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FORAMINIFERAL FAUNA AND BIOTOPES OF A BARRIER ESTUARY SYSTEM: ST GEORGES BASIN, NEW SOUTH WALES, AUSTRALIA

LUKE C. STROTZ

Department of Biological Sciences, Macquarie University, North Ryde, NSW, Australia, 2109. E-mail: luke.strotz@mq.edu.au

ABSTRACT

A 66-sample study of estuarine foraminifera within St Georges Basin identified 30 species from three biotopes that are divided almost equally in diversity between calcareous and agglutinated forms. The latter, however, are twice as abundant as the former, and the species *Ammobaculites exiguus*, *Portatrochammina sorosa*, *Rhumblerella subconica*, and *Ammonia aoteana* represent 78% of the fauna. The main driver of biotope distribution is water depth or factors related to it. Faunal composition and biotope distribution are similar to those found in other estuaries in the region, suggesting the possibility of a "standard fauna" for Australian estuaries with limited connections to the open ocean.

INTRODUCTION

Considering the length of coastline and number of estuaries (783 estuarine systems >50 m in width and >15 km^2 catchment area, from Bucher and Saenger, 1991), studies of Australia's estuarine and marsh foraminifera have received limited attention. Published studies have described foraminifera in <4% of Australian estuaries (McKenzie, 1962; Albani, 1968a, b, 1979; Johnson and Albani, 1973; Collins, 1974; Michie, 1975, 1987; Albani and Johnson, 1976; Quilty, 1977; Bell, 1978, 1995, 1996; Apthorpe, 1980; Yassini and Jones, 1989; Bell and Drury, 1992; Cotter, 1996; List, 1996; Cann and others, 2000; Revets, 2000; Clarke and others, 2001; Haslett, 2001; Wang and Chappell, 2001; Horton and others, 2003; Strotz, 2003; Woodroffe and others, 2005; Quilty and Hosie, 2006; Nash and others, 2010; Callard and others, 2011). Not all of these studies include detailed taxonomic analysis and many are not systematic studies, providing little or no detailed information on species distribution or ecology. While a number of unpublished theses contribute additional data (e.g. Mikulandra, 1988; Benocci, 1993), these works can sometimes be difficult to access (particularly for international workers).

The response of foraminiferal assemblages to changes in environmental conditions can be used to assess the overall biological impact of that change in estuaries and other shallow-water settings (Hayward and others, 1999; Murray, 2006). Combined with the importance of estuarine systems environmentally, economically, and recreationally (Costanza and others, 1997; Robinson, 2001), and given the increasing impact of anthropogenic activities upon Australian estuarine systems (e.g., Chenhall and others, 1995, 2001; Sloss and others, 2011), improving our understanding of Australian estuarine and marsh foraminifera has significant implications for enhancing environmental management in the region.

With limited urbanization around the estuary fringes and no major industrial operations in the surrounding area, St Georges Basin is relatively "pristine" in comparison to other estuaries of similar size in eastern Australia. Data on the composition and biodiversity of the extant foraminiferal fauna and the environmental factors, both physical and chemical, that control its distribution, therefore, represent an important baseline, particularly for comparison with other eastern Australian faunas subject to greater anthropogenic impact.

STUDY AREA

ST GEORGES BASIN

St Georges Basin (Fig. 1) is located on the New South Wales south coast, 190 km south of Sydney. It is a large, bilobate, wave-dominated estuary (Roy, 1984) with a water-surface area of 44 km^2 and a catchment area of 390 km^2 (Bell and Edwards, 1980), 80% of which is forested (Haese and others, 2007). The remainder of the catchment is agricultural or urbanized. The estuary infills a shallow, broadly incised valley eroded into the Pleistocene land surface and mid-Permian sandstone/siltstone basement during periods of lower sea level (Sloss and others, 2006). It is impounded by the Bherwerre Barrier system, which forms the largest sand barrier complex on the New South Wales south coast (Bradshaw, 1987, 1993; Sloss and others, 2006).

The estuary consists of two distinct parts (Fig. 1). The main basin has an average depth of ~8 m and a maximum of 10 m (Fig. 2). It is connected to the Pacific Ocean by a sinuous, narrow, shallow 6.3-km-long channel (Sloss and others, 2011), that is permanently open to the sea. Due to the constricted nature of the entrance channel, onshore waves generated within the basin dominate (Gray and Kennelley, 2003), and the tidal range within the estuary is reduced to 3.5 cm (Shoalhaven City Council, 1998; Sloss and others, 2007), compared to ~2 m along the associated coastline (Gray and Kennelley 2003). Most freshwater entering the system consists of runoff from the edges of the basin, and despite its sizeable catchment, only two major tributaries enter the estuary, Wandandian Creek in the northwest and the smaller Tomerong Creek in the northeast (Fig 1). The restricted marine opening, combined with limited fluvial input (Sloss and others, 2011), ensures conditions within the estuary remain relatively constant year round.

SEDIMENTOLOGY

Sedimentary facies, which can be a controlling factor on the distribution of foraminiferal taxa (List, 1996; Murray, 2006), have been described and mapped previously within St Georges Basin (Bradshaw 1987, 1993; Sloss and others, 2006). Haese and others (2007) have also undertaken

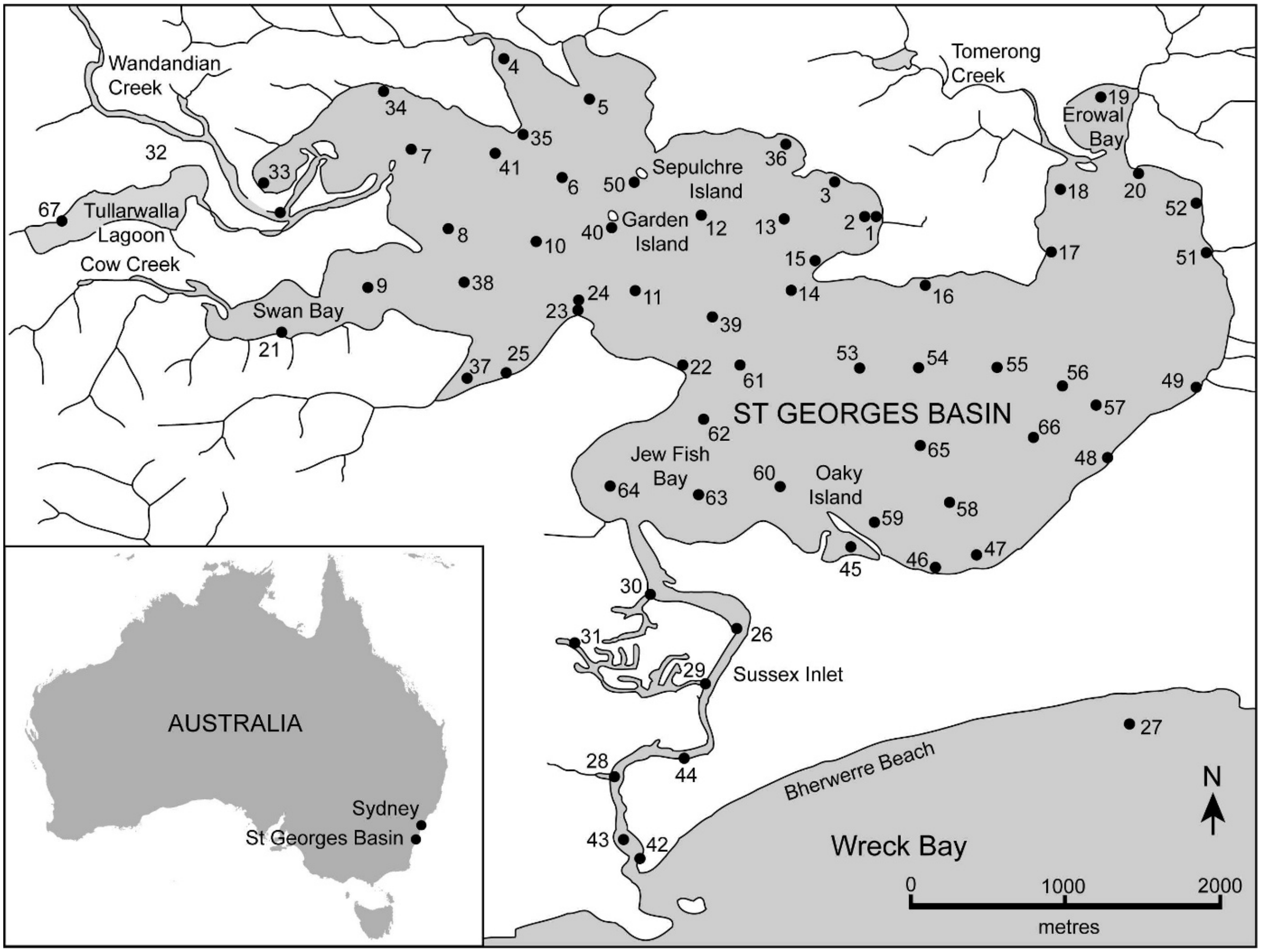

FIGURE 1. Location and map of St Georges Basin, New South Wales, Australia (35°07′ S, 150°40′ E). Map dots indicate sample sites used in this study.

detailed investigations of benthic nutrient fluxes and sediment chemistry in the area.

Sediments within the basin are dominantly clastic, with the central basin composed of mud with a substantial proportion of biogenic material, including mollusc shells [largely the bivalve *Anadara trapezia* (Deshayes)] and fecal material. The inlet-channel deposits also contain some marine shell material. Sea-grass beds are common around the margins of the estuary and are comprised of genera such as *Zostera*, *Caulerpa*, and *Posidonia*.

Six discrete sedimentary facies, controlled by water energy, can be identified in the St Georges Basin (Sloss and others, 2006). These are: inlet channel/floodtide delta deposits, central lagoon muds, intertidal sand flat/sea-grass beds, muddy sands, fluvial bay-head delta sands, and fluvial channel deposits. The first is limited to the inlet channel that connects the main basin to the sea, and consists of light-colored, clean, siliciclastic sands. The last three are confined to the northeast and northwest parts of the estuary, specifically the mouths of Tomerong and Wandandian creeks. The remaining two make up the majority of sediments in the estuary. The central lagoonal muds, composed primarily of fine silt and clay-sized particles that have settled from suspension (Roy and others, 2001), are widespread in the low energy, deeper parts of the basin, and the intertidal sands/sea grass beds, composed of muddy, grey-colored sands, are confined to the basin edges.

Fluvial input into the system is minimal, with the sedimentation rate for much of the basin only 0.5 mm/yr (Sloss and others, 2011). Increased sedimentation has been identified around the major centers of human habitation, particularly Erowal Bay (Fig. 1), where sedimentation rates as high as 4.4 mm/yr have been recorded (Sloss and others, 2011).

ANTHROPOGENIC ACTIVITIES AND IMPACTS

The St Georges Basin catchment is relatively undeveloped (Sloss and others, 2011). No obvious polluters, such as factories or agricultural runoff, are present in the region. The population is concentrated in small towns along the northern and western shorelines of the basin and along the western shoreline of the inlet channel, and numbers ~15,000 (Australian Bureau of Statistics, 2008). The only obvious human impact is an increase in sedimentation rate above pre-European settlement levels around Erowal Bay as mentioned above.

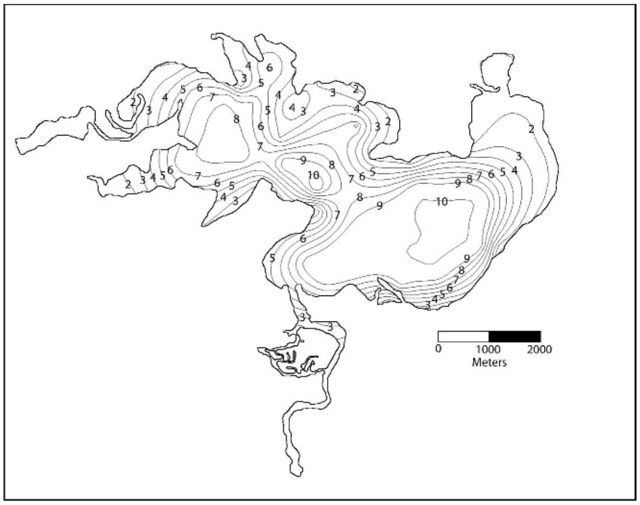

FIGURE 2. Bathymetric map of St Georges Basin. Depth in meters below sea level.

In contrast, the southern and eastern shorelines are largely uninhabited, dominated by bushland and native forest that has been designated as a national park. The estuary itself is not commercially fished, but recreational fishing and boating are common, particularly during the warmer months and holiday periods.

MATERIALS AND METHODS

Sixty-six sediment samples were collected in the basin (Fig. 1) in December 2003 using a standard Van Veen style grab sampler lowered from a small boat. Because of the consolidated nature of the sediments, the grab sampler often returned undisturbed sediment "blocks," allowing collection of only the top 1 cm. No sediment sample was collected offshore at station SGB 27. Sediment was placed into 100-ml vials, and treated with ethanol to preserve foraminifer protoplasm for later staining.

Because hydrological characteristics are known to affect foraminiferal distribution (e.g., Murray, 1973; Boltovskoy and Wright, 1976; Haynes, 1981; Boltovskoy and others, 1991; Murray, 2001), three chemical (conductivity, dissolved oxygen, pH) and two physical (depth, temperature) parameters were measured in the basin to determine which factors influence the foraminiferal distribution. Data were collected at the sediment-water interface with the use of a Hydrolab 4 datasonde. Multiple readings were taken over a one-month period at varying times of day. These results were then averaged to account for potential variations based upon ambient temperatures and diurnal cycles. Hydrological data were additionally collected at a single offshore location (SGB 27 in Wreck Bay; Fig. 1) to establish an "open-ocean" water-chemistry baseline.

Sediment samples were stained with rose Bengal to identify live or dead foraminifera at the time of collection. Because of difficulties in discriminating stained from unstained agglutinated specimens, all analyses and discussions of the foraminiferal fauna are based upon total assemblages, using the methodology developed by Scott and Medioli (1980).This also allows for easy comparison with other Australian estuarine foraminiferal studies, particularly from the east coast, the majority of which have used a total assemblage approach (e.g. Albani 1968a,b, 1979; Yassini and Jones, 1989; Cotter, 1996).

Samples were washed through a 1000-μm and 63-μm sieve and dried in an oven at 30°C. Only the 63-μm aliquot was examined for foraminifera, which were concentrated from the residue by floatation in a sodium polytungstate solution (Anderson and others, 1995) that yielded the best results at a specific gravity of 2.35. Although some authors have expressed reservations concerning this technique (List, 2001) because the tests may end up with a crystalline surface residue, there is no problem if samples are adequately washed (at least 3–4 times) with deionized water immediately following separation (Strotz, 2003).

Following floatation, samples were split with a microsplitter, and 300 individuals were picked from the splits. Two samples, SGB 45 and SGB 67, did not yield 300 specimens and were not included in the analyses (Appendix 1). Q-mode cluster analysis, using the Bray-Curtis similarity index and unweighted paired-group average linkage, canonical correspondence analysis (CCA), and diversity indices (Fisher-α, Shannon H, and Dominance) were calculated using PAST version 1.90 (Hammer and others, 2001). Fisher-α is preferred to strict diversity, as it accounts for differing sample size (Hayward and others, 1999). Shannon H incorporates relative abundance values and species "evenness," as well as overall diversity (Krebs, 1989). Dominance is the percentage of dominant species in the fauna (Walton, 1964). Data were standardized as percentage abundance for all calculations. All benthic foraminifera, including rare taxa, were included in the analyses. Planktic taxa were excluded from any statistical analysis. Contour maps depicting variations in each of the measured chemical parameters are based upon average values over the sampling period, and were created using Surfer version 8.04. All photomicrographs were taken with a JEOL-JSM 840 scanning electron microscope.

RESULTS

HYDROLOGICAL CHARACTERISTICS

Dissolved Oxygen

Dissolved oxygen (DO) values range from 64.7%–134% (Fig. 3A). Areas where the depth exceeds 6 m are generally less oxygen saturated than shallower parts of the estuary. Distance from the estuary mouth (by proxy, distance from the open ocean) also has an effect, with values generally lower at the landward extremities of the system. Both of these factors are characteristic of decreasing energy levels associated with decreasing water movement. Lower energy regimes result in reduced mixing of the water column, allowing oxygen-consuming bacteria to proliferate and thus bottom waters to become dysaerobic (Roy and others, 2001).

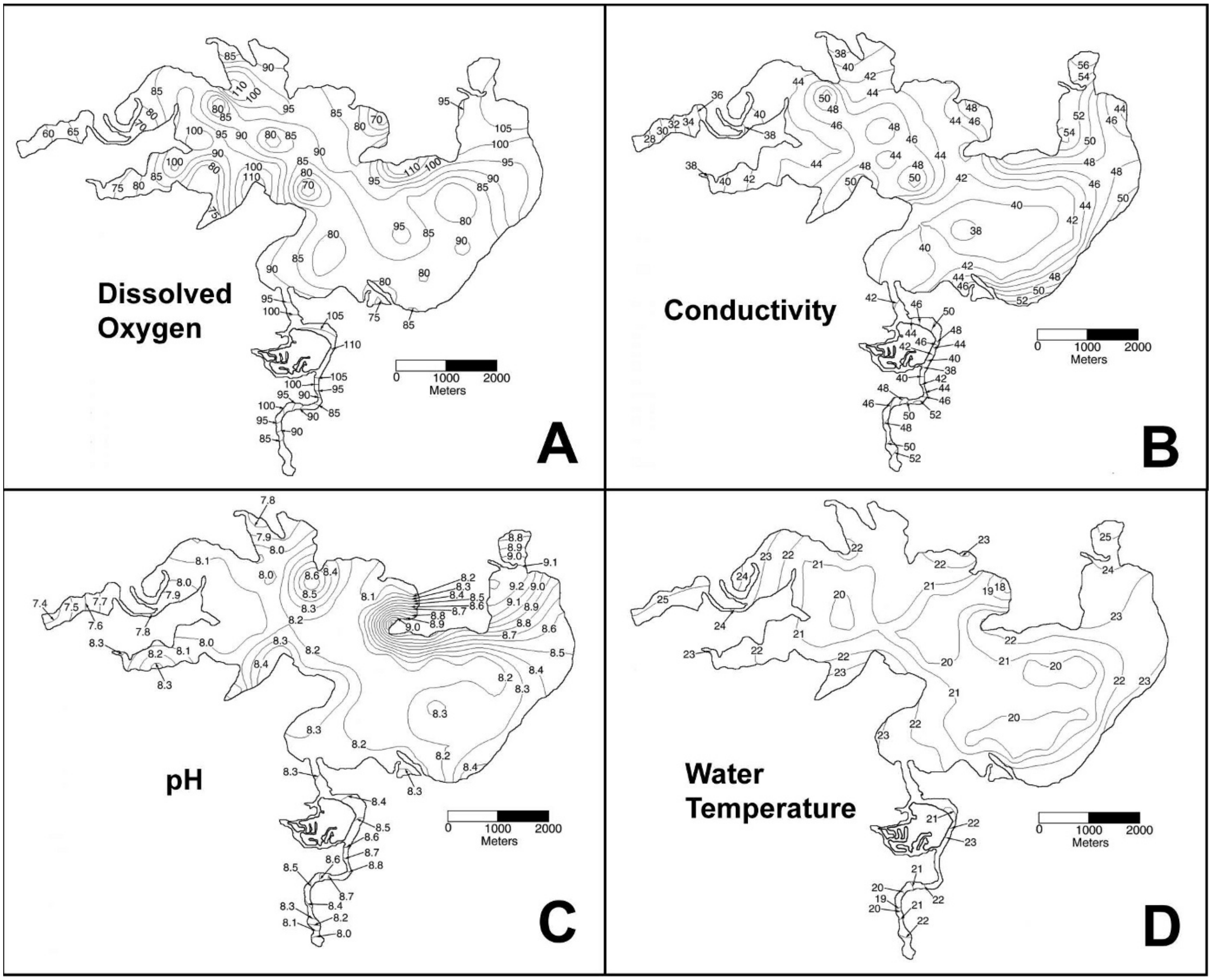

FIGURE 3. Contour maps of measured hydrological characteristics in St Georges Basin. **A** Dissolved oxygen (% saturation); **B** Conductivity (mS/cm); **C** pH; **D** Water temperature (°C).

Conductivity

Conductivity is directly analogous to salinity (Riley and Chester, 1971), with values ranging from 28 mS/cm, in the more isolated parts of the estuary, to ≤60.4 mS/cm at sampling station SGB 19 (Figs. 1, 3B). Open-ocean values at SGB 27 off Bherwerre Beach equal 50.01 mS/cm. Similar to DO, distance from the estuary entrance and bathymetric depth control conductivity values. Shallow areas also have higher values than those from the open ocean, likely due to higher evaporation rates. Erowal Bay, an in-filled embayment with water depths <0.1 m (Sloss and others, 2011), has the highest conductivity values recorded for the entire estuary (Fig. 2).

pH

Values for pH throughout the basin are relatively homogeneous. Almost all values fall between 7.5–8.4 (Fig. 3C), meaning that basin pH, on average, is only slightly higher than that of the open ocean at ~8.2 (Miller, 2000). The exception to this is the northeastern side of the basin, where pH ranges from 8.7–9.4 (Fig. 3C), near an area that is becoming increasingly urbanized, suggesting a link between increased pH and anthropogenic activity.

Temperature

Recorded temperatures correlate closely with water depth. Bottom-water temperatures in the deepest parts of St Georges Basin are ≤5C° cooler than those in shallower parts of the estuary (Fig. 3D). Readings were collected during summer, and lower values would be expected in winter.

FORAMINIFERA

All sediment samples collected in the basin yielded foraminifera. Thirty species of foraminifera were identified (Appendix 1; Figs. 4–6) and are described selectively in Appendix 2.

More than 87% of the recovered tests did not stain with rose Bengal, signifying absence of live protoplasm. Live

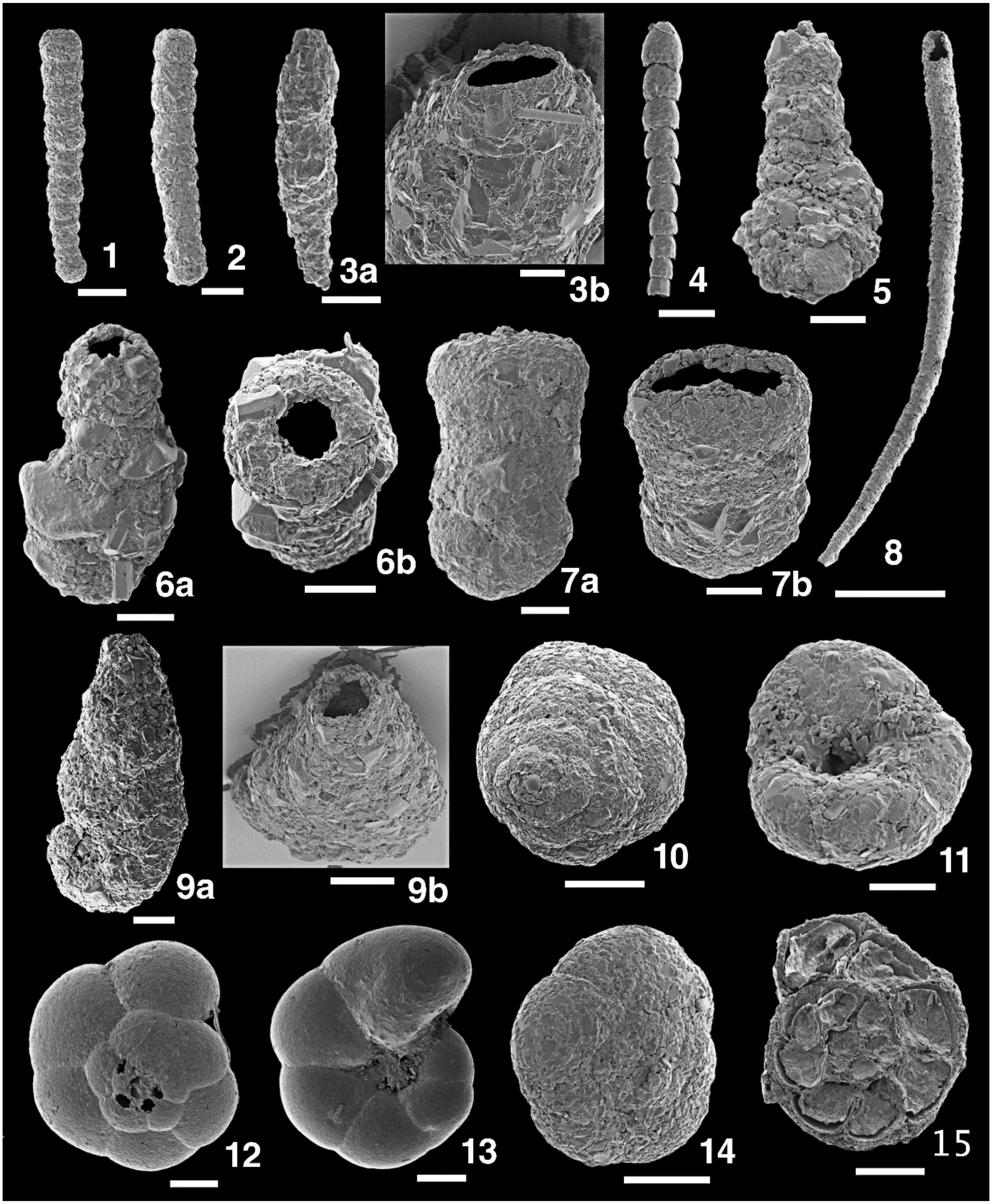

FIGURE 4. Scale bars = 100 µm unless otherwise specified, SGB = sample number (Fig. 1), MU = Macquarie University museum number. **1, 2** *Scherochorella barwonensis* (Collins): 1, SGB 6, MU 61978; 2, SGB 19, MU 61979. **3** *Reophax subfusiformis* Earland, SGB 6, MU 61980 (3b scale bar = 20 µm). **4** *Leptohalysis collinsi* Bell, SGB 6, MU 61981. **5, 6** *Ammobaculites exiguus* Cushman and Brönnimann: 5, SGB 3, MU 61982; 6, SGB 2, MU 61984 (scale bars = 50 µm). **7** *Simobaculites barwonensis* (Collins), SGB 17, MU 61985. **8** *Warrentia*? sp., SGB 14, MU 61986 (scale bar = 500 µm). **9** *Ammotium cassis* (Parker), SGB 40, MU 61987 (scale bars = 50 µm). **10, 11** *Portatrochammina sorosa* (Parr): 10, SGB 1, MU 61988; 11, SGB 2, MU 61989 (scale bars = 50 µm). **12, 13** *Trochammina inflata* (Montagu): 12, SGB 17, MU 61990; 13, SGB 17, MU61991. **14, 15** *Paratrochammina bartrami* (Hedley, Hurdle and Burdett): 14, SGB 24, MU 61992 (scale bar = 50 µm); 15, SGB 7, MU 61993.

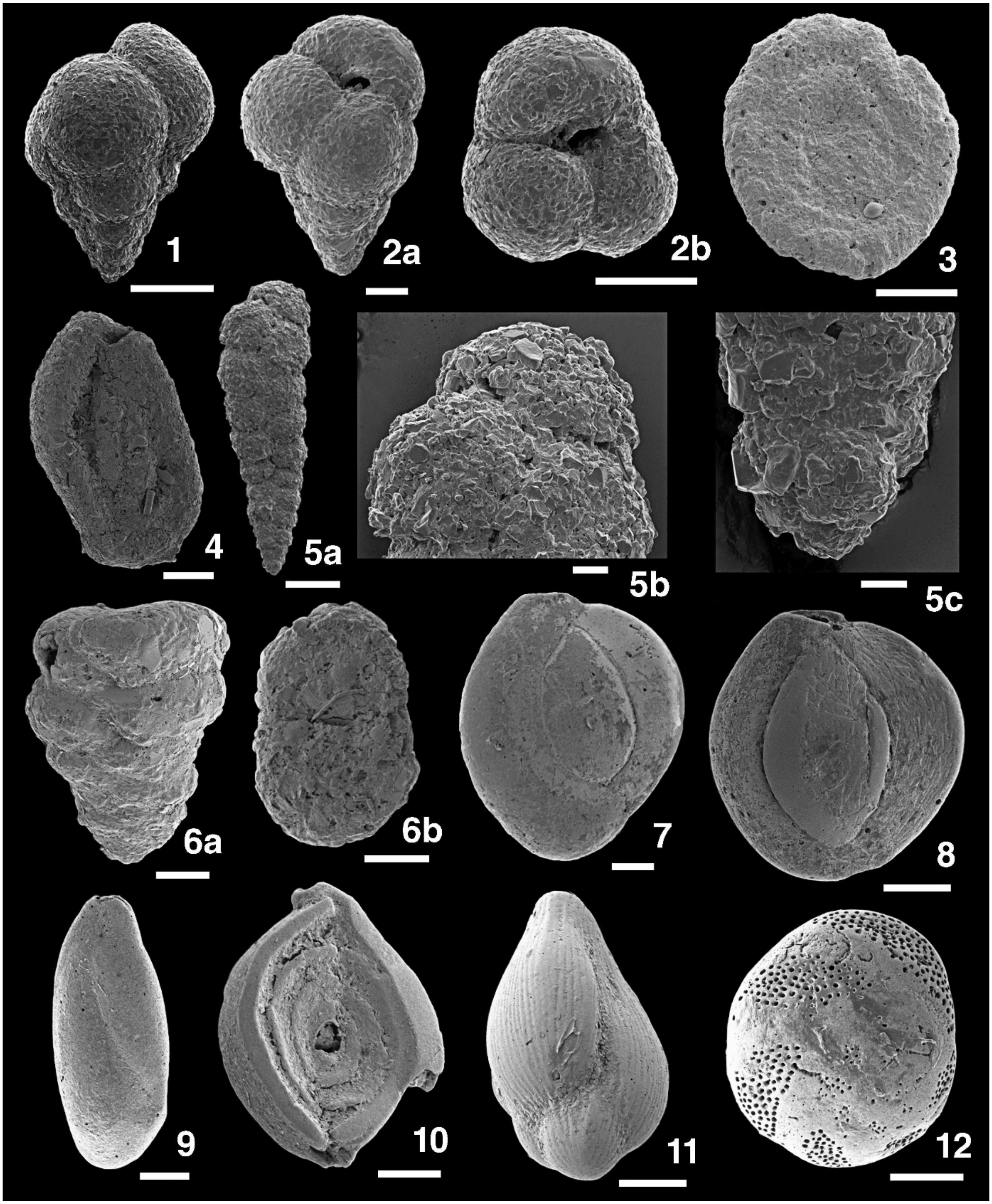

FIGURE 5. Scale bars = 100 μm unless otherwise specified, SGB = sample number (Fig. 1), MU = Macquarie University museum number. **1, 2** *Rhumblerella subconica* (Parr): 1, SGB 6, MU 61994; 2, SGB 6, MU 61995 (scale bars= 50 μm). **3** *Ammodiscus* sp., SGB 24, MU 61996. **4** *Miliammina fusca* (Brady), SGB 17, MU 61997. **5** *Palustrella earlandi* (Parker), SGB 6, MU 61998 (5b scale bar = 20 μm, 5c scale bar = 10 μm). **6** *Gaudryina convexa* (Karrer), SGB 28, MU 61999. **7** *Triloculina tricarinata* (d'Orbigny), SGB 28, MU 62001. **8** *Quinqueloculina suborbicularis* (d'Orbigny), SGB 28, MU 62002. **9** *Quinqueloculina oblonga* (Montagu), SGB 28, MU 62003. **10** *Spiroloculina communis* (Cushman and Todd), SGB 28, MU 62004. **11** *Guttulina regina* (Brady, Parker, and Jones), SGB 28, MU 62005. **12** *Rosalina australis* (Parr), SGB 28, MU 62006.

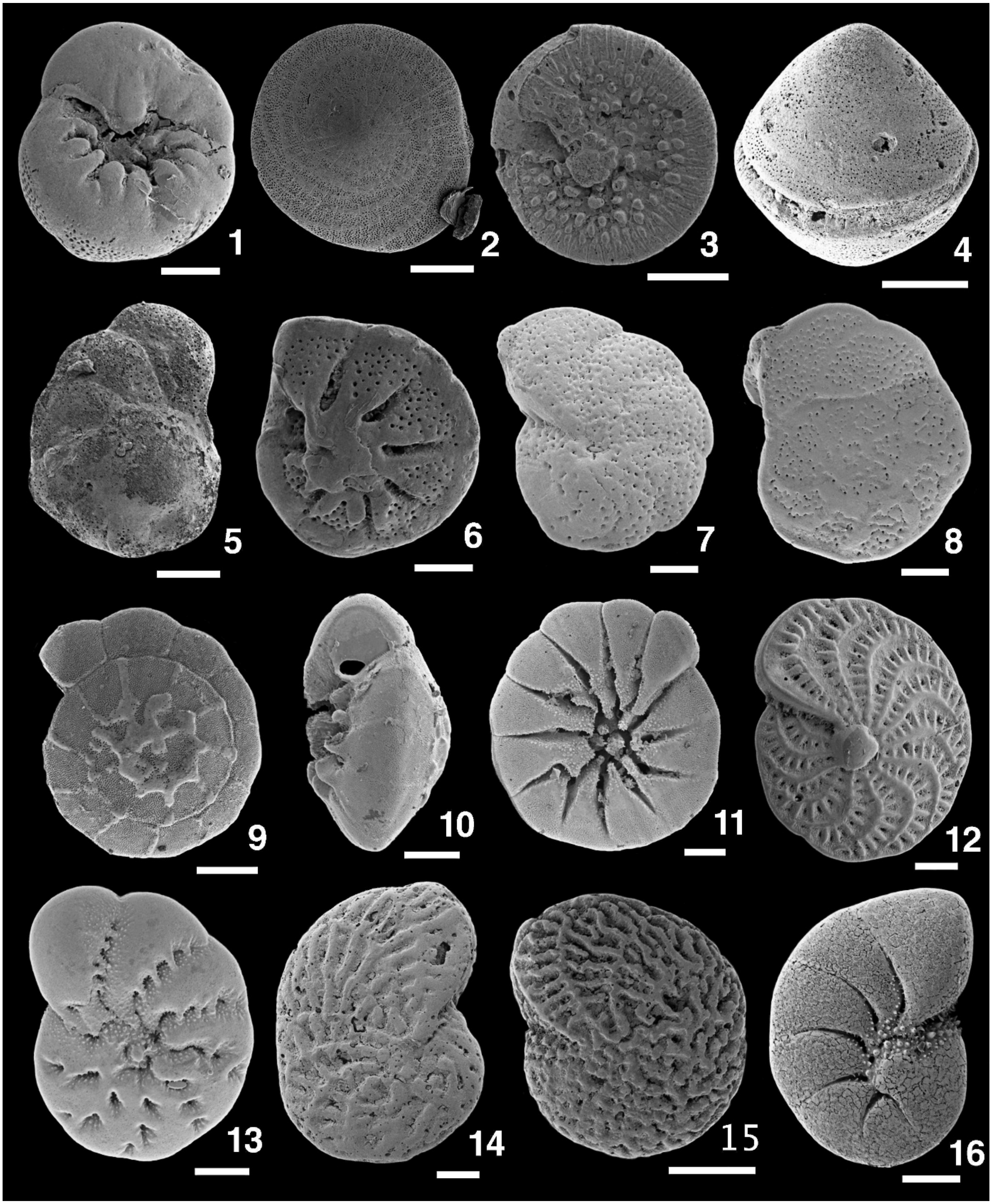

FIGURE 6. Scale bars = 100 μm unless otherwise specified, SGB = sample number (Fig. 1), MU = Macquarie University museum number. **1** *Rosalina australis* (Parr), SGB 28, MU 62007. **2–4** *Pileolina australensis* (Heron-Allen and Earland): 2, SGB 28, MU 62008. 3, SGB 28, MU 62009; 4, SGB 28, MU 62010. **5, 6** *Lamellodiscorbis dimidiatus* (Jones and Parker): 5, SGB 28, MU 62011 (scale bar = 200 μm); 6, SGB 28, MU 62012. **7, 8** *Cibicides dispars* (d'Orbigny): 7, SGB 28, MU 62013; 8, SGB 28, MU 62014. **9–11** *Ammonia aoteana* (Finlay): 9, SGB 6, MU 62015; 10, SGB 6, MU 62016; 11, SGB 6, MU 62017. **12** *Elphidium crispum* (Linné), SGB 28, MU 62018. **13** *Elphidium excavatum clavatum* Cushman, SGB 1, MU 62019 (scale bar = 50 μm). **14** *Elphidium macellum* (Fichtell and Moll), SGB 28, MU 62020. **15** *Parrellina verriculata* (Brady), SGB 28, MU 62021 (scale bar = 200 μm). **16** *Haynesina simplex* (Cushman), SGB 47, MU 62022.

TABLE 1. Diversity indices (Fisher-α, Shannon H, and Dominance) for 66 sampled sites in St Georges Basin.

Site	Fisher-α	Shannon H	Dominance
SGB1	1.73	1.01	0.46
SGB2	0.84	0.88	0.47
SGB3	1.12	0.51	0.79
SGB4	0.15	0	1
SGB5	1.12	0.96	0.52
SGB6	2.4	1.2	0.39
SGB7	1.12	0.74	0.68
SGB8	0.84	0.18	0.98
SGB9	0.83	0.19	0.96
SGB10	1.11	0.48	0.78
SGB11	0.84	0.57	0.74
SGB12	1.73	1.21	0.47
SGB13	2.06	0.60	0.78
SGB14	2.07	1.07	0.55
SGB15	1.74	1.15	0.46
SGB16	1.42	1.53	0.32
SGB17	2.43	1.91	0.19
SGB18	2.42	0.81	0.65
SGB19	2.07	0.7	0.74
SGB20	1.11	0.84	0.52
SGB21	0.59	0.29	0.90
SGB22	1.73	1.47	0.28
SGB23	0.84	0.79	0.54
SGB24	1.74	1.04	0.51
SGB25	1.12	0.94	0.48
SGB26	2.07	1.83	0.21
SGB28	6.17	2.37	0.19
SGB29	1.41	1.72	0.21
SGB30	0.58	1.02	0.39
SGB31	0.58	0.68	0.64
SGB32	1.41	1.59	0.25
SGB33	0.35	0.69	0.5
SGB34	2.06	0.93	0.52
SGB35	1.41	0.96	0.51
SGB36	1.41	0.59	0.73
SGB37	0.58	0.95	0.44
SGB38	1.42	0.93	0.58
SGB39	2.06	0.82	0.54
SGB40	2.44	1.52	0.31
SGB41	1.12	1.04	0.43
SGB42	3.22	2.01	0.23
SGB43	3.64	2.18	0.17
SGB44	1.11	1.02	0.54
SGB45	0.15	0	1
SGB46	0.84	1.13	0.37
SGB47	1.74	1.51	0.28
SGB48	2.07	1.29	0.36
SGB49	1.42	1.01	0.58
SGB50	1.11	0.82	0.62
SGB51	1.73	0.82	0.52
SGB52	2.41	1.38	0.43
SGB53	0.36	0.69	0.51
SGB54	0.58	0.83	0.47
SGB55	0.59	0.77	0.55
SGB56	0.58	0.41	0.78
SGB57	0.58	0.41	0.82
SGB58	0.36	0.08	0.99
SGB59	0.36	0.37	0.8
SGB60	0.36	0.33	0.82
SGB61	0.84	0.8	0.54
SGB62	0.36	0.57	0.62
SGB63	0.59	0.53	0.73
SGB64	0.59	0.49	0.78
SGB65	0.84	0.54	0.74
SGB66	0.84	0.71	0.57
SGB67	0.35	0.50	0.68

foraminifera rarely exceeded 15% of any assemblage and they were entirely absent at some sites. Since some individuals were recorded as stained across all identified biotopes, failure to recover significant numbers of live individuals cannot be attributed purely to user error. It is notoriously difficult to determine whether agglutinated foraminifera are stained (Murray and Bowser, 2000) and this may explain the low number of stained specimens identified, given the high proportion of agglutinated taxa.

Four taxa make up 78% of the foraminiferal fauna in St Georges Basin. These are *Rhumblerella subconica* (Parr) (22%), *Ammonia aoteana* (Finlay) (22%), *Portatrochammina sorosa* (Parr) (18%) and *Ammobaculites exiguus* Cushman and Brönnimann (15%). Agglutinated species dominate the assemblage in both relative and absolute abundance. Seventeen agglutinated taxa make up just over 66% of all recovered foraminifera. Calcareous taxa are absent from most samples sites, or if present, are rare except for *A. aoteana*, which occurs in large numbers in the main basin. Only at the mouth of the inlet channel does calcareous diversity increase. At SGB 28, SGB 42, and SGB 43 (Fig. 1), calcareous foraminifera average, 96% of the total assemblage. which is dominated by spiral, rotaliine taxa, including *Elphidium crispum* (Linné) (22%), *Lamellodiscorbis dimidiatus* (Jones and Parker) (18%), *Cibicides dispars* (d'Orbigny) (15%), and *Rosalina australis* (Parr) (11%).

Very few planktic foraminifera were recovered (seven out of >19,000 specimens). These were confined to sample SGB 28, located a quarter of the way up the inlet channel (Fig. 1), and indicate that open-ocean water does not penetrate beyond the initial part of the entrance channel.

Diversity Indices

Mean values for Fisher-α and Shannon H (Table 1) are considered "low," consistent with faunas from brackish-water settings (Hayward and others, 1999; Murray, 2006), or coastal lagoons, where contact with the open ocean is intermittent or absent. Highest diversity occurs near the estuary mouth (Fisher-α = 3.22–6.17; Shannon H = 2.01–2.37), but in the main basin there is no correlation between diversity values and distance from the entrance (Table 1; Fig. 1). However, there is correlation between diversity and water depth, with the mean values for sites in the deeper parts of the main basin (Fisher-α = 0.92; Shannon H = 0.63) lower than those from the shallower sites around the fringes of the estuary (Fisher-α = 1.5; Shannon H = 1.08).

Dominance shows similar trends to Fisher-α and Shannon H (Table 1). It is lowest at the estuary mouth (mean = 19), indicating relatively even abundance for the more common taxa. Inside the estuary, values can be correlated with depth (>3-m mean = 67, <3-m mean = 48); however, the differentiation is not as clear as for Fisher-α and Shannon H. The higher values at depth confirm that deeper-water faunas are dominated by a small number of taxa and that much of the diversity at these sites is composed of "rare" taxa.

FORAMINIFERAL BIOTOPES

Three distinct clusters, designated Biotopes I, II, and III, can be distinguished in St Georges Basin based upon

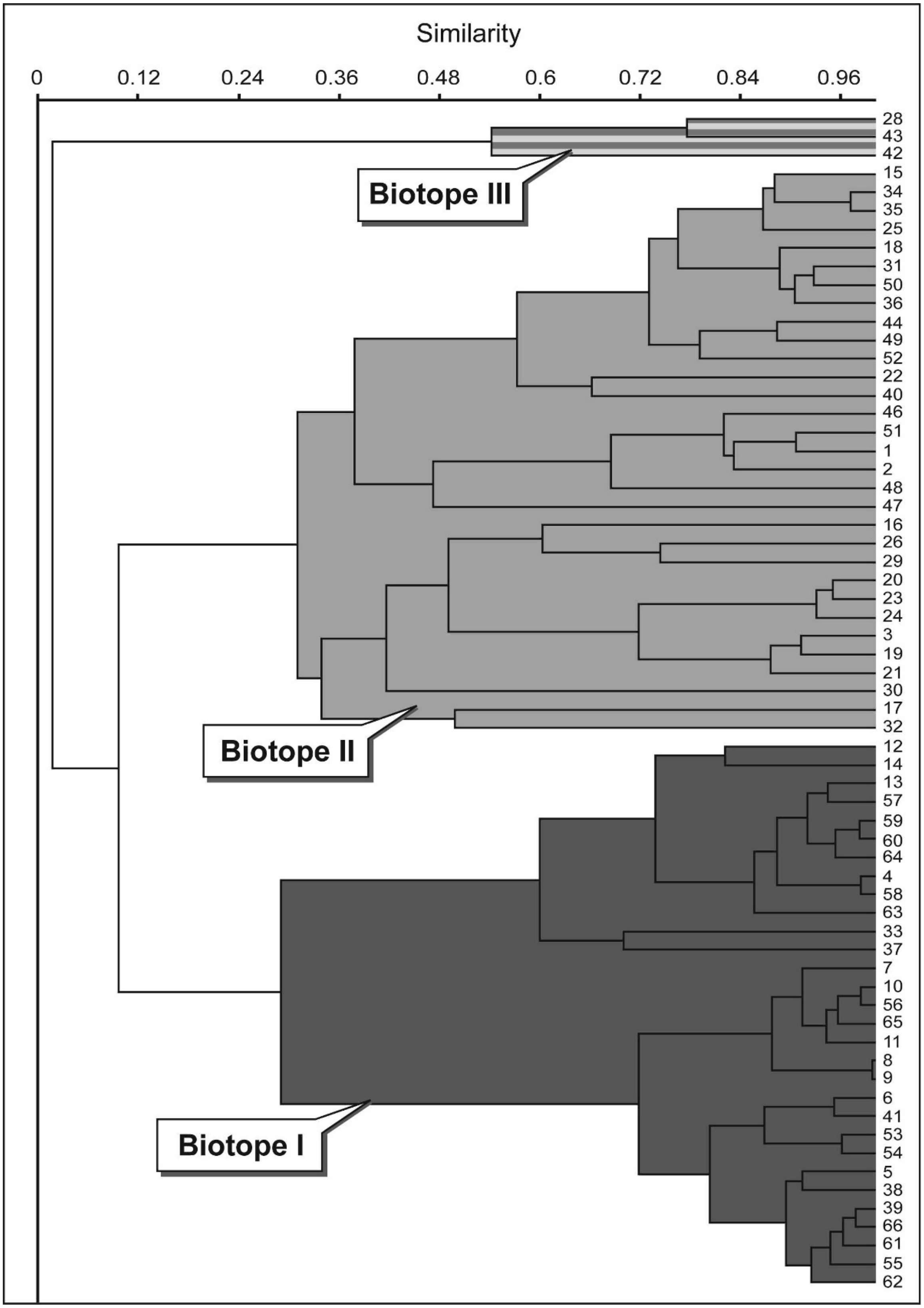

FIGURE 7. Q-mode cluster-analysis dendrogram (Bray-Curtis Similarity Index) for 66 sampled sites in St Georges Basin, divided into three biotopes (I, II, III).

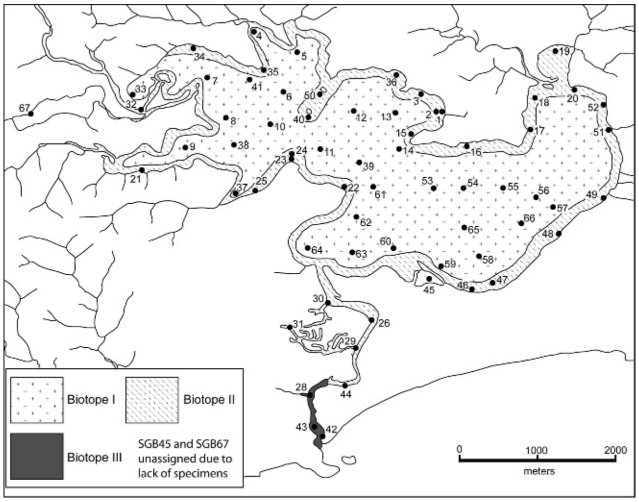

FIGURE 8. Distribution of biotopes in St Georges Basin. In areas where no sample has been collected, extrapolation of biotope is based upon the nature of the physical environment and composition of the fauna at the nearest sample site.

Q-mode cluster analysis (Fig. 7), with their geographic distribution shown in Figure 8. The average hydrodynamic parameters and the relative abundance of dominant taxa for each biotope a listed in Table 2. The distribution of each biotope can be correlated with the dominant sedimentary facies, delineated by Sloss and others (2006), and CCA shows correlation between each biotope and the measured hydrological parameters (Fig. 9).

Biotope I

This biotope occurs in the central part of the estuary (Fig. 8) at depths ≥2 m in low-energy settings dominated by the lagoonal-mud facies. CCA shows a strong correlation between Biotope I and increasing water depth (Fig. 9).

The fauna is dominated by *R. subconica* (mean abundance = 46%) and *A. aoteana* (45%). Their combined abundance is never <79%, and for a number of sites, particularly in the main basin, they are the only species present (Appendix 1). The remaining 9% of the Biotope I fauna is made up of seven, predominantly agglutinated taxa.

Cluster analysis identified two potential subassociations (Fig. 7), in one of which *R. subconica* abundance is >*A. aoteana* and vice versa in the other. Neither subassociation is exclusively dominated by one species, and therefore, separate biotopes were not established.

Biotope II

This biotope is confined to the edges of the main basin (0–3-m depth), rarely >100 m from the shoreline (Fig. 8). It correlates strongly to the intertidal sand flats/sea-grass-beds facies, but according to CCA, correlates negatively to water depth (Fig. 9). CCA also indicates some correlation between Biotope II and all of the measured hydrological parameters, potentially signifying that increasing values for these factors are important to the distribution of the biotope.

Biotope II is dominated by *A. exiguus* (39%) and *P. sorosa* (42%) (Appendix 1). Minor constituents include *Elphidium excavatum clavatum* Cushman (11%) and *Scherochorella barwonensis* (Collins) (4%). Nine taxa occur in the biotope, predominately agglutinated forms as in Biotope I.

Sample site SGB 32 is included in Biotope II, but its low similarity to other Biotope II sites suggest it could be considered an outlier (Fig. 7). It is dominated by *Simobaculites barwonensis* (37%), the only place in the estuary where this taxon is present at >9%.

Biotope III

This biotope is confined to the fully marine seaward portion of the inlet channel (Fig. 8), characterized by well-sorted sand, tidal influence, low turbidity, and frequent water exchange. CCA shows potential correlation with shallow depths, but no obvious correlation with the remaining measured environmental parameters (Fig. 9).

Biotope III is the most diverse with a total of 17 taxa (Appendix 1). Ten of these are confined to the biotope, constituting one-third of the taxa in St Georges Basin. The fauna is dominated by calcareous taxa (average relative abundance = 96%) and by characteristic marine species, including *E. crispum* (22%), *L. dimidiatus* (18%), *C. dispars* (15%) and *R. australis* (12%).This assemblage is typical of that found in the seaward portion of other southwest Pacific estuaries, particularly those in eastern Australia (e.g. Yassini and Jones, 1989; Hayward and others, 1999; Strotz, 2003).

DISCUSSION

DIVERSITY AND DISTRIBUTION

The dominance of agglutinated taxa and *A. aoteana* in St Georges Basin is consistent with previously described foraminiferal assemblages from estuarine systems in southeastern Australia (Albani, 1968a, b, 1979; Yassini and Jones, 1989; Albani and Yassini, 1993; Cotter, 1996; Strotz, 2003) and internationally (e.g., Scott and others, 1980; Goldstein, 1988; Patterson, 1990; Horton and others, 2003; Hayward and others, 2011). Total diversity (30 species), however, is considerably lower in St Georges Basin than values recorded for many previous studies from southeastern Australia, where >100 taxa have been recorded for a single estuary (Albani, 1968a, b, 1979; Yassini and Jones, 1989; Albani and Yassini, 1993). This significant disparity is attributed to the extent and magnitude of oceanic influence on the relevant systems. "High-diversity" systems are classified as "open" estuaries (Roy and others 2001), where the majority of the estuary is subject to significant oceanic influence. The reverse is true in St Georges Basin, where the constricted entrance limits water exchange between the open ocean and most of the basin (Murray and others, 2006). Given that oceanic influence is an important controlling factor of faunal diversity within an estuarine system (Roy and others, 2001), the diminished diversity in St Georges Basin is not unexpected.

Canonical correspondence analysis shows correlation between biotope distribution and bathymetry (particularly for Biotopes I and II), indicating that water depth, or more likely factors related to water depth, are the main drivers of faunal distribution within the estuary. Related factors include

TABLE 2. Mean hydrodynamic parameters and the relative abundance of dominant taxa for each biotope.

Biotope I	
Mean water depth (m)	6.8
Mean conductivity (mS/cm)	44.67
Mean dissolved oxygen (%)	90.4
Mean pH	8.13
Representative species	Mean abundance (%)
Rhumblerella subconica	42
Ammonia aoteana	40
Scherochorella barwonensis	9
Biotope II	
Mean water depth (m)	0.4
Mean conductivity (mS/cm)	49.32
Mean dissolved oxygen (%)	100
Mean pH	8.52
Representative species	Mean abundance (%)
Portatrochammina sorosa	39
Ammobaculites exiguus	28
Elphidium excavatum clavatum	10
Biotope III	
Mean water depth (m)	0.3
Mean conductivity (mS/cm)	50.47
Mean dissolved oxygen (%)	96.7
Mean pH	8.35
Representative species	Mean abundance (%)
Elphidium crispum	22
Lamellodiscorbis dimidiatus	18
Cibicides dispars	15
Rosalina australis	12

water movement, sediment grain size, light penetration, nutrient levels (Murray and others, 2006), and percentage vegetation cover (Bell and Edwards, 1980). Each of these parameters vary little throughout a particular biotope, making it difficult to identify single controlling factors, and it is likely that the interaction between all or many of them controls assemblage distribution (Hayward and others, 1999).

Diversity values (Fisher-α, Shannon H, and Dominance) indicate that proximity to the open ocean also plays a significant role in biotope distribution (chiefly biotope III). In St Georges Basin, diversity and the proportion of calcareous taxa decrease with increasing distance from the estuary mouth (Appendix 1; Table 1). Previous studies have identified distinct foraminiferal faunas associated with estuary inlets, generally more diverse than those present in the landward parts of the estuary (Yassini and Jones, 1995; Murray, 2006; Quilty and Hosie, 2006). This is attributed to consistently "high" salinities (conductivity = 50.01 mS/cm), well-oxygenated waters, and strong tidal currents because of close proximity to the open ocean. However, given that specific conductivity and dissolved oxygen values are higher in more isolated parts of St Georges Basin (Figs. 3A, 3B) where there is no associated increase in diversity, the high diversity in biotope III must be influenced by an interaction of factors associated with proximity to the open ocean.

For each of the biotopes identified in this study, equivalent associations can be found in those established by Hayward and others (1999) for brackish and normal marine foraminifera from the estuaries and harbors of New Zealand. Faunas are taxonomically similar, show similar distribution patterns, and are limited by similar environmental conditions. Previous studies have also identified commonalities between Australian and New Zealand faunas (Strotz, 2003; Quilty and Hosie, 2006). Similar associations have also been identified in brackish-water settings internationally (Murray, 1991; Scott and others, 1996), and the virtually circum-global distribution of some estuarine taxa suggests large ocean barriers have been traversed (Murray, 2006).

COMPARISONS WITH LAKE ILLAWARRA

Lake Illawarra, located approximately 60 km north of St Georges Basin, is the closest estuary where a comprehensive study of foraminifera has been undertaken (Yassini and Jones, 1989). Both areas are markedly similar barrier estuary systems (Roy and others, 2001), consisting of a large coastal basin with a narrow entrance channel and identical sedimentary facies distribution. Salinity, dissolved oxygen, and pH levels are also approximately the same. Comparing the two estuaries provides insight into the "consistency" of foraminiferal faunas in southeastern Australian estuaries and into whether localized variables can result in significant divergence. Lake Illawarra is surrounded by residential and industrial development, and Yassini and Jones (1989) noted that the lake receives pollutants of suspended solids, excess nutrients, and heavy metals. Thus, given the low level of anthropogenic impact on St Georges Basin, a comparison should also contribute to understanding how much influence anthropogenic pollutants have on foraminiferal distribution and diversity in a barrier estuary system.

Yassini and Jones (1989) recorded 123 benthic foraminiferal taxa from Lake Illawarra, far higher than the 30 recorded in St Georges Basin. Similar to St Georges Basin, the sites of highest diversity occur in the entrance channel and at the mouth of the estuary. Within the lake basin itself only 16 taxa were recorded, comparable to the 20 recorded from the main part of St Georges Basin.

The four "assemblages" mapped by Yassini and Jones (1989, fig. 8) directly parallel the biotopes described in this study. Biotope I is similar to Assemblage I, with both dominated by two taxa and confined to the deepest parts of the main basin, where sediments consist of dark-colored muds rich in decaying organic matter. In Lake Illawarra, *Ammonia beccarii* (=*A. aoteana* in Strotz, 2003) and *Cribrononion sydneyensis* (Albani) (=*Elphidium excavatum sydneyense* in Hayward and others, 1997) are the dominant taxa. The dominance of the latter, as opposed to *R. subconica*, in St Georges Basin, is attributed to higher salinity levels, as the ecological distribution of *E. excavatum sydneyense* has been reported to be "normal or near-normal marine salinity" (Hayward and others, 1997, p. 79).

Biotope II is a composite of Yassini and Jones' (1989) Assemblages II and III. Distribution is similar, with both faunas largely confined to the outer edges of their respective systems. The assemblages include *A. aoteana*, *E. excavatum sydneyense*, *Ammobaculites foliaceus* (Brady) (=*Simobaculites barwonesis* in Strotz, 2003), and *Tritaxis conica* (Parker and Jones) (=*P. sorosa*). Yassini and Jones (1989) noted that *P. sorosa* and *S. barwonesis* abundance increases where nutrients are greatest. The high proportion

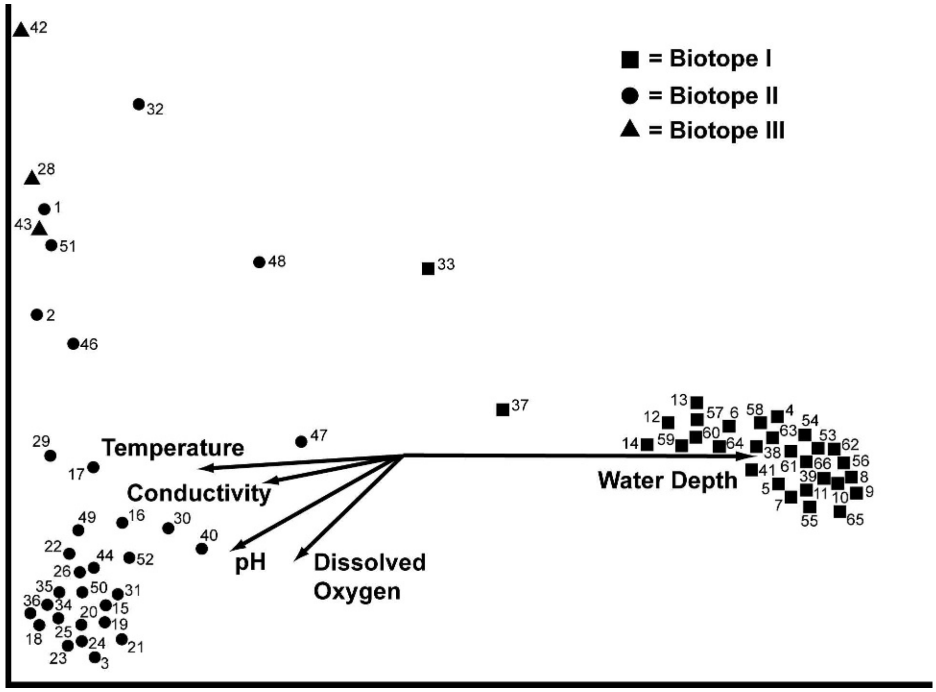

FIGURE 9. Canonical correspondence analysis (CCA) for 66-sampled sites in St Georges Basin. Parameters associated with each vector are indicated in the figure. Different symbols are used to identify the biotope of each sample.

of these taxa in St Georges Basin, particularly *P. sorosa*, suggests potential eutrophication, in agreement with previous descriptions of St Georges Basin as being somewhere between mesotrophic and eutrophic (Murray and others, 2006).

Biotope III is analogous to Yassini and Jones' (1989) Assemblage IV. Both faunas are composed largely of calcareous taxa and both are confined to the seaward portion of their respective systems. There is, however, a marked discrepancy in the number of taxa that make up Assemblage IV, because only 35 of the 89 taxa in the assemblage represent living species, with the remainder being reworked (Yassini and Jones, 1989). This still means that Assemblage IV is over three times more diverse than Biotope III, and this significant disparity is attributed to the presence of seagrass in the entrance channel to Lake Illawarra and its absence from the St Georges Basin channel. Seagrass provides a stable substrate (reducing wave energy), oxygenates the sediments, and reduces turbidity (Yassini and Jones, 1989).

The high degree of similarity between the two systems, both in terms of species composition and assemblage distribution, indicates that foraminiferal faunas along the southeastern Australian coastline may be relatively consistent in barrier estuaries, although further work is needed to confirm this assertion. Interestingly, despite the increased anthropogenic impact upon Lake Illawarra compared to St Georges Basin, there is little difference in faunal distribution or diversity in the affected areas.

SUMMARY

1) Thirty species of foraminifera are present within the St Georges Basin estuary. Diversity is almost equal between agglutinated and calcareous taxa; however, the abundance of agglutinated forms is double that of calcareous species. Four taxa, *A. exiguus*, *P. sorosa*, *R. subconica*, and *A. aoteana*, make up 78% of the fauna.
2) Three foraminiferal biotopes are present within the St Georges Basin estuary. Biotope I is confined to the deepest parts of the main basin; Biotope II, to the outer margins of the basin; and Biotope III, to the very seaward portion of the entrance channel.
3) Faunal distribution is controlled by factors related to water depth and proximity to the open ocean.
4) The distribution of foraminifera within St Georges Basin is remarkably similar to nearby Lake Illawarra. This suggests the possibility of a "standardized" fauna for southeastern Australian estuaries with limited connection to the open ocean.

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APPENDIX 1

Abundance data for foraminifera recovered from sampled sites (Fig. 1) in St Georges Basin. Values equal % relative abundance of taxon. This table can be found on the Cushman Foundation website in the JFR Article Data Repository (http://www.cushmanfoundation.org/jfr/index.html) as item number JFR_DR2012012.

APPENDIX 2

Taxonomic notes for selected foraminiferal species from St Georges Basin This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (http://www.cushmanfoundation.org/jfr/index.html) as item number JFR_DR2012012.