and a discontinuous and mixed seagrass meadow. Low populations abundance recognized in this central zone could be mainly related to high sediment mobility and active reworking as also shown by the lower content of carbonate component in these sediments. This sediment is likely transported to the East by the seasonal longshore current (Ryan et al., 2007; Sanderson et al., 2000). According to Tecchiato et al. (2019), this central area is characterized by an alternating of dense seagrass meadow and mixed seagrass, macroalgae and sand benthic habitat associated with anchoring scours that impacted the seabed. These scours may be linked to the boats approaching the Port of Esperance located on the West side of the Bay (Figure 1). The low abundance of benthic foraminifera at these sites corresponds to an area of fragmentation of the seagrass meadow, where unvegetated seabed patches are present. Carbonate sediment constituents (including foraminiferal tests) are transported onshore from the seagrass meadow by ocean currents (Tecchiato et al., 2019). This environment showed a benthic foraminiferal assemblage very similar to the transitional zone from the coastline to the meadow's upper limit (Cluster IV), from which it differed by the increased relative abundance of *E. macellum*, *C. refulgens* and *Quinqueloculina* spp. (*Q. poeyana*, *Q. seminula*) and a lesser abundance of *R. elegans*. Among these species, *Q. seminula* was reported from a wide range of natural and anthropized environments, such as Mediterranean lagoons, marshes and coastal areas (Buosi et al., 2013b; Frezza and Carboni, 2009; Sgarrella and Moncharmont Zei, 1993) and inner-shelf zones of Australia and New Zealand (Hayward et al., 1999; Narayan and Pandolfi, 2010; Quilty and Hosie, 2006). This species exhibits a potentially opportunistic behaviour and it is considered capable of surviving the early stages of anoxia, but sensitive to prolonged anoxia in combination with sulphides (Langlet et al., 2014). *Quinqueloculina seminula* also occurred in moderately sheltered shallow coastal areas located in bays and inside harbour entrances (Hayward et al., 1999). According to Martins et al. (2019b), *Q. seminula* can survive in environments with unstable substrate. *Cibicides refulgens, Q. poeyana* and *E. macellum* are dominant in shallow sites marine environments. In particular, *E. macellum* is a major component of shallow (0–20 m) normal marine benthic communities around the Australian coasts, often in association with *Quinqueloculina*, *Spiroculina*, *Triloculina*, *Discorbis* and other species of Elphidiidae (Cann et al., 1988; Hayward et al., 1997). This benthic foraminiferal assemblage was similar to that found in the "Harbour Biotope" of Twofold Bay (Eden, SE Australia; Dean and De Deckker, 2013). Considering the proximity of this area to the entrance of Esperance Harbour, and to hypothesize for this environment that the maritime traffic could have several impacts. In fact, boats approaching to the port could cause turbidity, pollution and toxicity with the consequently development of a discontinuous mixed seagrass-algae meadow. The seabed in this zone is also affected by evident anchoring scours, as reported by Tecchiato et al. (2019). These environmental perturbations seem to affect the benthic foraminiferal assemblage with the presence of potentially opportunistic species (like *Q. seminula*, *E. macellum*).

Unvegetated seabed in the central area of the Bay (Cluster II: *Lamellodiscorbis dimidiatus-Elphidium crispum-Quinqueloculina disparilis* assemblage - additional common species *T. pseudogramen, T. trigonula*, *R. australis, T. truncata* and *A. arenata*)

This assemblage was recognized in the unvegetated portion of seabed located in the central area of the Bay, at around 30-35 m depth. The sediment was composed of medium sand with high percentage of carbonates. The benthic foraminifera assemblage was dominated by *L. dimidiatus* and *E. crispum* associated with an increasingly abundance of *Q. disparilis* and agglutinated-wall foraminifera *(T. pseudogramen, T. truncata* and *A. arenata*). According to Ryan et al. (2008), this sector is characterized by a great availability of sandy sediments and corresponds to the "bare sand" facies. This mostly planar benthic habitat occurs throughout the inner bay and on the lee side of islands and appears linked to moderate-low wave exposure. The increasingly abundance of agglutinated-wall foraminifera *(T. pseudogramen, T. truncata* and *A. arenata*) could be related to the higher availability of sandy sediments. In fact, for agglutinated species, the sediment is not only a habitat but also a source of material for test building (Armynot du Châtelet et al., 2013). For example, Buosi et al. (2012) observed an increase of the proportion of agglutinated foraminifera in sandy sediment of the Strait of Bonifacio (between Sardinia and Corsica, Mediterranean Sea), where infaunal species (like the genus *Textularia*), provided to thick test, are enables them to live in coarser surface sediment, heavily influenced by hydrodynamics. Moreover, in the Marmara Sea, sand favours the settlement of agglutinated species, whereas silt sediment is important for shell development (Armynot du Châtelet et al., 2013). The Cluster II assemblage appeared consistent with that observed in the shallow environment along a transect adjacent to Woody Island (Cann and Clarke, 1993), where sediments were dominated by *L. dimidiatus* (reported as *D. dimidiatus*) and *N. lucifuga*, associated with other common species: *Textularia* spp., *P. planatus, Planorbulina* spp. and *E. crispum*. According to Cann and Clarke (1993), the highest abundance of *N. lucifuga* can be attributed to wave sorting. In fact, this species has denser and thicker test with heavier walls and chambers often arrange in a more planar way. Consequently, it tends to accumulate in the lee side of topographic highs, like Woody island. *Marginopora vertebralis* was also observed in a small bay on the northern side of the island, in water depths of 2-20 m relatively protected from the strong wave activity associated with both the summer swell and winter storms of the Southern Ocean (Cann et al., 1993). This species normally prefers a tropical environment and its abundance at Esperance Bay, facing the cool Southern Ocean, can be attributed to the Leeuwin Current (Cann and Clarke, 1993).

Epiphytic Assemblages

The sediment samples of Esperance Bay were characterized by epiphytic foraminifera assemblages as revelead by the E_p index (Table 4). The composition and diversity of these epiphytic communities seemed influenced by the structure of the meadow. At Esperance, Morphotype B foraminifera (temporary attached species) was the most represented group in the bay, followed by

Morphotype C (suspension feeding, motile species) and D (permanent motile, grazing epiphytes). These species have short life cycles and they are able to rapidly increase their abundance when the environmental conditions are favourable (Martins et al., 2018). Permanently attached forms belonging to morphotype A (permanently attached forms), A* (long-living sessile attached forms) and SB (sessile, symbiont bearing) were poorly represented in all the investigated samples. The lower relative abundance of these morphotypes could indicate stressed conditions of the seagrass meadow, in agreement with the FI' values ≤2 (Table 4). Morphotype B was the most abundant in all sectors of the bay, which is explained by the fact that this morphotype mostly consists of *L. dimidiatus*. This species is characteristic of shallow marine environments (water depth of about 20 m) of the Australian coast, where it dominates foraminiferal assemblages (Cann et al., 2002).

The relative abundance of taxa belonging to Morphotype A* (long-living sessile attached forms) was the highest in Cluster I and it appears consistently with the presence of a continuous seagrass meadow in the seabed. Cluster I groups samples collected in the most sheltered areas of the embayment from ocean swell waves, where seagrasses form denser and more continuous meadows. In the other sectors of the bay, the almost total lack of encrusting and symbiont-bearing foraminifera can be related to turbidity and related low-light conditions that often occur in high energy transitional environment located from the coastline to the upper limit of the seagrass meadow (Cluster IV) and in proximity of the entrance of Esperance Harbour (Cluster III). In fact, boats approaching to the port contribute to the development of a discontinuous mixed seagrass-algae meadow causing anchoring scours, turbidity, pollution and the increasing of organic matter content. These perturbations affect the symbiont-bearing foraminifera assemblages and favour the presence of potentially opportunistic species belonging to morphotype D (like miliolids and textularids) and heterotrophic forms B and C that have a relatively short life span and are able to quickly react to environmental changes.

In Cluster II, Morphotype B and D showed similar relative abundances, with non-negligible amount of Morphotype C. Samples belonging to this cluster were collected in the unvegetated portion of seabed with a high sediment content. *Lamellodiscorbis dimidiatus* (morphotype B)*, E. crispum* (morphotype C), *Q. disparilis* and agglutinated-wall foraminifera (morphotype D) were the main foraminiferal species, able to live in an environment characterized by a great availability of sandy sediments. In fact, this is an area of biogenic sediment deposition adjacent to the lower limits of the meadow.

The analysis of epiphytic assemblages and their morphotypes may represent a starting point for monitoring future changes of the seagrass meadow's state and ecological conditions, using the percentages of epiphytic foraminiferal morphotypes, and related sedimentological parameters as indicators of changes. In addition, this study provides useful information for a proper interpretation of the fossil record and for comparing Mediterranean and Australian *Posidonia*-dominated environments. In fact, as recently published, the presence of the seagrass meadow, especially *Posidonia* sp., outlines similar nearshore settings between the coastal areas of South Australia and Mediterranean basin (De Muro et al., 2018; Tecchiato et al., 2016), where *Posidonia* meadow supports abundant benthic biota, including numerous epiphytic organisms (bryozoans, mollusks, and foraminifers) that contribute to the production of carbonate sediments (Pergent et al., 1995). In the Mediterranean basin, this biogenic sediment mainly deposits within the meadow, in the intermattes and in the uncolonized seabed adjacent to the upper and lower limits of the meadow, contributing to increase the carbonate content of these sediments (e.g., De Muro et al., 2008, 2010a,b, 2017a,b; Ruju et al., 2018; Simeone et al., 2008). Further studies are thus required to better outline differences and similarities in the distribution of benthic foraminiferal assemblages in Mediterranean and Australian shallow water environmts characterized by the presence of *Posidonia* meadow.

Conclusions

The microtidal wave-dominated inner-shelf of Esperance Bay shows a diversified benthic foraminiferal fauna, with 92 species identified. High foraminiferal density was mainly recorded in the shoreface zone from the coastline to 10 m depth, whereas low population abundance was recognized in the central zone at about 20-30 m depth. Four foraminiferal assemblages dominated by epiphytes were distinguished by Q-mode HCA. Sediment texture, seagrass coverage, depth and shoreface morphology can be considered the main parameters influencing the distribution of species. The transitional zone from the coastline to the upper limit of the mixed seagrass-algae meadow is characterized by *E. crispum*, *C. dimorpha*, *P. biconcava*, *P. opercularis*, *R. elegans* and *L. dimidiatus* on well sorted, mixed bioclastic-siliciclastic, fine sand. Towards offshore, the benthic foraminiferal assemblage of the continuous seagrass meadow is dominated by *L. dimidiatus*, *E. craticulatum*, *E. crispum*, *C. lobatulus*, and *T. pseudogramen*, on moderately sorted, medium sand. The central sector of the bay that is covered by a discontinuous and mixed seagrass-algae meadow shows a predominance of *L. dimidiatus*, *E. crispum*, *E. macellum*, *C. refulgens*, and *Q. poeyana* on moderately well sorted, fine sand; whereas, the areas characterized by unvegetated seabed at approximately 30 m depth reveal an assemblage dominated by *L. dimidiatus*-*E. crispum*, *Q. disparilis* with additional common species like *T. pseudogramen*, *T. truncata*, *T. trigonula*, and *R. australis* on medium sand and slightly gravelly medium sand.

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Figure Captions

Figure 1 – Study area and location of sampling sites in the Esperance Bay (SW Australia). The coordinate system used was UTM WGS84 Zone50S.

Figure 2 – Ternary diagram of benthic foraminiferal tests composition.

Figure 3 – Dendrogram with imaginary vertical line (phenon line) to define 4 groups (clusters I, II, III, IV) based on Q-mode Hierarchical Cluster (HCA) of the samples from the inner shelf of Esperance Bay, produced using Euclidean distance.

Figure 4 – PCA ordination diagram plotting componenst 1, 2 and 3 of sampling based on the percentage of the most frequent species. A: Component 1 vs Component 2; B: Component 1 vs Component 3; C: eigenvalues of components.

Figure 5 – Geographic distributions of the four benthic foraminiferal clusters according to the HCA of the samples from the inner shelf of Esperance Bay.

Table Captions

Table 1 – Geographic coordinate of sampling station, water depth, sediment classification, grain-size statistics and parameters, and carbonate content. The coordinate system used was UTM WGS84 Zone50S.

Table 2 – Benthic foraminiferal biotic indices.

Table 3 – Relative abundance of the thirty-five species showing a relative abundance higher than 3% in at least one sample.

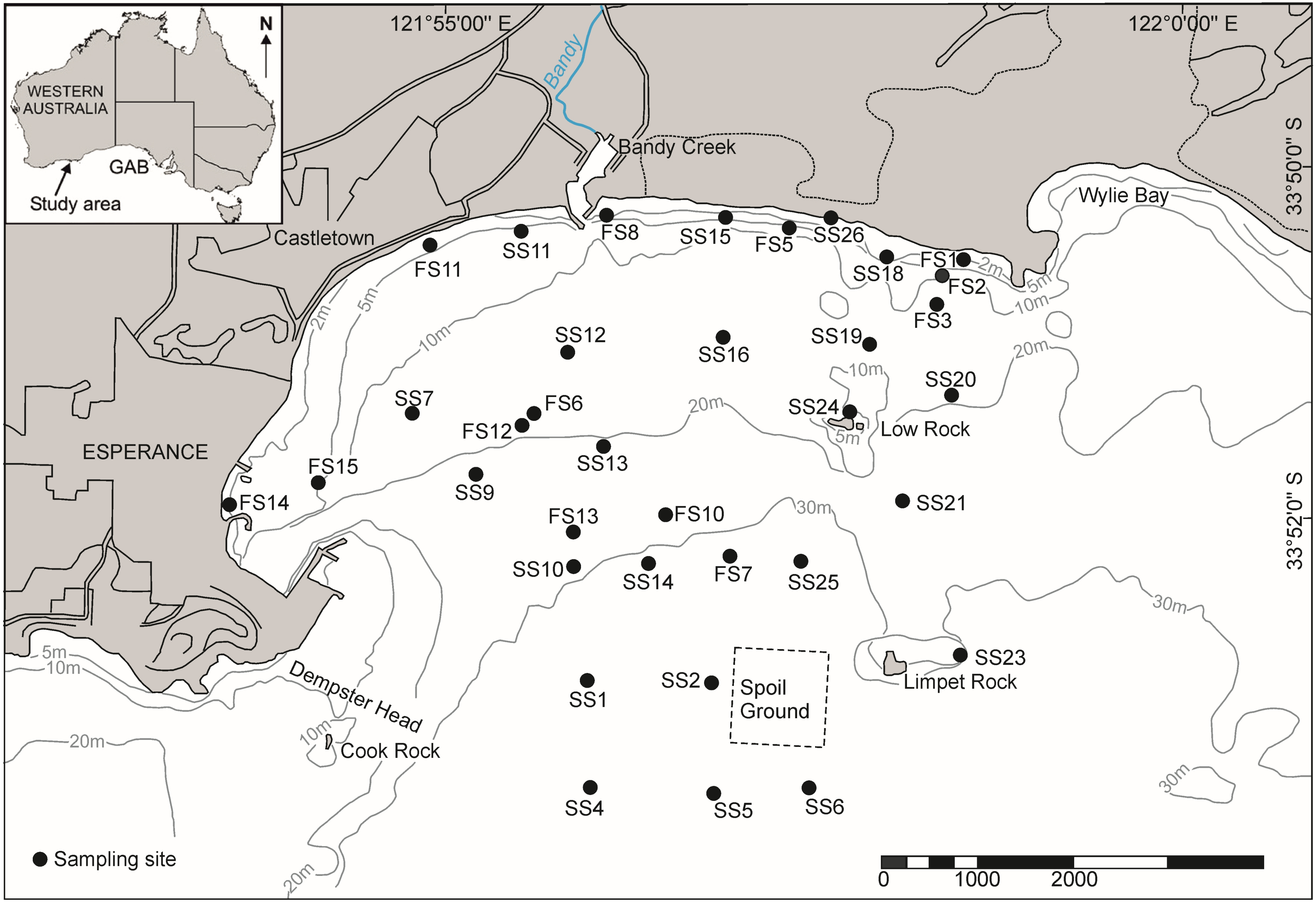
Table 4 – Relative abundance of the epiphytic Morphotypes according to Langer (1993) and Mateu-Vicens et al. (2014) in the investigated area.

Table 5 – Range values of relative abundance of main benthic foraminifera species, depth, sediment component and grain-size parameters, and biotic indices of the four clusters identified in the studied area.

Supplementary Materials

Appendix 1 – List of species identified in this study.

Figure 1



121°55'00" E
122°0'00" E
33°50'0" S
33°52'0" S
N
WESTERN AUSTRALIA
GAB
Study area
Bandy
Bandy Creek
Castletown
Wylie Bay
ESPERANCE
Dempster Head
Cook Rock
Low Rock
Limpet Rock
Spoil Ground
FS1
FS2
FS3
FS5
FS6
FS7
FS8
FS10
FS11
FS12
FS13
FS14
FS15
SS1
SS2
SS4
SS5
SS6
SS7
SS9
SS10
SS11
SS12
SS13
SS14
SS15
SS16
SS18
SS19
SS20
SS21
SS23
SS24
SS25
SS26
2m
5m
10m
20m
30m
Sampling site
0
1000
2000

Figure 2

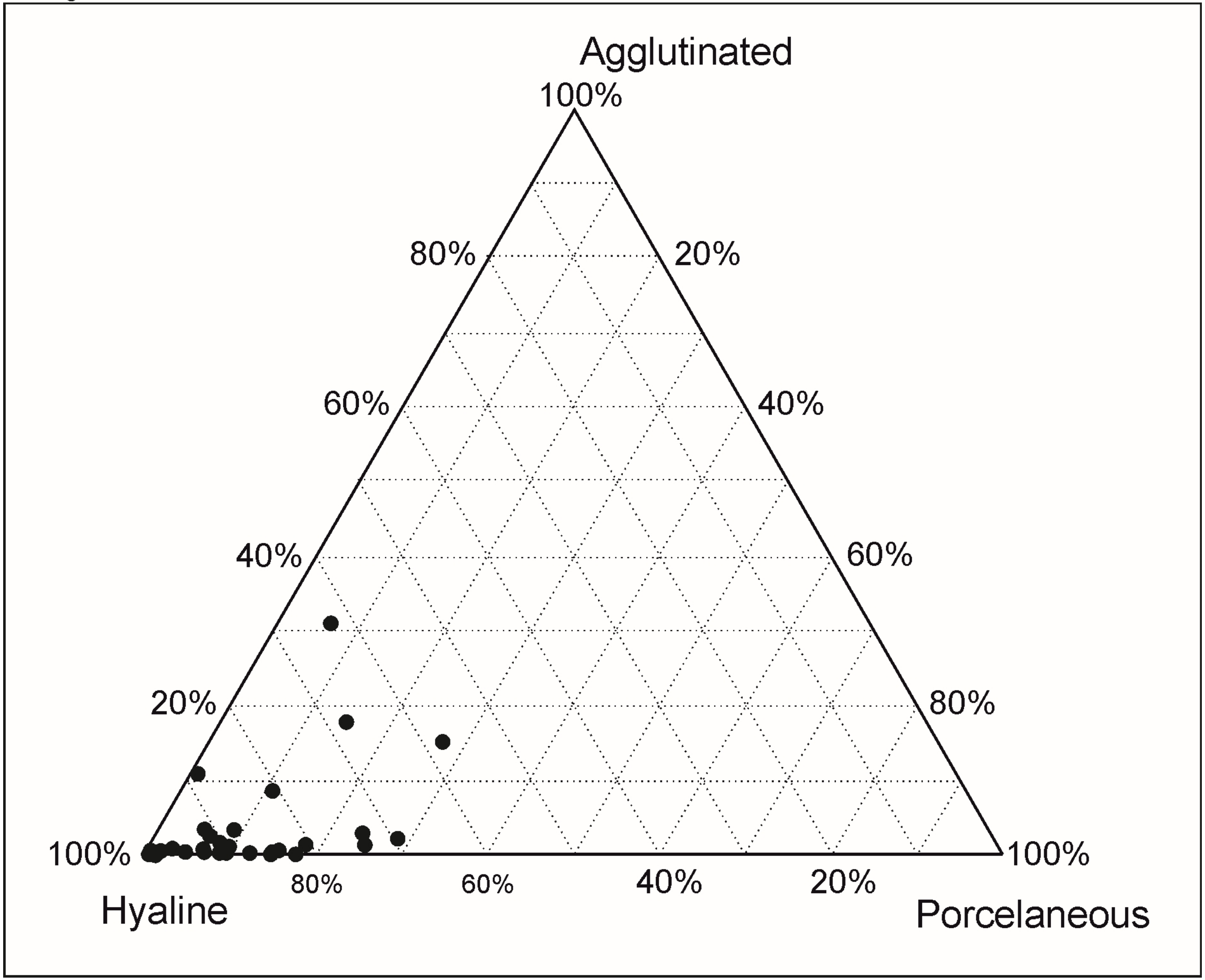

Agglutinated
100%
80%
20%
60%
40%
40%
60%
20%
80%
100%
100%
80%
60%
40%
20%
Hyaline
Porcelaneous

Figure 3

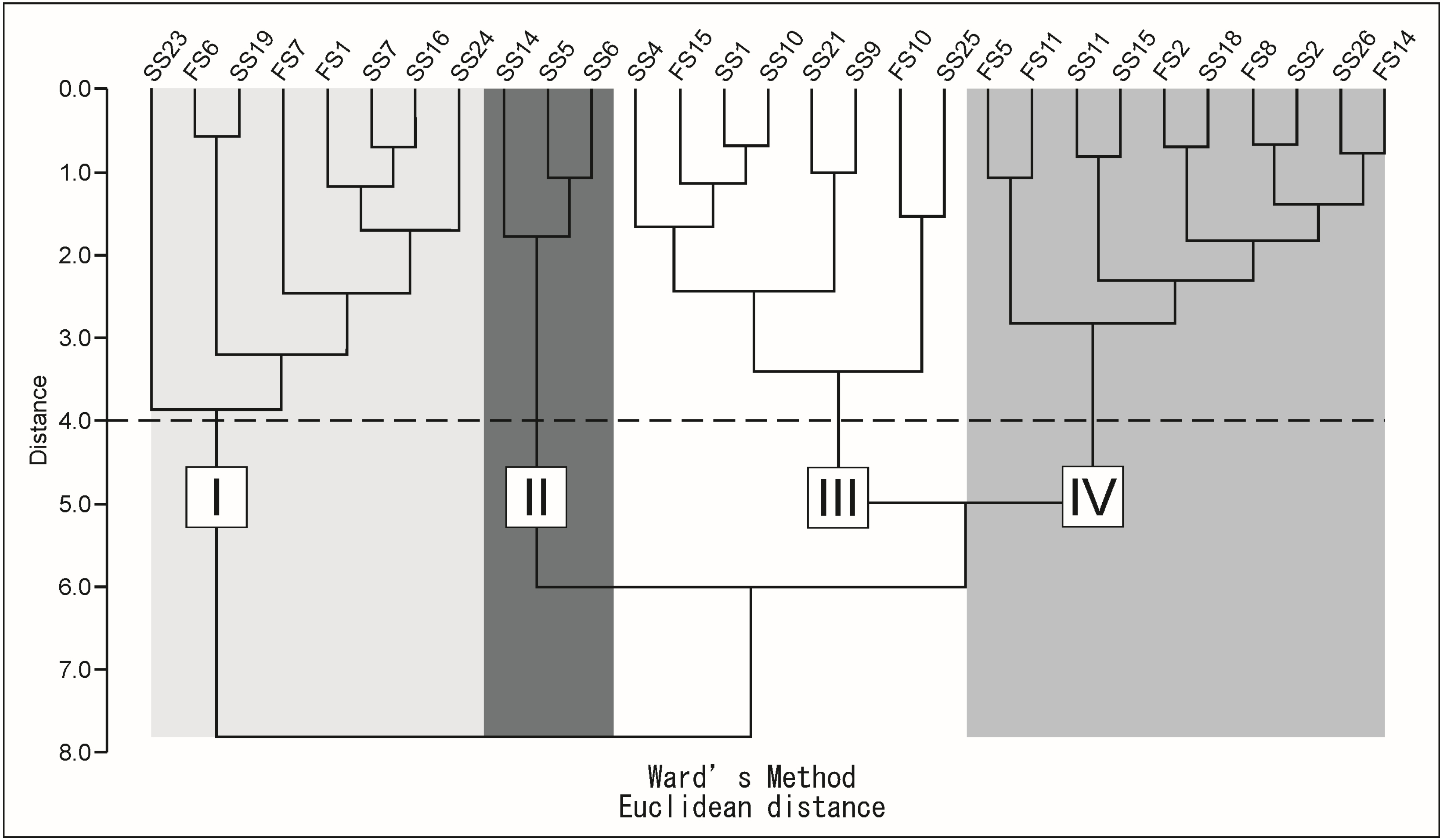

SS23
FS6
SS19
FS7
FS1
SS7
SS16
SS24
SS14
SS5
SS6
SS4
FS15
SS1
SS10
SS21
SS9
FS10
SS25
FS5
FS11
SS11
SS15
FS2
SS18
FS8
SS2
SS26
FS14
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Distance
I
II
III
IV
Ward' s Method
Euclidean distance

Figure 4

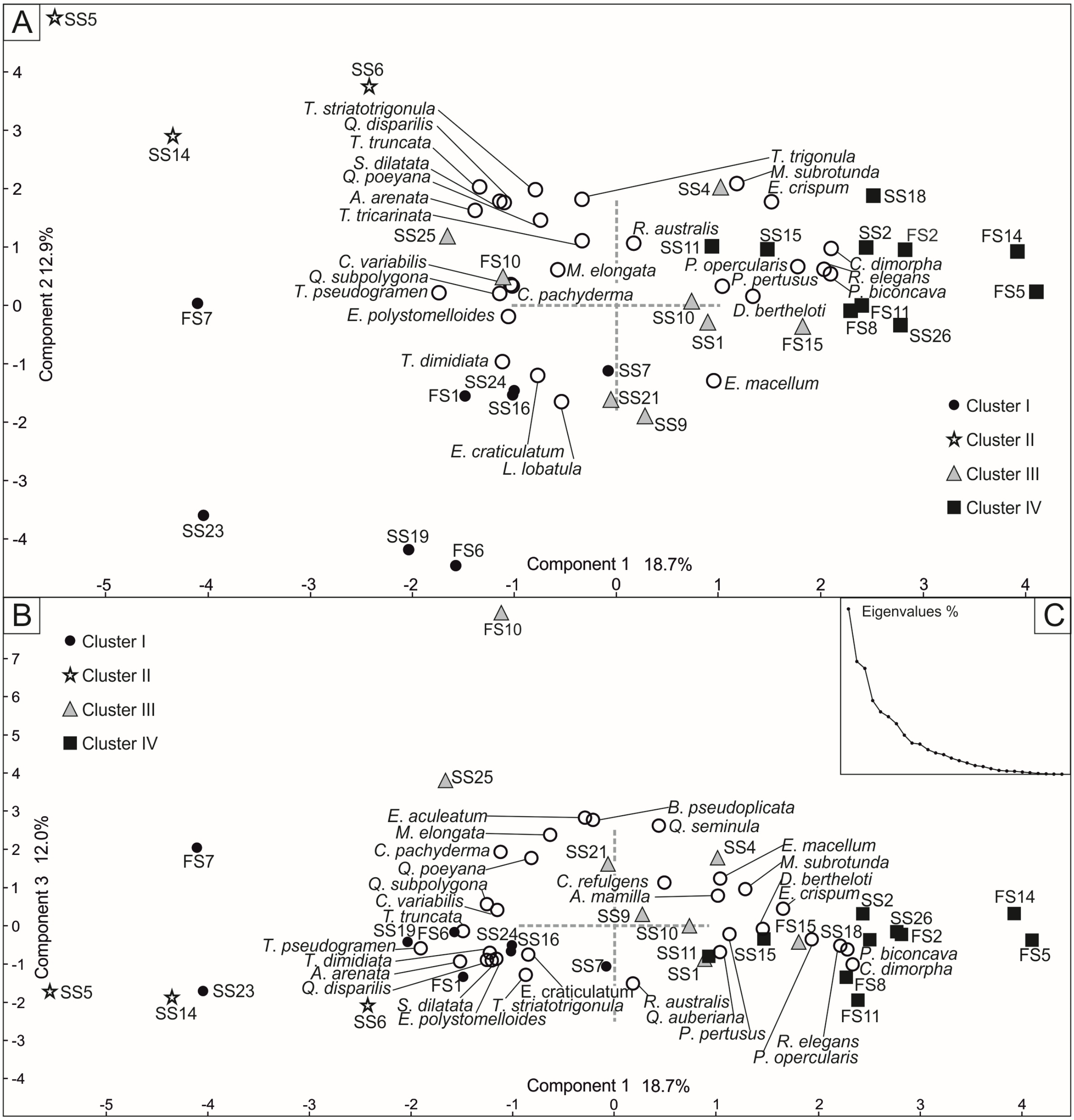
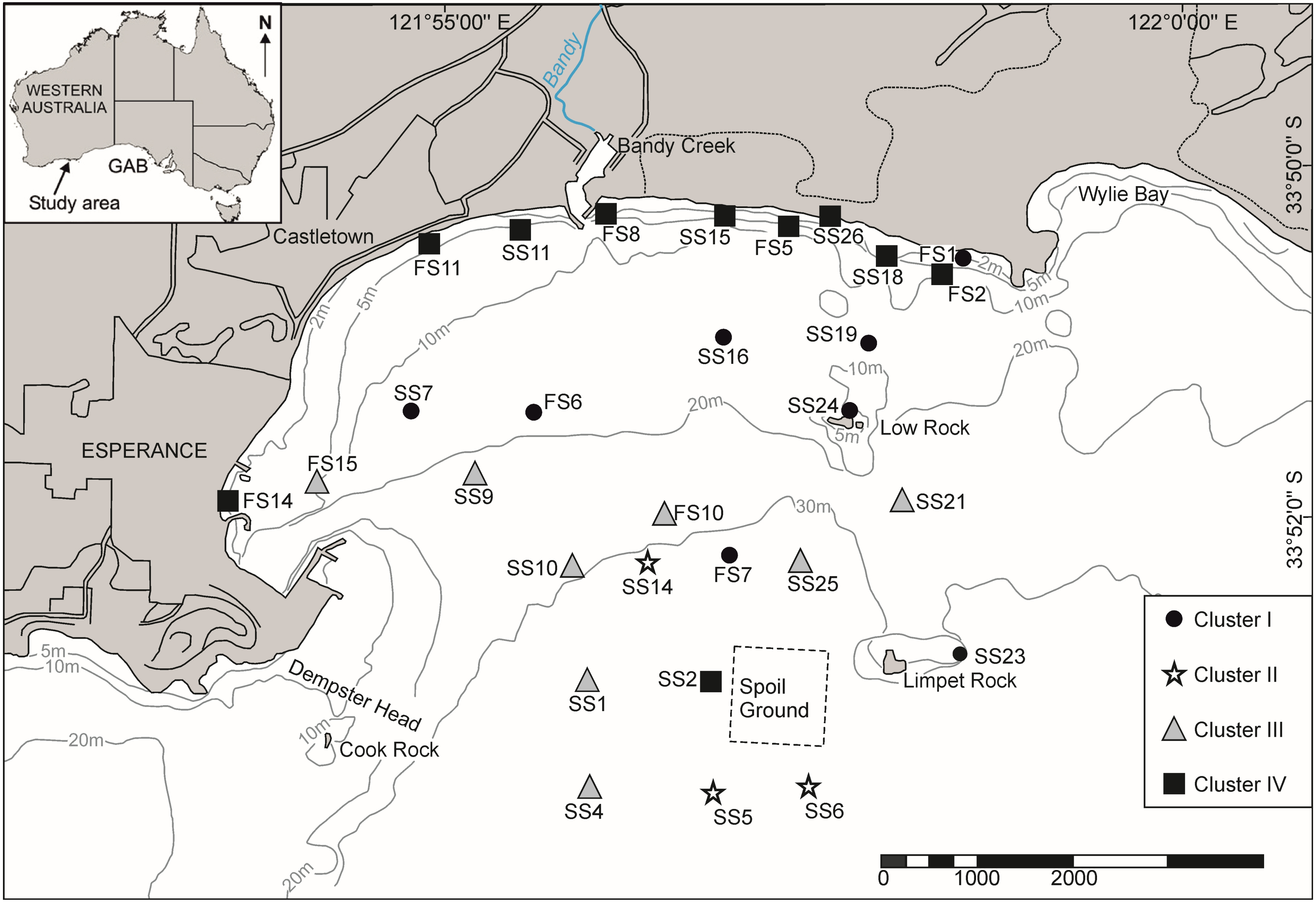

A
B
C
Component 1 18.7%
Component 2 12.9%
Component 3 12.0%
Eigenvalues %
Cluster I
Cluster II
Cluster III
Cluster IV
SS1
SS2
SS4
SS5
SS6
SS7
SS9
SS10
SS11
SS14
SS15
SS16
SS18
SS19
SS21
SS23
SS24
SS25
SS26
FS1
FS2
FS5
FS6
FS7
FS8
FS10
FS11
FS14
FS15
T. striatotrigonula
Q. disparilis
T. truncata
S. dilatata
Q. poeyana
A. arenata
T. tricarinata
C. variabilis
Q. subpolygona
T. pseudogramen
E. polystomelloides
C. pachyderma
M. elongata
T. trigonula
M. subrotunda
E. crispum
R. australis
P. opercularis
P. pertusus
C. dimorpha
R. elegans
P. biconcava
D. bertheloti
E. macellum
T. dimidiata
E. craticulatum
L. lobatula
E. aculeatum
B. pseudoplicata
Q. seminula
C. refulgens
A. mamilla
Q. auberiana

Figure 5



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SS7
SS9
SS10
SS11
SS14
SS15
SS16
SS18
SS19
SS21
SS23
SS24
SS25
SS26
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5m
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20m
30m
Cluster I
Cluster II
Cluster III
Cluster IV
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2000