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Foraminiferal response to Holocene environmental changes of a tidal estuary in Victoria, southeastern Australia

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Abstract

The Holocene strata in the Anderson Inlet area in Victoria can be stratigraphically divided into four units, Unit I, Unit II, Unit III, and Unit IV. Unit I and Unit IV lack fossils and were deposited in non-marine, probably fluvial environments. Unit II and Unit III contain abundant foraminifera with molluscs, ostracods and bryozoans. Foraminiferal analysis suggests that Unit III was formed in a partially sheltered marine environment, while the high plankton content and relatively high diversity of benthic species in Unit II indicate that this unit was deposited in an open bay at water depths possibly less than 5 m. The foraminiferal data are integrated with radiocarbon dates to arrive at the following Holocene palaeoenvironmental history in this area: (1) low alluvial plain stage (10,000–7000 yr B.P.); (2) open bay environment stage (7000–5500 yr B.P.); (3) partially sheltered marine environment stage (5500–4500 yr B.P.); (4) alluvial plain and coastal lagoon environment stage (since about 4500 yr B.P.). The foraminiferal fauna show a clear response to these palaeoenvironmental changes. *Globigerina bulloides* can be used as an indicator for cold water marine environments. The high concentration of this species in these middle Holocene sediments shows a strong cold water influence on the coastal environments which reduced the effect of regional warm currents during this period. The Holocene palaeoenvironmental changes in the area were controlled by the Holocene sea-level fluctuations associated with the deglaciation history during this period. Similar integrated studies of shallow to marginal marine strata in southern Africa, America and New Zealand will lead to a better understanding of Holocene relative sea-level change and the interplay between Holocene cold and warm water regimes in the Southern Hemisphere.

Keywords: Holocene; foraminifera; palaeoenvironment; stratigraphy; tidal estuary; Australia

1. Introduction

The Anderson Inlet in southeast Australia preserves marine sediments that were deposited facing the Southern Ocean during the Holocene. This detailed microfossil study reveals information on Holocene palaeoenvironmental changes relating to sea-level fluctuations and changing ocean conditions. Similar analyses of other marginal to fully marine strata elsewhere in the Southern Hemisphere will lead to a better understanding of Holocene relative sea-level change and oceanic processes.

The Anderson Inlet is a tidal estuary, situated on the eastern Victorian coastline approximately 100 km southeast of Melbourne in southeast Australia

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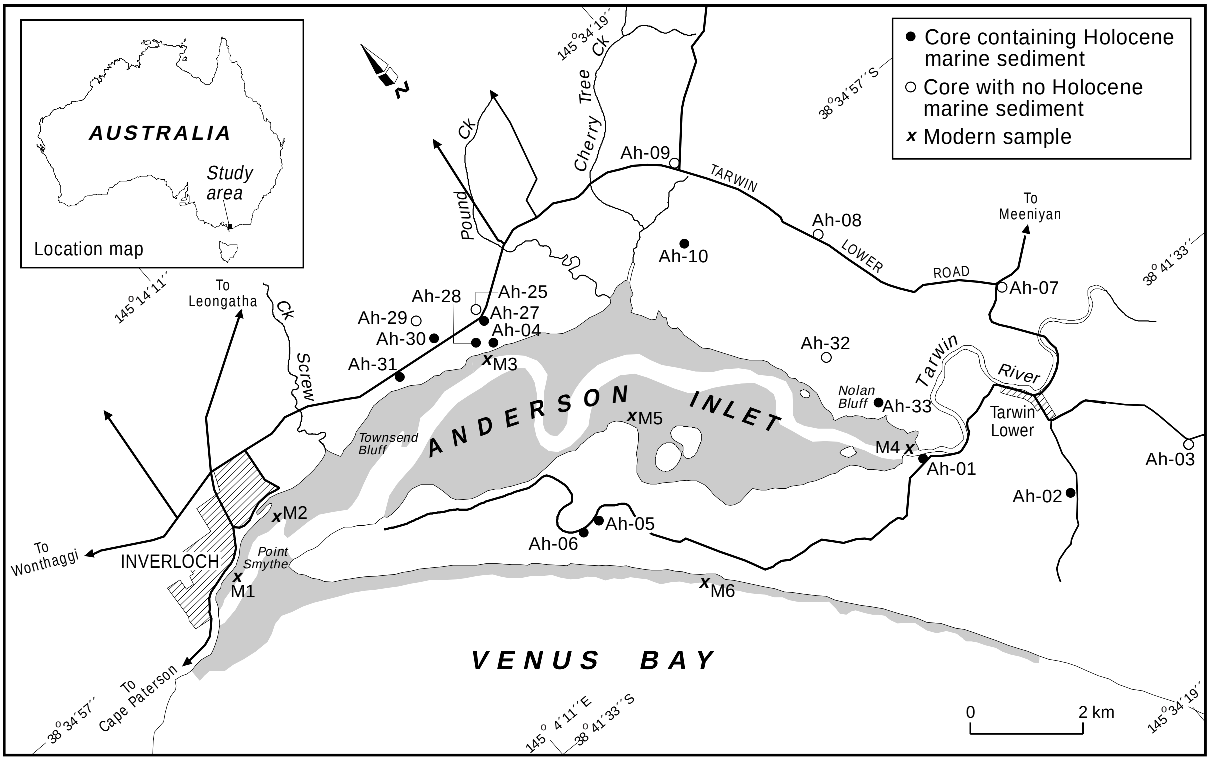

Fig. 1. Locality and main topographic features of Anderson Inlet, Victoria. Dots refer to the cores containing Holocene marine sediment; circles indicate the cores with no Holocene marine sediment; crosses refer to locations of modern samples.

(Fig. 1). It is a long, narrow estuary running roughly parallel to the coast. There are several streams feeding the inlet, the largest being the Tarwin River which originates to the east and flows into the head of the inlet about 2 km west of Tarwin Lower.

The low coastal plateau and bluffs flanking the inlet are composed of Jurassic, Cretaceous and Tertiary formations, which have weathered to form a thin capping of sandy clays and gravel. Around the inlet is a low plain of variable topographic height. Three terraces corresponding to higher sea levels surround the inlet (Fig. 2). Terrace 1 occurs around the inlet at an elevation of about 1–1.5 m. Terrace 2, with a height of about 2 m above mean sea level, can be observed immediately east of Townsend Bluff. Terrace 3 occurs 6 m higher than modern mean sea level and cuts into the Tertiary clays. Terrace 3 corresponds to a higher Last Interglacial sea level (ca. 125,000 yr B.P.) about 7 m above present mean sea level; Terrace 2 corresponds to the first higher Holocene sea level (ca. 7000–6000 yr B.P.) which is 1.8 m higher than the present one; Terrace 1 corresponds to the second higher Holocene sea level (ca. 5500–4500 yr B.P.) which is 0.5 m higher than modern mean sea level. The sea-level history of the Anderson Inlet area has been briefly reported by Li et al. (1998). The microfauna discussed in this paper come from the boreholes on Terraces 1 and 2 (Fig. 1) which have a Holocene age, no fossils have been observed in the older formations in the area.

Anderson Inlet is situated at the eastern margin of the Great Australian Bight (GAB in Fig. 3). This area and adjacent coasts are influenced by three hydrological systems: the Subtropical Convergence (STC), the Leeuwin Current and the East Australian Current. Howard and Prell (1992) show that over the past 500,000 years, there have been repeated latitudinal shifts by the STC. For most of that time the STC has been equatorward of its present position and only four brief times poleward by several degrees. It has been observed that the Leeuwin Current carries warm, low-salinity water from north-

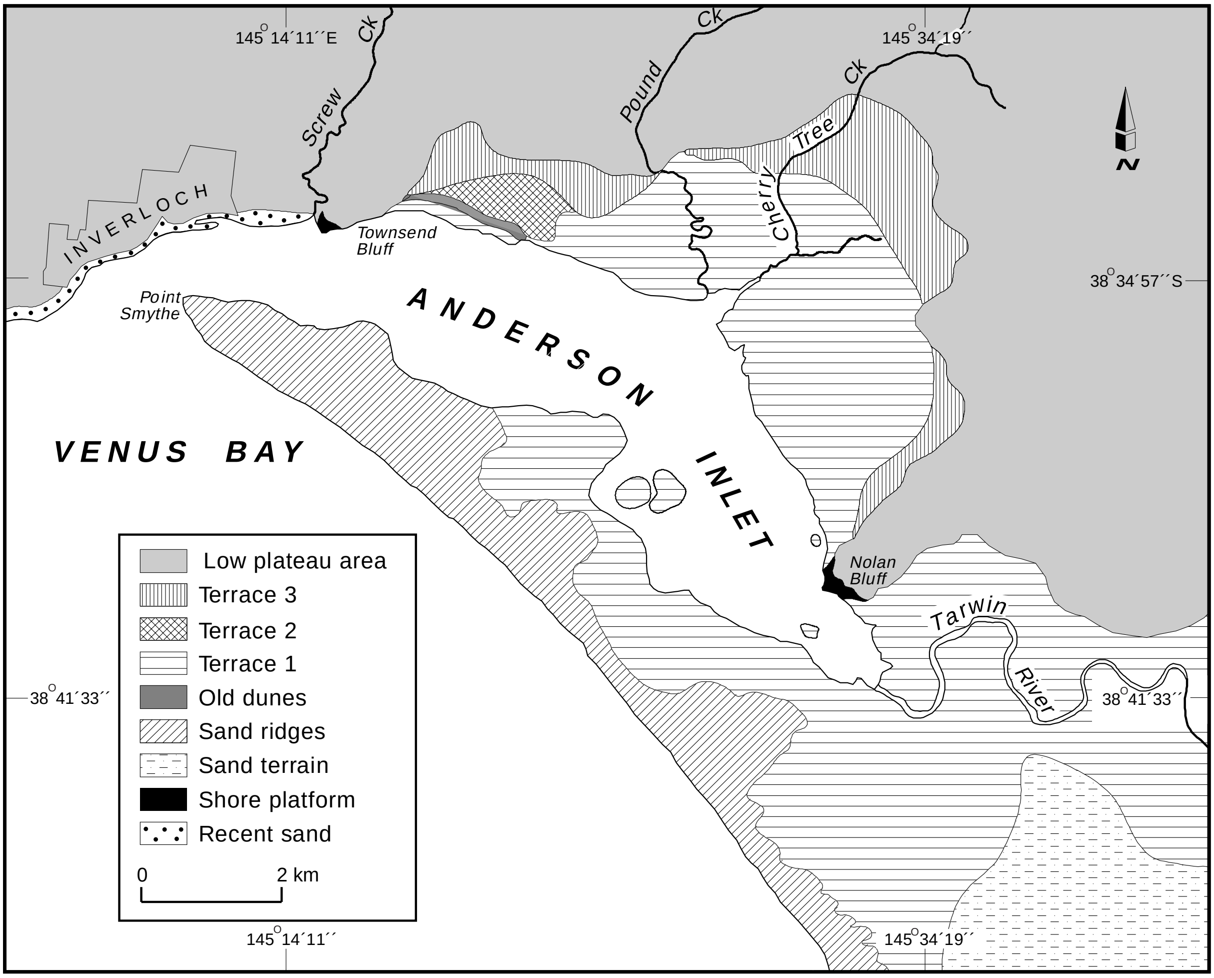

Fig. 2. Geomorphological structure of Anderson Inlet area. Terrace 1 and Terrace 2 are depositional terraces formed during the Holocene. Terrace 3 is a terrace cut through Tertiary clays during the Last Interglacial.

western Australia around Cape Leeuwin into the GAB (McGowran et al., 1997). However, due to the blocking effect of Tasmania and a northwards-shifting STC, the East Australian Current deflects eastward (Fig. 3). It is the Leeuwin Current which accounts for the dispersal of a tropical marine fauna along the southern margin of Australia (Maxwell and Cresswell, 1981). Almond et al. (1993) suggest that the Leeuwin Current's influence reached to the central GAB during the Last Interglacial and Holocene.

The aim of the contribution is to study foraminiferal distributions in the Holocene sediments and to examine the influence of oceanographic conditions on the marine fauna and coastal environments during this period.

2. Methods

2.1. Coring and sampling

To obtain samples, shallow auger borings (Fig. 1) have been made to sample the near-surface sediments in the area. The types of auger used were a bucket-type auger and a conventional soil auger; the former was used to obtain large samples particularly retaining samples of wet silt and sand which may contain

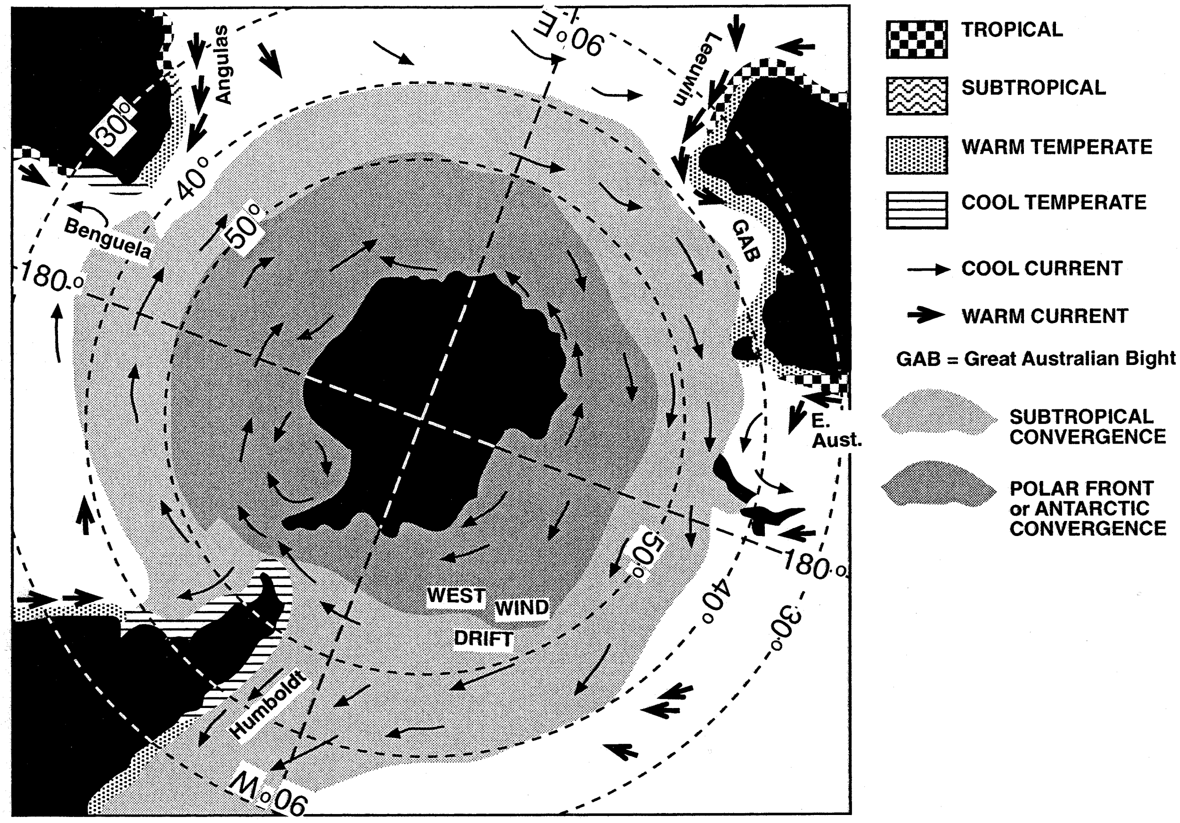

Fig. 3. Modern biogeographic and oceanographic configuration on the shelves of the southern continents. Adapted from McGowran et al. (1997).

shell material for radiocarbon dating, the latter was used because it has good cutting characteristics in tight clay or silty clay.

Auger cores were taken to depths of 5.2 m, but most bores range from 2 to 3.5 m. The auger was retrieved every 0.1 to 0.2 m, depending on the nature of sediments. The samples were described in the field using colour, composition and grain size, and then sealed in plastic bags and brought to the laboratory.

2.2. Foraminiferal analysis

For foraminiferal analysis, about 50 g of sediment was disaggregated with distilled water, left for 24 h, then sieved with a 63-μm sieve. The coarse fraction retained on the sieve was put in a beaker and dried in the oven. The dried material was then placed in a container and the microfossils separated by floatation with carbon tetrachloride. Microfossils were extracted from the residue, identified and counted.

The foraminiferal classification used in this study follows that of Loeblich and Tappan (1964). Additional taxonomic references used to identify southeastern Australian foraminifera include Brady (1884), Cushman (1932), Chapman and Parr (1935), Albani (1974, 1979), Murray (1975), Seibold (1975), McCulloch (1977, 1981), Kohl (1985) and Yassini and Jones (1989, 1995).

3. Lithostratigraphy and biostratigraphy

Based on lithological, geomorphological and foraminiferal analyses with radiocarbon dating, four Holocene sedimentary units can be defined in the area, denoted Unit I, Unit II, Unit III, and Unit IV (Fig. 4).

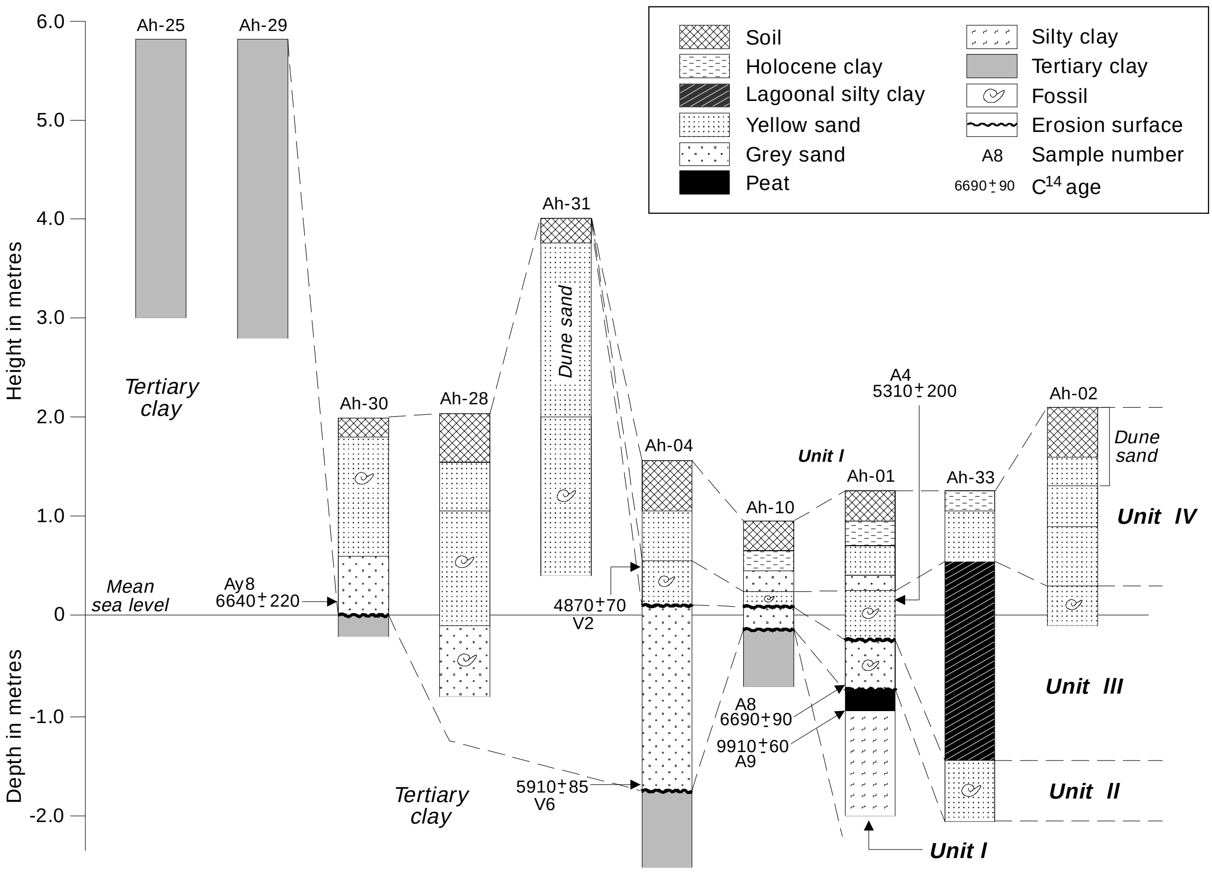

Fig. 4. Stratigraphic correlation of the four Holocene sedimentary units in the Anderson Inlet. For location of the cores, see Fig. 1.

3.1. Unit I (10,000–7000 yr B.P.)

Unit I occurs in core Ah-01 in the interval 2–3.2 m (Fig. 4). The upper layer consists of peat containing wood fragments, the lower layer is composed of dark-grey sandy clay. The wood fragments at the bottom of the peat layer yielded a radiocarbon date of 9910 ± 60 yr B.P., indicating that the sediment was deposited during the early Holocene (10,000–7000 yr B.P.). No foraminifera were found in this unit.

3.2. Unit II (7000–5500 yr B.P.)

Unit II, geomorphologically correlating with Terrace 2 (Fig. 2), was deposited during the first higher Holocene sea-level stage. Core Ah-30 contains a 2-m-thick representative section of this unit which unconformably overlies Tertiary sediments (Fig. 4). A radiocarbon date from the base of this unit gives an age of 6640 ± 220 yr B.P.

With the exception of the upper 0.2 m, this unit contains abundant foraminifera. A total of 29 genera occur in this unit, including 62 benthonic species and 5 plankton species. The distribution of the 8 common genera in core Ah-30 is shown in Fig. 5. Unit II is characterised by three foraminiferal assemblages. Assemblage A is characterised by *Elphidium*, *Quinqueloculina*, *Triloculina*, and *Miliolinella*. The relatively lower percentages of plankton in this assemblage may correspond to the start of middle Holocene transgression. Assemblage B contains abundant *Globigerina*, *Elphidium*, *Ammonia*, *Quinqueloculina*, *Triloculina*, *Miliolinella*, *Cibicides* and *Globorotalia.* The relatively high plankton percentages in Assemblage B may suggest a relatively higher sea level than Assemblage A. Assemblage C

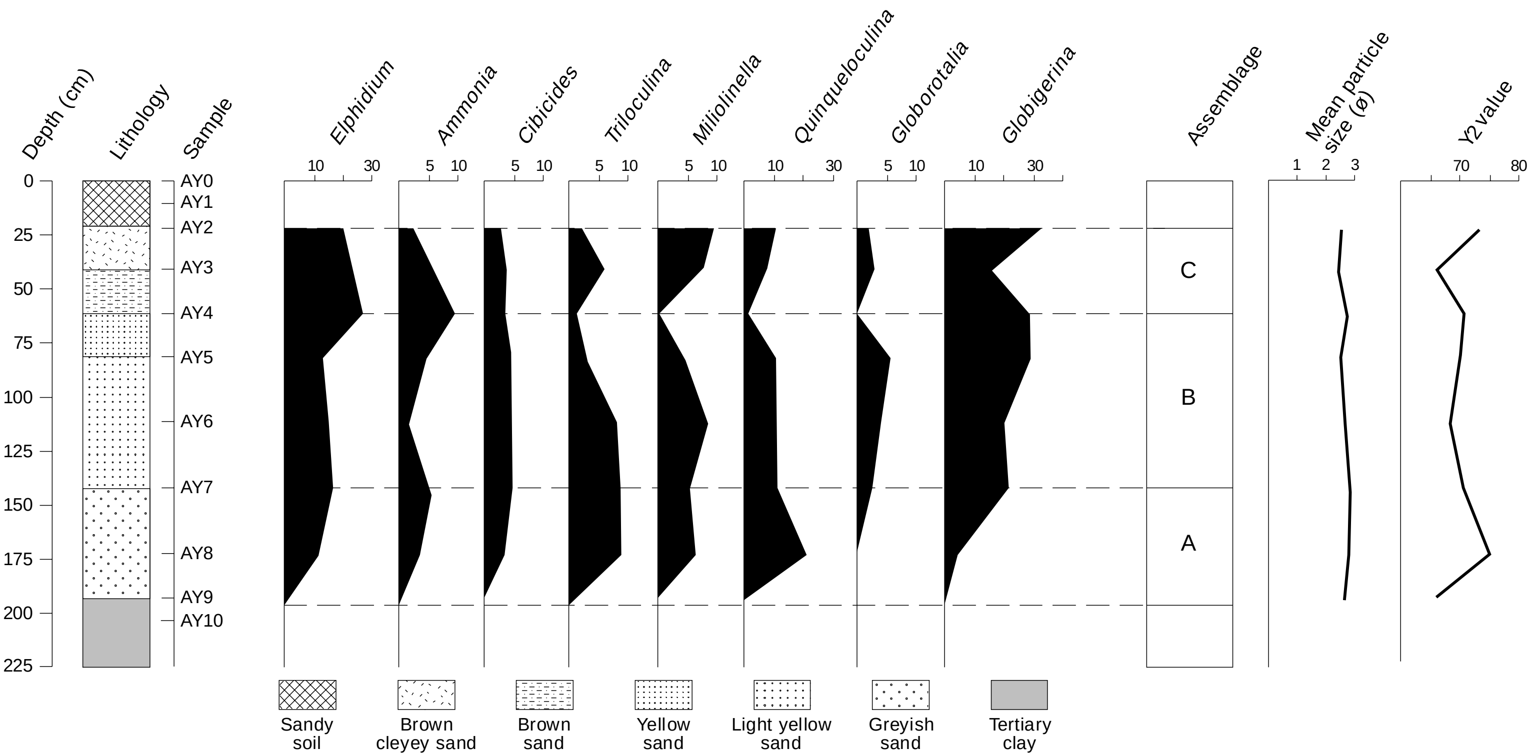

Fig. 5. Distributional pattern of the main foraminiferal genera in core Ah-30.

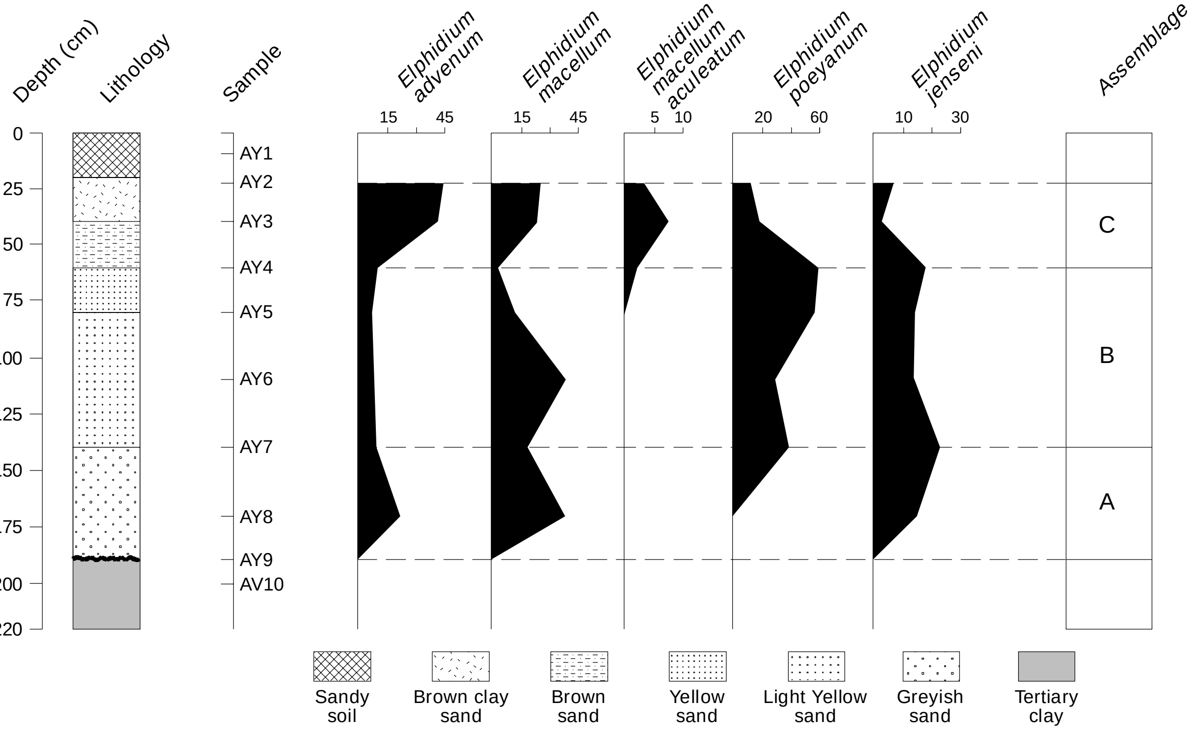

Fig. 6. Distributional diagram of some species of the family Elphidiidae in core Ah-30.

is similar to Assemblage B, except that *Elphidium* and *Ammonia* are relatively more abundant. *Elphidium* species are shown in Fig. 6. Data in Figs. 5 and 6 show trends in foraminiferal percentages that follow lithological changes. However, mean particle size seems to have minor influence on foraminiferal distribution.

Y2 value ($Y2 = 15.6534M + 65.7091\partial i2 + 18.1071Ski + 18.5053Kg$, where M represents mean size, ∂i represents standard deviation, Ski represents skewness, and Kg represents kurtosis), calculated according to Sahu's formula (Sahu, 1964), is used to distinguish between beach and shallow marine sediments, and may reflect relative sea-level fluctuations because its change correlates with planktonic fluctuations.

3.3. Unit III (5500–4500 yr B.P.)

Unit III, 0.3–0.5 m thick and consisting of grey sand at the top and yellow sand at the base, was formed during the second higher Holocene sea-level stage. Radiocarbon ages of 4870 ± 70 yr B.P. from core Ah-01 and 5310 ± 200 yr B.P. from core Ah-04 suggest that this unit correlates to the final stage of the mid-Holocene from about 5500 to 4500 yr B.P. Fifteen species from ten genera of foraminifera occur in this unit. Figs. 7 and 8 show the distribution of foraminifera in core Ah-01 and core Ah-04.

In Fig. 7, two foraminiferal assemblages (Assemblage **a** and Assemblage **b**) are identified. Assemblage **b**, belonging to Unit II, contains a high percentage of *Elphidium*, *Cibicides* and plankton (15%). Assemblage **a**, belonging to Unit III, contains a high percentage of *Ammonia* (up to 60%). Planktonic foraminifera decrease upward to 10%.

Three assemblages can be identified in core Ah-04 (Fig. 8). Assemblages A and B of Unit II contain a high proportion of *Elphidium*, *Quinqueloculina*, *Triloculina*, and *Globigerina bulloides*, a taxon which decreases in Assemblage C of Unit III. *Globorotalia* and *Ammonia* occur in low amounts in Assemblages A and B, but increase in abundance in Assemblage C.

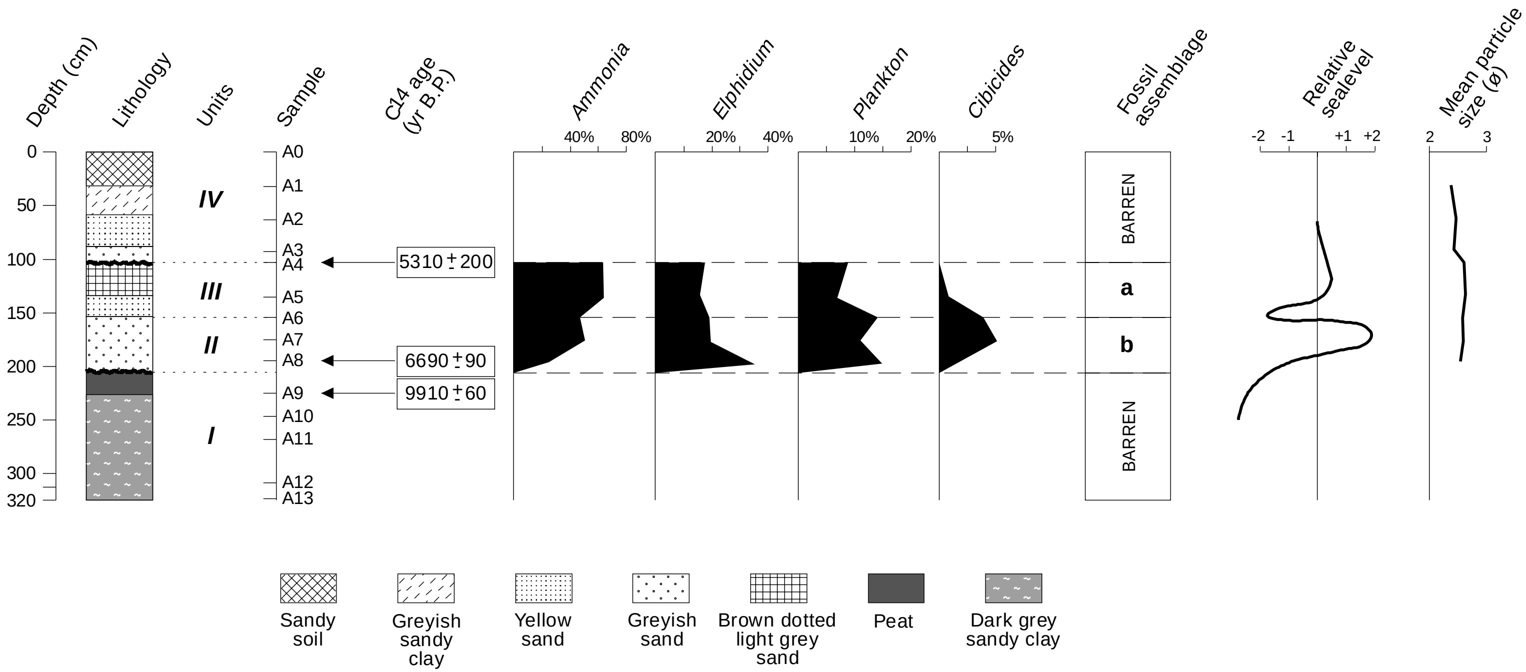

Fig. 7. Distributional diagram of the main foraminiferal genera in core Ah-01.

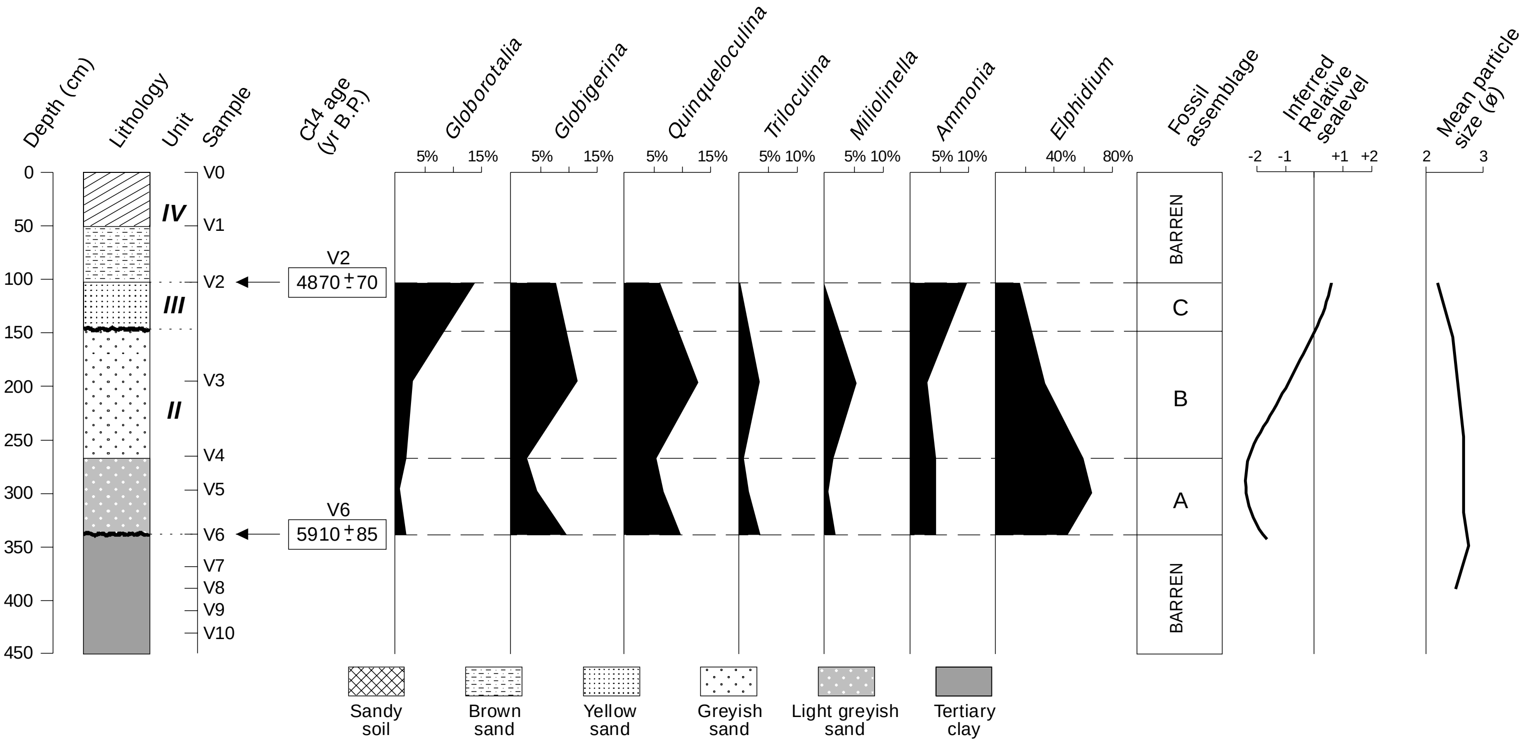

Fig. 8. Distributional diagram of the main foraminiferal genera in core Ah-04.

3.4. Unit IV (deposited since 4500 yr B.P.)

Unit IV is widely distributed around Anderson Inlet, and geomorphologically coincides with the upper part of Terrace 1. This unit is preserved in cores Ah-01 and Ah-04 from the surface of Terrace 1 down to 1 m, and is composed of humic soil, dark-grey clay, yellowish sand and greyish sand. This interval contains no foraminifera. Due to a lack of suitable material for radiocarbon dating, we were unable to absolutely date this unit; however, it overlies Unit III and therefore was deposited after the late Holocene (after 4500 yr B.P.).

4. Interpretation of depositional environment

The foraminiferal distribution data, combined with the stratigraphic analyses can be used to determine the palaeoenvironmental evolution at Anderson Inlet during the Holocene. This will be discussed in four time intervals.

4.1. 10,000–7000 yr B.P. (Unit I)

No foraminifera occur in Unit I, which may suggest that the early Holocene sediment has a non-marine origin. The existence of dark peats and statoblasts of fresh-water bryozoa *Fredericella* sp. in silty clays at the bottom of core Ah-01 appears to indicate a backswamp or a lagoonal depositional environment (cf. Pennak, 1989) during the early Holocene.

4.2. 7000–5500 yr B.P. (Unit II)

A large diversity of foraminifera occur in Unit II with a maximum of 60 species in each sample. Common benthic genera in Unit II are *Elphidium*, *Globigerina*, *Quinqueloculina*, *Triloculina*, *Miliolinella*, *Cibicides* and *Ammonia* (Fig. 5), with lesser amounts of *Discorbis*, *Lagena* and *Uvigerina*. Miliolinids have a wide distribution in the shallow marine area along Windang Peninsula in New South Wales (Yassini and Jones, 1989). *Discorbis dimidiatus* and *Cibicides refulgens* frequently occur at water depths between 80 and 100 m in South Australia, while *Ammonia beccarii* is found in water depths less than 60 m, with a maximum faunal abundance of 64% near the River Murray mouth in South Australia (Li et al., 1996). *Ammonia beccarii* is a widespread euryhaline species occurring worldwide in almost all foraminiferal assemblages from marine lagoons, tidal channels, intertidal and shallow subtidal environments, estuaries, and bays (Cann et al., 1993). This taxon dominates at water depths of less than 1 m where substrates are sandy and decreases in relative abundance from marine lagoons to the open ocean (Yassini and Jones, 1989). *Ammonia beccarii* has been recorded around the coasts of New South Wales and Victoria (Apthorpe, 1980).

Foraminifera of the family Elphidiidae are generally lagoonal to shelf species. In South Australia, the recent species *Elphidium macellum* and *Elphidium macellum aculeatum* are restricted to shallow marine conditions (Cann et al., 1988). Hayward et al. (1997) observed that *Elphidium* live in their greatest abundance in intertidal and shallow subtidal environments shallower than 2 m. *Elphidium* is the most common genus in Unit II, suggesting that this unit was deposited in a shallow intertidal or subtidal environment. In addition, several recent *Elphidium* species have distinct environmental preferences and ecological distribution patterns. Taxa living exclusively in stenohaline conditions are *E. macellum* and *E. craticulatum*. *E. advenum* can tolerate slightly brackish to normal marine conditions (Hayward et al., 1997). *E. macellum* is often a major component of intertidal to shallow subtidal (0–20 m), normal marine foraminiferal associations around the east coast of Australia, with common *Quinqueloculina*, *Spiroculina*, *Triloculina*, *Discorbis* and other species of Elphidiidae (Hayward et al., 1997). *E. craticulatum* has been recorded off the coast of Victoria by Albani and Yassini (1993). This taxon is common in normal marine, intertidal to subtidal foraminiferal assemblages inhabiting clean sand.

Johnson and Albani (1973) recognised four recent foraminiferal biotopes in Broken Bay, New South Wales; these include an outer bay biotope, an intermediate shallow biotope, an inner shallow biotope and a deep water biotope. The outer bay biotope occurs in the outer part of the Broken Bay in New South Wales where the water is shallow (about 5 m) with a sandy bottom. The intermediate shallow biotope is restricted to sandy shallow areas close to the shore. The foraminiferal composition of Unit II is similar to both the outer bay biotope and intermediate shallow biotope of Johnson and Albani (1973). The foraminiferal assemblages in Unit II also show similarity to the marginal marine assemblage described by Hayward and Hollis (1994). We therefore infer that Unit II was deposited in a shallow marine environment at water depths of less than 5 m.

The planktonic foraminifera that dominate the samples from Unit II are *Globigerina bulloides* and *Globorotalia trunctulinoides* with lesser amounts of *Globorotalia hirsuta*, *Globorotalia* sp., *Globorotalia inflata* and *Globigerinoides ruber*. Li et al. (1996) observed that planktonic foraminifera are absent from the samples taken close to the river mouths in South Australia, but they increase in abundance to 10% of total assemblage at water depths of 100 m and can comprise 40–50% of the assemblage in deeper waters. However, the relatively high percentage of plankton (up to 33%) in Unit II may not be due to a deep-water shelf environment because of the presence of a benthic assemblage of shallow biotope. It may be attributed to the influence from the Southern Ocean because of the presence of cool-water species such as *Globigerina bulloides* (cf. Li et al., 1996). *Globigerina bulloides* is abundant in polar and transitional regions, but *Globorotalia inflata* is confined to temperate regions (Be, 1977). Yassini and Jones (1995) observed that *Globorotalia hirsuta, Globigerinoides ruber,* and *Globigerina bulloides* also commonly occur in continental slope deposits. *Globigerinoides ruber* is predominantly a subtropical species and is thought to be one of the shallowest dwelling planktonic foraminiferal species (Be, 1977; Hemleben et al., 1989).

Based on the benthic and planktonic data, Unit II was deposited in an open marine (without sand barrier system) but shallow water environment. The relatively high proportion of *Globigerina bulloides* in Unit II indicates influence by the cool waters from the Southern Ocean.

4.3. 5500–4500 yr B.P. (Unit III)

Foraminiferal diversity decreases upward in Unit III. The planktonic foraminiferal content also decreases in both number and diversity (Figs. 7 and 8). This marked change in faunas suggests that Unit III was deposited in an environment different from normal open ocean conditions inferred for Unit II.

Marked faunal changes were recorded in Unit III in cores Ah-01 and Ah-04. *Quinqueloculina*, *Triloculina*, *Miliolinella* and *Spiroculina* do not occur in this unit in core Ah-01, but they occur in core Ah-04. *Ammonia beccarii* becomes dominant in Unit III in core Ah-01, making up to 60% of the total assemblage, but it only increases slightly in Unit III in core Ah-04 from 5% to 10%. *Globigerina bulloides*, *Globorotalia trunctulinoides* and *Gr. hirsuta* occur and comprise around 10% of the total assemblage in Unit III in core Ah-01, but they comprise 20% of the total assemblage in Unit III in core Ah-04. *E. macellum*, *E. poeyanum* and *E. advenum* comprise relatively large proportions in Unit III in core Ah-01 (Fig. 9), but *E. craticulatum*, in addition to *E. macellum* and *E. poeyanum*, occurs in relatively higher abundance in Unit III in core Ah-04 (Fig. 10). Modern samples M1–M6 were collected from Anderson Inlet and Venus Bay (for locations see Fig. 1). Their faunal contents are listed in Appendix B. Although cores Ah-01 and Ah-04 are located at different positions (Fig. 1), modern samples M3 (near Ah-04) and M4 (near Ah-01) show only minor faunal difference and contain a low proportion (4% and 0%, respectively) of planktonic species (Appendix B). The foraminiferal contents in samples M3 and M5 show similarity to samples S6 and S7 in Port Pegasus in the southern tip of New Zealand (Hayward and Hollis, 1994), indicating an estuarine environment. The concentration of planktonic species reduced markedly towards the head of the inlet, probably due to the narrowness of the entrance of this inlet. Therefore, the faunal difference between Ah-01 and Ah-04 suggests that these two sites were deposited in different environments during Unit III times. The high percentage of *Ammonia beccarii* and relatively larger proportion of *E. advenum* in this unit may be due to salinity variations in the environment. The faunal and geomorphological evidence suggest that the appearance of an offshore barrier system during Unit III times caused a restriction in marine circulation in the area around core Ah-01, while open marine conditions existed near core Ah-04. Therefore the depositional environment for Unit III was probably a partially barred estuary that was more exposed to oceanic conditions than today's Anderson Inlet. This result suggests that the geomorphological features of the modern Anderson Inlet are relatively young.

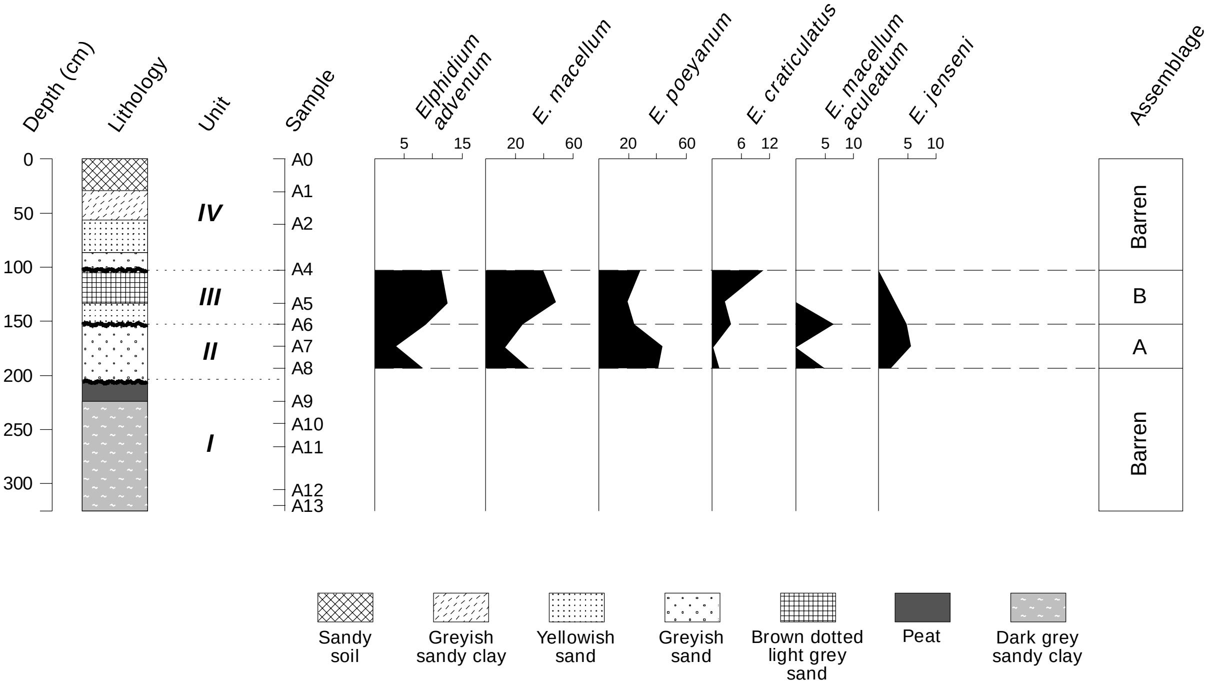

Fig. 9. Distributional diagram of some *Elphidium* species in core Ah-01.

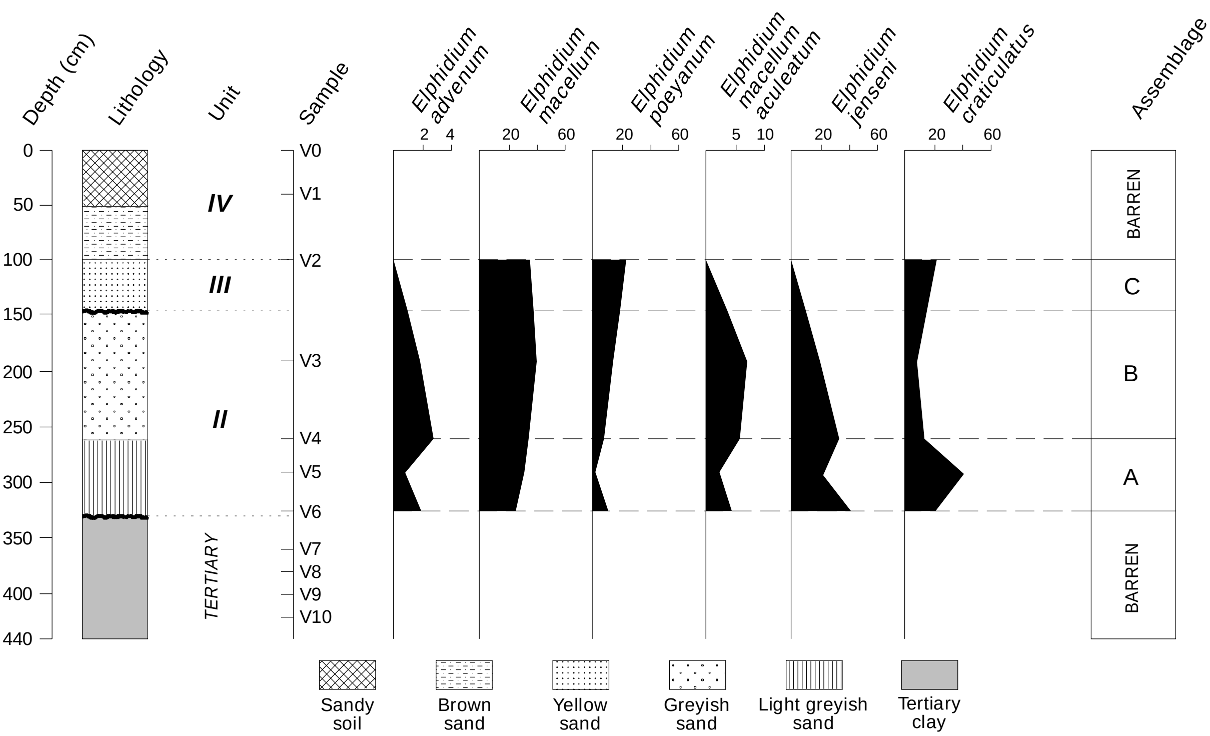

Fig. 10. Distributional diagram of some *Elphidium* species in core Ah-04.

The low terraces in the area were formed since the middle Holocene. The barrier system in the area was formed during the late Holocene. Figs. 6 and 7 also show that mean particle size has little to do with foraminiferal distribution, and that major foraminiferal changes accord with lithological changes which indicate that substrates and environmental changes may exert significant influence on the foraminiferal distribution. Sea-level fluctuation has an apparent influence on foraminiferal assemblages.

4.4. Since 4500 yr B.P. (Unit IV)

Unit IV does not contain any marine fossils and contains rootlets and wood debris, suggesting a terrestrial origin. It overlies the marine sediment (Unit III), suggesting a regressive event during Unit IV times. With the fall of sea level since about 4500 yr B.P., rivers deposited a sequence of fluvial sediments around the Anderson Inlet. These fluvial sands were an important clastic supply to the 'modern' barrier system forming the Anderson Inlet.

5. Discussion

The maximum occurrence of the planktonic foraminifera species *Globigerina bulloides* is associated with greater nutrient concentration and lower sea-surface temperatures during the southwestern monsoon period in the Arabian Sea (Prell, 1984). This relationship enabled Naidu and Malmgren (1995) to use the relative abundances of *Globigerina bulloides* in the sediment cores to trace the upwelling history. Naidu and Malmgren (1995) noted a lower abundance of *Globigerina bulloides* in the Arabian Sea in the last glacial and late Holocene periods and recorded higher values in the early and middle Holocene. *Globigerina bulloides* is also commonly used as a cool-water indicator in the study of an interplay between warm water currents and the West Wind Drift during climatic cycles (Almond et al., 1993; McGowran et al., 1997).

In our study, the relatively high abundances (up to 33%) of *Globigerina bulloides* occur during the middle Holocene (7000–4500 yr B.P.), suggesting that the Anderson Inlet area of Venus Bay had concentrated nutrients and was strongly influenced by the West Wind Drift and upwelling from the Southern Ocean during that time. This agrees with Naidu and Malmgren's results as well as proxy records such as those derived from pollen (Prell and Van Campo, 1986), sediments (Sirocko et al., 1993), climate simulation models (Prell and Kutzbach, 1987), and foraminiferal data (Li et al., 1996), which also suggest that the upwelling was common and widespread both in the Indian Ocean and southwestern Pacific Ocean during the middle Holocene.

Typical warm water planktonic foraminifera are absent in the middle Holocene marine sediments, hence neither the Leeuwin Current nor the East Australian Current influenced this part of Australia's coast. Higher sea levels may accompany warming and an active Leeuwin Current in southern Australia (McGowran et al., 1997). This suggestion may be true, but our data show that the Leeuwin Current's effect was limited to the west side of the GAB by stronger West Wind Drift and upwelling during the middle Holocene. The stronger West Wind Drift and upwelling might relate to the worldwide deglaciation history, particularly the deglaciation of the Antarctic ice cap during this time. In the Northern Hemisphere, melting of the Laurentide ice sheet is assumed to have been completed by 6000 yr B.P. According to the study on Antarctic deglaciation (Goodwin, 1993), the southern Windmill Islands were deglaciated by 8000 yr B.P., while the northern Islands were deglaciated by 5500 yr B.P. The 8000 yr B.P. minimum date for deglaciation of the southern Windmill Islands agrees with the 7700 yr B.P. age for deglaciation of the northern Bunger Hills to the west of the Windmill Islands (Colhoun and Adamson, 1991), the 8000–9000 yr B.P. age for ice-sheet recession on the Wilkes Land coast, and the 7000–8000 yr B.P. date for glacier thinning in the D10 ice core on the Adelie Land coast (Raynaud et al., 1979) when eustatic sea level was rising rapidly. The date of ca. 5500 yr B.P. for the Bailey Pond and Lake Holl may correspond to the onset of a warm summer climate associated with a mid-Holocene warm period between 6000 and 5000 yr B.P. inferred from the Dome C ice core (Lorius et al., 1979). The dates for Units II and III in our study broadly agree with a worldwide deglaciation history during the Holocene, strongly suggesting the relationship between the upwelling of the Southern Ocean and the worldwide deglaciation and the eustatic nature of the higher sea levels during Units II and III deposition times. The concentration of *Globigerina bulloides* in modern samples M1 and M2 (Fig. 1; Appendix B) is much lower than that in samples of middle Holocene marine sediments, suggesting that at present cold water from the Southern Ocean is of less influence. This observation agrees with the studies made by Naidu and Malmgren (1995) and McGowran et al. (1997). Similar studies along the coasts of New Zealand, southern Africa and southern America will lead to a better understanding of the interplay between warm and cold water regimes and the effects of oceanographic systems on coastal environmental changes.

6. Conclusions

This multidisciplinary integrated foraminiferal, stratigraphic, and geomorphological study of Holocene sediments in the Anderson Inlet in southeast Australia has yielded the following conclusions.

(1) Four stratigraphic units can be identified based on shallow core data and geomorphological evidence in the area. Unit I was probably deposited in a coastal wetland during the early Holocene. Unit II was formed in an open marine environment between 7000 and 5500 yr B.P. Unit III was deposited in a partially barred estuary between 5500 and 4500 yr B.P. Unit IV was formed in a fluvial environment after 4500 yr B.P.

(2) The Holocene palaeoenvironments in the Anderson Inlet ranged from coastal wetland to normal open ocean, partially barred estuary and river-dominated coastal lowland. Two transgressive events occurred during the Holocene, corresponding to Units II and III. These events correlate with events in the worldwide deglaciation history, suggesting a glacio-eustatic cause.

(3) Foraminifera were found to be more abundant in the normal open marine environment (Unit II) than in the relatively restricted environment (Unit III) in the Anderson Inlet area. The distribution pattern of dominant genera or species has little to do with mean particle size. However, major faunal changes occur where main lithological changes take place, suggesting that except for mean particle size, substrates and environmental changes have a significant influence on foraminiferal distribution. Sea-level fluctuations have a clear relation to foraminiferal assemblages.

(4) The relatively high proportions of planktonic foraminifera such as *Globigerina bulloides* suggest that the Anderson Inlet area had been influenced by the upwelling of the cool water regime from the Southern Ocean during the middle Holocene transgression. The upwelling during this time appears to be associated with the worldwide deglaciation history. During the middle Holocene, stronger West Wind Drift and upwelling of the Southern Ocean reduced the effect from a warm current like the Leeuwin Current in the region.

(5) The interplay of cold and warm water regimes has an important role in the faunal assemblage and distribution. Deglaciation and sea-level changes may have modified oceanographic processes. Similar studies in the Southern Hemisphere will lead to a better understanding of the evolution of the Holocene Southern Ocean.

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Appendix A. Foraminiferal taxa cited in the text

References for the original descriptions of the following species can be found in Albani (1979) and Yassini and Jones (1995).

Ammonia beccarii (Linné)
Cibicides refulgens (Montfort)
Discorbis dimidiatus (Jones and Parker)
Elphidium advenum (Cushman)
Elphidium craticulatum (Fichtel and Moll)
Elphidium macellum (Fichtel and Moll)
Globigerina bulloides (d'Orbigny)
Globigerinoides ruber (d'Orbigny)
Globorotalia hirsuta (d'Orbigny)
Globorotalia inflata (d'Orbigny)
Globorotalia trunctulinoides (d'Orbigny)

Appendix B

Identifications and counts of foraminifera in 50 g sediment samples used in quantitative analysis. Sample numbers are those used in Figs. 1-7

	Samples in core Ah-30										
	AY0	AY1	AY2	AY3	AY4	AY5	AY6	AY7	AY8	AY9	AY10
Ammonia	0	0	16	22	15	19	5	23	3	0	0
Elphidium	0	0	96	79	40	49	57	68	10	0	0
Cibicides	0	0	11	13	6	18	16	20	3	0	0
Globorotalia	0	0	10	10	0	20	13	11	0	0	0
Globigerina	0	0	154	55	44	113	73	89	4	0	0
Bolivina	0	0	11	12	9	14	8	7	4	0	0
Bulimina	0	0	1	1	0	0	0	0	0	0	0
Oolina	0	0	15	11	6	13	11	15	3	0	0
Lagena	0	0	6	5	1	4	4	5	1	0	0
Fissurina	0	0	7	3	3	2	2	7	5	0	0
Uvigerina	0	0	0	1	2	8	6	8	0	0	0
Trifarina	0	0	0	9	2	12	10	2	0	0	0
Planulinoides	0	0	3	3	2	6	2	4	3	0	0
Patelinella	0	0	5	3	3	5	5	1	4	0	0
Glabritella	0	0	4	5	0	2	0	3	0	0	0
Quinqueloculina	0	0	51	28	3	38	41	47	17	0	0
Triloculina	0	0	9	19	1	12	27	33	7	0	0
Miliolinella	0	0	45	25	0	17	28	25	5	0	0
Guttulina	0	0	2	4	1	2	3	4	0	0	0
Lenticulina	0	0	2	2	0	3	2	2	1	0	0
Discorbis	0	0	13	12	5	3	16	14	6	0	0
E. advenum	0	0	41	32	4	4	5	8	3	0	0
E. macellum	0	0	24	19	2	7	24	15	5	0	0
E. macellum aculeatum	0	0	3	6	1	0	0	0	0	0	0
E. poeyanum	0	0	11	15	25	30	17	31	0	0	0
E. craticulatum	0	0	0	0	0	0	2	0	0	0	0
E. jenseni	0	0	7	3	8	8	9	19	2	0	0

Appendix B (continued)

	Samples in core Ah-01													
	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13
Ammonia	0	0	0	0	58	141	112	119	69	0	0	0	0	0
Elphidium	0	0	0	0	16	37	45	47	85	0	0	0	0	0
Cibicides	0	0	0	0	0	3	10	11	5	0	0	0	0	0
Globorotalia	0	0	0	0	2	3	8	6	2	0	0	0	0	0
Globigerina	0	0	0	0	6	13	25	18	33	0	0	0	0	0
Bolivina	0	0	0	0	0	3	7	3	10	0	0	0	0	0
Bulimina	0	0	0	0	1	1	4	2	0	0	0	0	0	0
Oolina	0	0	0	0	3	4	2	3	4	0	0	0	0	0
Lagena	0	0	0	0	1	6	7	6	10	0	0	0	0	0
Fissurina	0	0	0	0	0	3	1	3	5	0	0	0	0	0
Uvigerina	0	0	0	0	3	0	5	8	7	0	0	0	0	0
Trifarina	0	0	0	0	1	3	3	5	6	0	0	0	0	0
Planulinoides	0	0	0	0	0	2	0	2	3	0	0	0	0	0
E. advenum	0	0	0	0	2	5	4	2	8	0	0	0	0	0
E. macellum	0	0	0	0	7	20	12	7	29	0	0	0	0	0
E. macellum aculeatum	0	0	0	0	0	0	3	0	5	0	0	0	0	0
E. poeyanum	0	0	0	0	5	8	11	22	38	0	0	0	0	0
E. craticulatum	0	0	0	0	2	1	2	0	2	0	0	0	0	0
E. jenseni	0	0	0	0	0	1	2	3	2	0	0	0	0	0

	Samples in core Ah-04										
	V0	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
Ammonia	0	0	4	5	24	25	22	0	0	0	0
Elphidium	0	0	7	57	290	323	241	0	0	0	0
Cibicides	0	0	5	3	8	4	14	0	0	0	0
Globorotalia	0	0	5	5	9	6	8	0	0	0	0
Globigerina	0	0	3	19	12	24	47	0	0	0	0
Bolivina	0	0	1	8	11	5	12	0	0	0	0
Oolina	0	0	1	7	15	11	12	0	0	0	0
Lagena	0	0	2	9	10	9	6	0	0	0	0
Fissurina	0	0	0	2	8	2	3	0	0	0	0
Uvigerina	0	0	2	2	5	5	7	0	0	0	0
Trifarina	0	0	1	3	3	4	5	0	0	0	0
Planulinoides	0	0	1	2	4	1	4	0	0	0	0
Patelinella	0	0	0	0	0	2	3	0	0	0	0
Glabritella	0	0	0	1	1	1	4	0	0	0	0
Quiqueloculina	0	0	2	21	26	35	49	0	0	0	0
Triloculina	0	0	0	7	3	9	19	0	0	0	0
Miliolinella	0	0	0	9	7	6	11	0	0	0	0
Guttulina	0	0	2	0	8	4	3	0	0	0	0
Lenticulina	0	0	0	1	3	0	2	0	0	0	0
E. advenum	0	0	0	1	8	3	6	0	0	0	0
E. macellum	0	0	3	26	113	106	70	0	0	0	0
E. macellum aculeatum	0	0	0	5	19	9	12	0	0	0	0
E. poeyanum	0	0	1	11	33	13	35	0	0	0	0
E. craticulatum	0	0	2	7	51	146	62	0	0	0	0
E. jenseni	0	0	1	6	15	3	6	0	0	0	0

Appendix B (continued)

	Modern sample					
	0M1	0M2	0M3	0M4	0M5	0M6
Ammonia	3	4	18	3	8	4
Elphidium	15	10	10	1	3	18
Cibicides	2	1	1	0	0	2
Globorotalia	2	1	0	0	0	4
Globigerina	12	4	2	0	1	11
Bolivina	3	1	1	0	1	2
Bulimina	0	0	0	0	0	0
Oolina	3	2	1	0	0	4
Lagena	1	1	1	0	1	2
Fissurina	0	1	1	0	1	2
Uvigerina	4	3	2	0	1	6
Trifarina	1	1	0	0	1	2
Planulinoides	2	0	1	0	0	1
Patelinella	0	1	0	0	0	1
Glabritella	0	0	0	0	0	0
Quiqueloculina	18	4	1	0	2	9
Triloculina	12	2	0	0	1	6
Miliolinella	13	5	2	0	2	7
Guttulina	1	1	1	0	0	2
Lenticulina	3	2	0	0	1	1
Discorbis	49	8	1	0	2	14
E. advenum	6	1	4	0	0	8
E. macellum	4	8	1	0	0	6
E. macellum aculeatum	1	0	0	0	0	1
E. poeyanum	4	1	5	1	3	2
E. jenseni	0	0	0	0	0	1
G. bulloides (%)	8	6	4	0	4	9

References

Albani, A.D., 1974. New benthonic Foraminiferida from Australian waters. J. Foraminiferal Res. 4 (1), 33–39.

Albani, A.D., 1979. Recent Shallow Water Foraminiferida from New South Wales. AMSA Handbook No. 3, The Australian Marine Sciences Association, Sidney.

Albani, A.D., Yassini, I., 1993. Taxonomy and distribution of the Foraminiferida of the family Elphidiidae from shallow Australian waters. Univ. New South Wales Technical contribution 5, pp. 28–29.

Almond, D.O., McGowran, D., Li, Q., 1993. Late Quaternary foraminiferal record from the Great Australian Bight and its environmental significance. Assoc. Aust. Palaeontol. Mem. 15, 395–405.

Apthorpe, M., 1980. Foraminiferal distribution in the estuarine Gippsland lake system, Victoria. Proc. R. Soc. Vic. 91, 207–232.

Be, A.W.H., 1977. An ecological, zoogeographic and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), Oceanic Micropaleontology. Academic Press, London, pp. 1–100.

Brady, H.B., 1884. Reports on the foraminifera dredged by H.M.S. Challenger Expedition Reports. Zoology 9, 1–814.

Cann, J.H., Belperio, A.P., Gostin, V.A., Murray-Wallace, C.V., 1988. Sea level history 45,000 to 30,000 years B.P. inferred from benthic foraminifera, Gulf St. Vincent, South Australia. Quat. Res. 29, 153–175.

Cann, J.H., Belperio, A.P., Gostin, V.A., Rice, R.L., 1993. Contemporary benthic foraminifera in Gulf St. Vincent, South Australia, and a refined Late Pleistocene sea level history. Aust. J. Earth Sci. 40, 197–211.

Chapman, F., Parr, W.J., 1935. Foraminifera and ostracoda from soundings made by the trawler Bonthorpe in the Great Australian Bight. J. R. Soc. West. Aust. 21, 1–7.

Colhoun, E.A., Adamson, D.A., 1991. Raised beaches of the Bunger Hills. In: Gillieson, D., Fitzsimons, S. (Eds.), Quaternary Research in Australian Antarctica: Future Directions. Special Publication, No. 3, Department of Geography and Oceanography, University College, Australian Defence Force Academy, Canberra, pp. 79–84.

Cushman, J.A., 1932. The foraminifera of the tropical Pacific collections of the Albatross, 1899–1900. Bull. U.S. Natl. Mus. 161, Part 1.

Goodwin, I.D., 1993. Holocene deglaciation, sea level change, and the emergence of the Windmill Islands, Budd coast, Antarctica. Quat. Res. 40, 70–80.

Hayward, B.W., Hollis, C.J., 1994. Brackish foraminifera in New Zealand: a taxonomic and ecologic review. Micropaleontology 40, 185–222.

Hayward, B.W., Hollis, C.J., Grenfell, H.R., 1997. Recent Elphidiidae (Foraminiferida) of the southwest Pacific and fossil Elphidiidae of New Zealand. N.Z. Geol. Surv. Paleontol. Bull. 72, 11–17.

Hemleben, C., Spindler, M., Anderson, O.R., 1989. Modern Planktonic Foraminifera. Springer, Berlin.

Howard, W.R., Prell, W.L., 1992. Late Quaternary surface circulation of the southern Indian Ocean and its relationship to orbital variations. Paleoceanography 7, 79–118.

Johnson, K.R., Albani, A.D., 1973. Biotopes of recent benthic foraminifera in Pitt Water, Broken Bay, New South Wales, Australia. Palaeogeogr., Palaeoclimatol., Palaeoecol. 14, 265–267.

Kohl, B., 1985. Early Pliocene benthic foraminifers from the Salina Basin, southeastern Mexico. Bull. Am. Paleontol. 88, 1–173.

Li, L., Finlayson, B., Gallagher, S., 1998. Higher Holocene sea levels and related environmental changes in Anderson Inlet, Victoria, Australia. Abstract of AQUA Biannual Conference, p. 28.

Li, Q., James, N.P., Bone, Y., McGowran, B., 1996. Foraminiferal biostratigraphy and depositional environments of the mid-Cenozoic Abrakurrie limestone, Eucla Basin, southern Australia. Aust. J. Earth Sci. 43, 437–450.

Loeblich, A.R., Tappan, H., 1964. Treatise on Invertebrate Paleontology, Part C. Protozoa, Vols. 1 and 2. Geographical Society of America, University of Kansas Press, Lawrence, KS.

Lorius, C., Merlivat, L., Fouchet, M., 1979. A 30,000 year isotope climatic record from Antarctic Ice. Nature 280, 644–648.

Maxwell, J.G.H., Cresswell, G.R., 1981. Dispersal of tropical marine fauna to the Great Australian Bight by the Leeuwin Current. Aust. J. Mar. Freshwater Res. 32, 493–500.

McCulloch, I., 1977. Quantitative Observations on Recent Foraminiferal Tests with Emphasis on the Eastern Pacific, Parts 1–3. University of Southern California Publication, Los Angeles.

McCulloch, I., 1981. Quantitative Observations on Recent Foraminiferal Tests with Emphasis on the Eastern Pacific, Part 4. University of Southern California Publication, Los Angeles.

McGowran, B., Li, Q., Cann, J., Padley, D., McKirdy, D.M., Shafik, S., 1997. Biogeographic impact of the Leeuwin Current in southern Australia since the late-Middle Eocene. Palaeogeogr., Palaeoclimatol., Palaeoecol. 136, 19–40.

Murray, J.W., 1975. An Atlas of British Recent Foraminiferids. Heinemann Educational Books, London, 244 pp.

Naidu, P.D., Malmgren, B.A., 1995. Do benthic foraminifer records represent a productivity index in oxygen minimum zone areas? An evaluation from the Oman Margin, Arabian Sea. Mar. Micropaleontol. 26, 49–55.

Pennak, R.W., 1989. Fresh-Water Invertebrates of the United States, Protozoa to Mollusca. Wiley, New York, pp. 269–285.

Prell, W.L., 1984. Variation of monsoon upwelling: a response to changing solar radiation. In: Hansen, J.E., Takahashi, T. (Eds.), Climate Processes and Climate Sensitivity. Am. Geophys. Union, Geophys. Monogr., 29, 48–57.

Prell, W.L., Kutzbach, J.E., 1987. Monsoon variability over past 150,000 years. J. Geophys. Res. 92, 8411–8425.

Prell, W.L., Van Campo, E., 1986. Coherent response of the Arabian Sea upwelling and pollen transport to late Quaternary monsoonal winds. Nature 323, 526–528.

Raynaud, D., Lorius, C., Budd, W.F., Young, N.W., 1979. Ice flow along an IAGP flow line and interpretation of data from an ice core in Terre Adelie, Antarctica. J. Glaciol. 24, 103–115.

Sahu, B.K., 1964. Depositional mechanism from the size analysis of clastic sediments. J. Sediment. Petrol. 34 (1), 73–83.

Seibold, I., 1975. Benthonic foraminifera from the coast and lagoon of Coshin (South India). Rev. Esp. Micropaleontol. 7, 65–79.

Sirocko, F., Sarnthein, M., Erlen Keuser, H., Lange, H., Arnold, M., Duplessy, J.C., 1993. Century-scale events in monsoonal climate over the past 24,000 years. Nature 364, 322–324.

Yassini, I., Jones, B.G., 1989. Estuarine foraminiferal communities in Lake Illawarra, New South Wales. Proc. Linn. Soc. N.S.W. 110, 229–266.

Yassini, I., Jones, B.G., 1995. Foraminiferida and Ostracoda from Estuarine and Shelf Environments on the Southeastern Coast of Australia. University of Wollongong Press, pp. 1–213.