



Foraminifera as Holocene environmental indicators in the South Alligator River, Northern Australia

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Abstract

Samples of plankton, surface sediments and Holocene deposits from the South Alligator River, an energetic macrotidal river in northern Australia, are examined to evaluate the usefulness of estuarine foraminifers for palaeoenvironmental interpretation of sediments deposited in tropical macrotidal conditions. Although marine and estuarine foraminifers in the estuarine channel are mixed by strong tidal currents, there are significant trends along the 80-km length of the tidal river. The relative proportions of marine and porcellaneous taxa decrease upstream from the mouth, but hyaline taxa and those with brackish affinities increase upstream. Foraminifers in intertidal sediments have distinctly different assemblages in the uppermost intertidal, mid-tidal (mangrove), lower intertidal and subtidal zones. In addition to the effects of tidal mixing, preserved thanatacoenoses are affected by selective dissolution and/or pyritisation within the sediment bodies. Despite the effects of adverse taphonomic factors, foraminiferal assemblages preserved in drill cores provide an accurate guide to original depositional environments (intertidal/subtidal; brackish estuarine/coastal marine), in mid-Holocene sediments in the South Alligator area. Foraminifers are found to improve the precision of previous palaeoenvironmental reconstructions made on the basis of sedimentary facies and pollen analyses. © 2001 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

Estuarine foraminifers have been used extensively as environmental indicators in investigations of past sea-level changes; in hydro- and engineering-geology in maritime areas, and in the geological exploration of deltaic sequences. However, these studies are largely restricted to the temperate zone in the Northern Hemisphere, particularly in North America and Western Europe (e.g. Scott and Medioli, 1980). In Australia, studies on estuarine foraminifers started over a hundred years ago (Howchin, 1889) and several contributions deal with taxonomy and ecological distribution of foraminifers in modern Australian estuaries (e.g. Albani and Johnson, 1975; Albani, 1978; Apthorpe, 1980; Collins, 1981; Yassini and Jones, 1989; Loeblich and Tappen, 1994; Yassini and Jones, 1995). Cann et al. (2000a, b) utilise estuarine foraminifers for palaeoenvironmental reconstruction but such work in Australia has

been concerned with marine settings (Cann and Gostin, 1985; Cann et al., 1988, 1993).

2. Study area: The South Alligator River

The South Alligator River, Northern Territory, Australia, is of particular interest as regards estuarine foraminifers. This macrotidal river, with a catchment of 9000 km², emptying northward into Van Diemen Gulf, Timor Sea, is one of the larger rivers on the north Australian coast. It drains an ancient catchment of Proterozoic rocks and has an extensive floodplain in its lower reaches (Fig. 1). The maximum tidal range is about 6 m and the tidal river extends 105 km inland, passing through a floodplain with a very low gradient (<1 in 60,000) that is frequently inundated by fresh water during the monsoonal wet season (December–April). The climate and hydrology are highly seasonal; towards the end of the wet season, the tidal river is mostly fresh water, but in the dry season, the rainfall and freshwater runoff are negligible (Woodroffe et al., 1986). After recession of the wet-season floods, sea water mixes slowly upstream and

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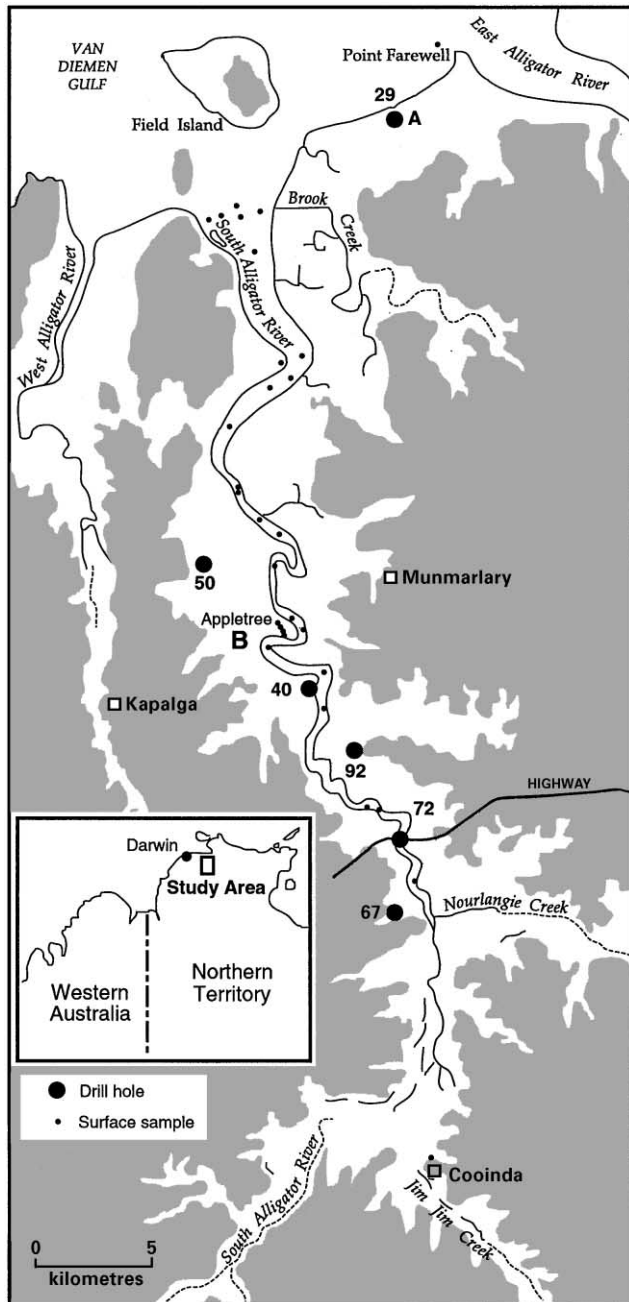


Fig. 1. Map of South Alligator tidal river showing locations of sediment samples and drillholes. Blank areas = coastal plain and floodplain; shaded = lateritic uplands; B = Appletree traverse.

salinity reaches 25 ppt near the tidal limit at the end of the dry season.

The evolution of Holocene estuarine and deltaic sediment tracts in northern Australia has been the subject of a number of studies, reviewed by Chappell and Woodroffe (1994). Evolution of the South Alligator River system, for example, was determined from 131 stratigraphic drillholes and 149 radiocarbon dates (Woodroffe et al., 1986, 1989). In most of these studies

it was found that the ancestral estuaries were very large mangrove swamps towards the end of the post-glacial marine transgression, and it appeared that most of the sediment filling the swamps had entered the estuarine system from the seaward direction. The mechanisms and net direction of sediment transport are strongly influenced by tidal behaviour, and tidal reconstruction has been seen as a key to understanding the evolution of these sediment tracts (Chappell and Woodroffe, 1994; Wolanski and Chappell, 1996). Hitherto, this was based largely on pollen-based determinations of ancient mangrove habitats, which provides a guide to upper tidal levels (Chappell and Grindrod, 1984, 1985; Woodroffe et al., 1986). The intention of the present study was to build on previous work with estuarine foraminifera (Wang and Murray, 1983; Wang, 1990), to discover the extent to which foraminifera can be used to reconstruct palae-tidal conditions and salinities in macrotidal tropical rivers.

Our study is based on foraminiferal analysis of over two hundred samples from cores and surface sediments, as well as plankton samples, taken in 1983 and 1986 from throughout the tidal river, ranging from the nearshore marine zone to a point about 82 km upstream. The sampling and environmental details are given below. Specific features of thanatocoenoses are described, including mixing and taphonomic alteration of source assemblages. Despite the strong seasonal variations of salinity and the tidal mixing of sediment, we demonstrate that foraminiferal faunas are useful for palaeoenvironmental reconstruction in macrotidal estuarine sediment bodies.

2.1. The South Alligator tidal environment

The South Alligator macrotidal river is several kilometres wide at the mouth and about 80 m wide near the tidal limit. The maximum (spring) tidal range is 5–6 m near the entrance falling to 4–5 m about 80 km upstream. Tidal currents are strong: peak flood-tide velocities exceed 1.6 m s^{-1} and peak ebb velocities exceed 1.1 m s^{-1} . Tidal asymmetry increases upstream. The flow is highly turbulent and suspended sediment concentrations (SSC) are $1\text{--}20 \text{ g l}^{-1}$, highest near the channel bed (Wolanski et al., 1988). Light penetration is low, owing to the high SSC (Secchi depth is typically $<0.2 \text{ m}$), and primary productivity measured as chlorophyll A and B is low. The salinity of the tidal river is low during wet season floods except near the entrance, where salt wedge circulation is established (Chappell and Ward, 1985), but seawater mixes upstream during the dry season and the salinity approaches seawater almost to the tidal limit, late in the wet season (Fig. 2).

The sediment moves up-river during the dry season, owing to the tidal asymmetry, but temporarily moves downstream during wet season floods (Vertessy, 1990).

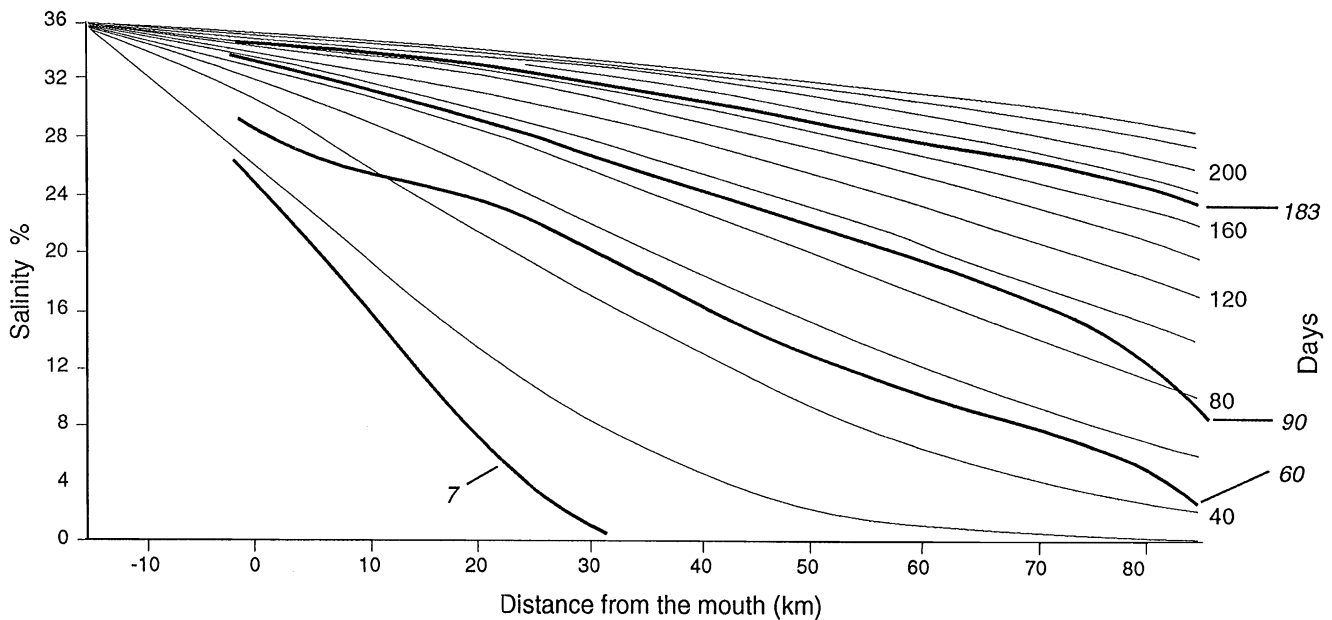


Fig. 2. Longitudinal profiles of salinity from offshore to 85 km up the South Alligator River. Profiles are numbered in days following recession of a typical wet season flood: thick lines = observed profiles; thin lines = profiles calculated by a numerical diffusion model (after Woodroffe et al., 1986).

Channel sediments are dominantly fine sandy muds, varying locally between the banks (laminated muds), channel (muddy sand) and shoals (rippled fine sand and laminated mud). The sediments near the river mouth contain 1–5% shell carbonate. Sediment input from the fluvial catchment and output to offshore are both very low (Woodroffe et al., 1986). Considering that there is a net inflow of seawater during the dry season and that fresh water is largely trapped by a salt wedge in the wet season (Chappell and Ward 1985; Woodroffe et al., 1986), the residence time of particles within the tidal river may exceed several decades.

The tidal river and its floodplain have evolved from an extensive mangrove swamp that existed in the South Alligator valley during mid-Holocene times. Most of the floodplain is underlain by mangrove sediments (compacted organic mud) that were deposited during the later stages of the post-glacial sea-level rise. Near the tidal river, estuarine and channel deposits of muddy sand, often rippled or laminated, interdigitate with the mangrove sediments. Coastal mangrove and nearshore sediments underlie the coastal plain adjacent to the river mouth (Woodroffe et al., 1986, 1989). Although mangroves were much more extensive in mid-Holocene times than today, all the Holocene sediments have modern counterparts.

3. Distribution of modern foraminifers

Dredge sediment samples were taken from the following habitats at the sites shown in Fig. 1: nearshore

marine (1 site); the estuary mouth (5 sites); channel bed sites from the mouth to Nourlangie Creek, 82 km upstream (18 sites); and from a channel-to-riverbank transect at Appletree Point, 47 km upstream (5 sites) (Fig. 1). Plankton net samples were taken from the river at the nearshore and channel-bottom sample sites. All the samples were stained with Rose Bengal to distinguish living and dead specimens. Fourteen of the surface sediment samples were quantitatively analysed, following wet sieving (63 μm) and volumetric measurement of the > 63 μm residue. The dried residue was floated in CCl_4 ; the float was dry sieved (125 μm) and the coarse fraction was used for foraminiferal census (the sample was split if the fauna was very rich). Generally, each census was based on > 200 individuals and special attention was paid to the taphonomic condition of the tests.

In total, 92 taxa of foraminifers were identified, of which only 12 were found as living specimens (Appendix A). Almost no living foraminifers were found in channel deposits, and sparse living specimens of a full-marine species (*Quinqueloculina ferrussacii*) occurred in the sample from outside the estuary. Several brackish-water forms were found live in supra- and inter-tidal zones, such as *Thurammina? limnetes*, *Trochammina inflata*, *Arenoparella asiatica*, *Lituola salsa*, *Miliammina fusca*, *Stomoloculina multiangula*, *Pseudononionella variabilis* and *Trichohyalus tropicus*. The dead fauna is significantly different. Practically all thanatocoenoses were dominated by small-sized specimens (< 150 μm) with full-marine affinities that are prone to floating (globigerinids, lagenids, *Reusella spinulosa*, *Shackoinella globosa*,

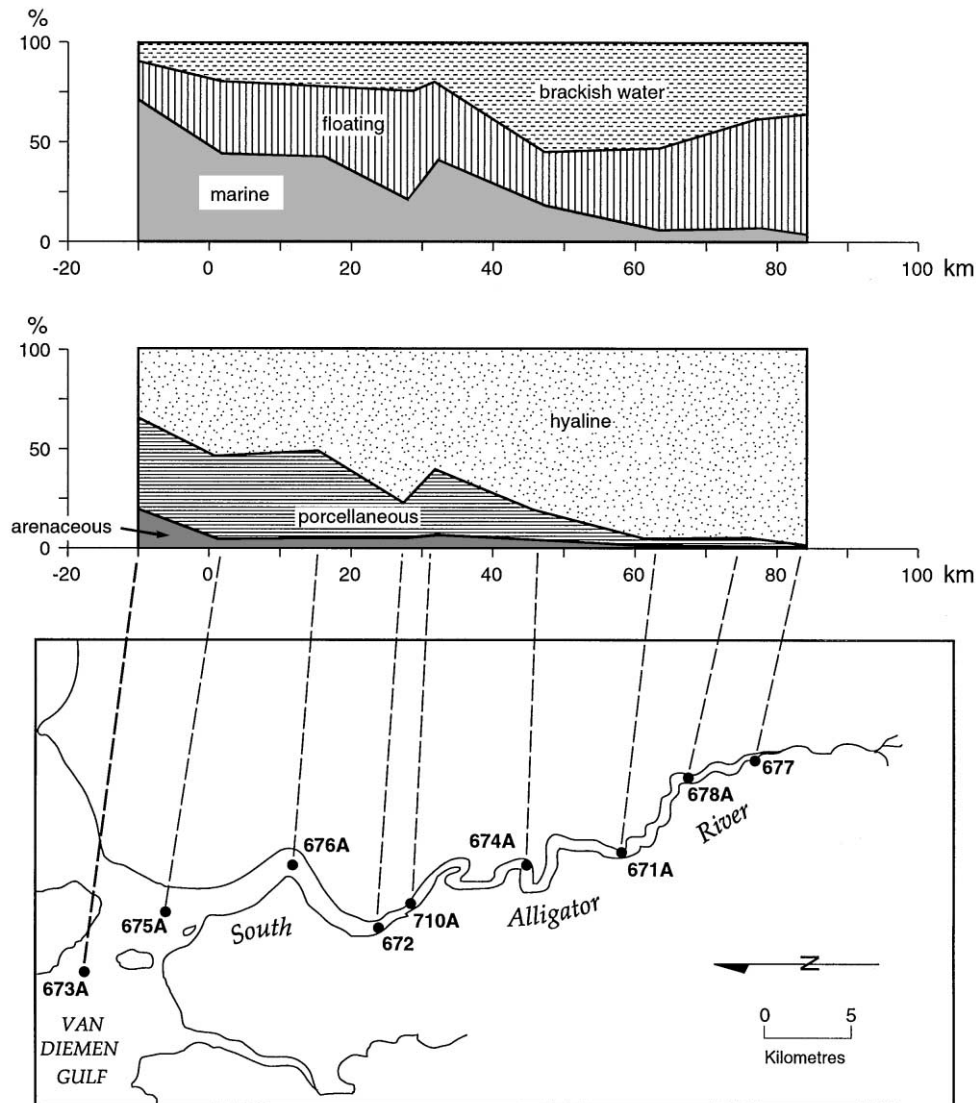


Fig. 3. Percentages of principal groups of foraminiferal fauna at selected surface sediment sites along the South Alligator River. The faunal list (Appendix A) lists taxa in arenaceous, porcellaneous and hyaline groups, and indicates habitat affinities (marine; relatively small forms prone to floating; and brackish) for each taxon.

Brizalina striatula, *Siphonigerina ambullacea*, etc.). Marine taxa, forms prone to floating and brackish-water taxa are three distinctive groups of foraminifers with different affinities in the South Alligator tidal river. Appendix A includes the affinities of the identified taxa, which were used to interpret South Alligator palaeoenvironments, and also divides the faunas texturally into hyaline, porcellaneous and arenaceous forms. There is some correlation between the affinity and textural groupings: arenaceous forms tend to be marine and many hyaline forms are prone to floating, although many brackish water forms are also hyaline. Taken together, both the groupings provide useful environmental information.

Figs. 3 and 4 summarise distributions of the environmental and textural groups in channel deposits along the

South Alligator tidal river. The proportion of marine forms in the channel sediments decreases upstream, especially those with arenaceous and porcellaneous tests, whereas brackish-water forms and small-sized lighter forms prone to floating increase upstream (Figs. 3 and 4). The most frequent species in channel deposits coarser than 125 μm are *Ammonia beccarii* s.l., *Shackoinella globosa* and *Reussella spinulosa*, all with hyaline tests that are easily transported by tides. There is a good correlation between foraminiferal concentration and sediment grain size (rows 2 & 3 in Fig. 4), which indicates the influence of tidal transport of foraminiferal tests in the river sediments.

In contrast with the channel sediments, which are dominated by small-sized forms and are distinguished mainly by the proportions of various groups, the

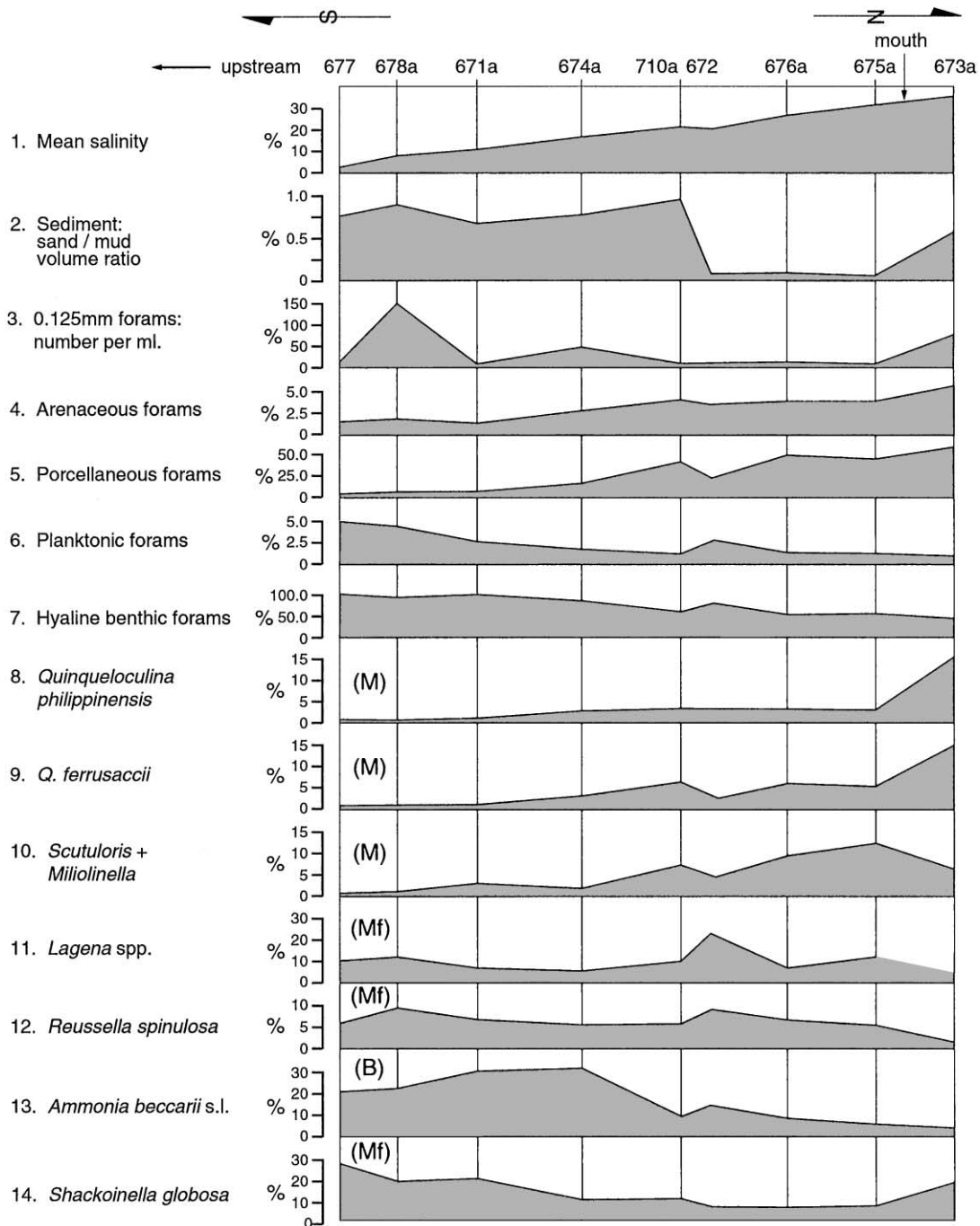


Fig. 4. Variations of mean salinity, sediment texture, numbers of foraminifera >0.125 mm test diameter, percentages of arenaceous and hyaline tests, and percentages of selected taxa, along the South Alligator River. Please note that rivermouth is to right (opposite to Fig. 3).

intertidal river banks have well defined faunas with distinctive species compositions that include characteristic living taxa. These were examined at Appletree bend, 47 km upstream (locality B, Fig. 1). Fig. 5 shows a schematic profile and dominant taxa in surface sediments at this transect, from the subtidal zone up to the highest tidal zone, which is flooded only by highest spring tides during the dry season (when locally it

becomes hypersaline) but is more frequently submerged during the wet season. Living foraminifers comprise about 5% of specimens in thanatocoenoses samples from Appletree (Table 1). The fauna in subtidal and intertidal zones at the Appletree traverse is dominated by floating forms whose relatively small tests are likely to be carried out in suspension, plus estuarine species (*Ammonia beccarii* s.l.) with a significant proportion of

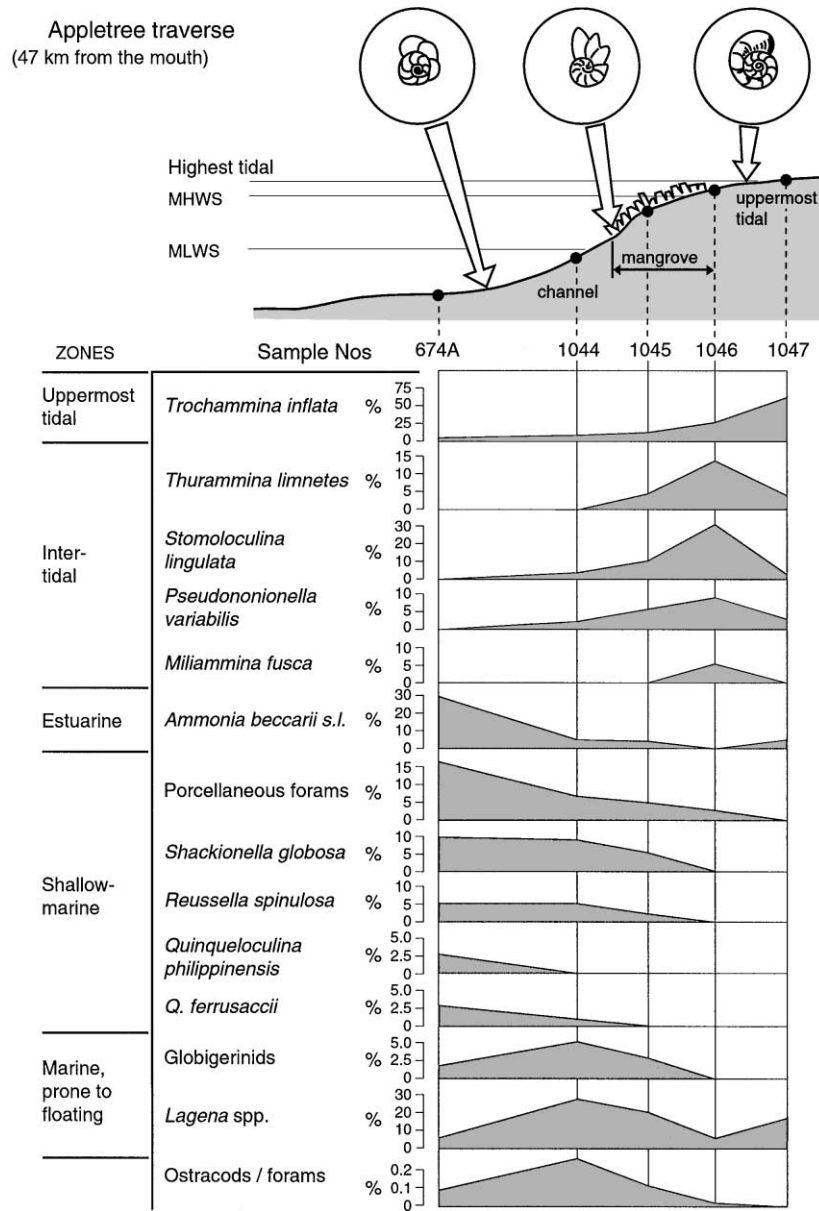


Fig. 5. Numerical distribution of foraminifers in surface sediments on a traverse from the uppermost intertidal to the subtidal zone at Appletree Point, 47 km upstream of South Alligator mouth (location: Fig. 1, point B). Living forams were found in samples 1045–1047 (Table 1); further data for sample 674A appear in Fig. 4.

marine species. In the lower intertidal zone brackish water species like *Thurammina ?limnetes*, *Stomoloculina lingulata*, *Pseudononionella variabilis* and *Miliammina fusca* become major elements of the fauna, and the uppermost tidal fauna is characterised by the predominance of the brackish-water arenaceous form *Trochammina inflata*.

4. Ecological control of foraminiferal faunas

Foraminifers mainly inhabit the lower intertidal zone, mangroves and high-tide mudflats of the South

Alligator River. Channel deposits are characterised by allochthonous forms transported by tidal currents and the assemblages reflect the hydrodynamics rather than ecological conditions. The primary productivity in South Alligator waters is low, owing to the very high turbidity caused by rapid tidal flow, and numbers of living foraminifers are low. However, despite their small numbers, a few simple ecological factors control the distribution of living foraminifers.

Salinity is the first ecological control for estuarine foraminifers (Murray, 1973). In the South Alligator River area, living specimens of full-marine species like *Quinqueloculina ferrusaccii* occur only outside the

Table 1
Living foraminifers from appletree traverse^a

Sample number	1045	1046	1047
<i>Thurammina ? limnetes</i>	0	1	1
<i>Trochammina inflata</i>	3	6	2
<i>T. squamata</i>	1	0	0
<i>Lituola salsa</i>	1	3	0
<i>Arenoparella mexicana</i>	0	2	0
<i>Miliammina fusca</i>	0	1	0
<i>Stomoloculina lingulata</i>	1	6	0
<i>Pseudononionella variabilis</i>	4	4	0
<i>Pseudononionella sp.</i>	1	0	0
<i>Bisaccioides cuspatus</i>	0	1	0
<i>Trichohyalus tropicus</i>	0	1	0
Sum	11	25	3
Total (living + dead)	230	432	67
Living/total (%)	4.8	5.8	4.5

^aNote: number 1045 mid intertidal mangrove; 1046 upper intertidal mangrove; 1047 highest intertidal flat (see Fig. 5).

estuary and all species living in the estuary are euryhaline or brackish-water forms. The eleven living species at the Appletree traverse (Table 1) are either cosmopolitan brackish-water forms (*Trochammina inflata*, *T. squamata*, *Miliammina fusca*), or are known in brackish water in America (*Lituola salsa*, *Thurammina ? limnetes*, *Arenoparella mexicana*), in brackish water in China (*Pseudononionella variabilis*), or endemic Australian brackish-water forms (*Trichohyalus tropicus*, *Bisaccioides cuspatus*, *Pseudononionella sp.*). Various brackish water species have adapted to different salinity ranges; for example, *Stomoloculina lingulata* favours significantly lower salinity than another brackish-water form, *Schwartzia elegantissima*, whereas *Quinqueloculina seminula* can live in hypo- to hypersaline waters and comprises a monospecific fauna in supralittoral hypersaline environments.

Submergence time also controls the distribution of brackish-water foraminifers (Scott and Medioli, 1980). In the South Alligator, for example, living *Ammonia beccarii* s.l. and *Elphidium hughesi* are restricted to the subtidal zone; *Stomoloculina lingulata*, *Pseudononionella variabilis* and *Pseudononionella sp.* occur in the lower intertidal zone, and *Trochammina inflata* and *Thurammina ? limnetes* occur mostly in the uppermost intertidal zone. While there are no clear-cut boundaries in their distributions, the general trends are palaeoecologically useful.

Finally, the distribution of calcareous versus arenaceous foraminifers in marginal marine environments is controlled by pH (Apthorpe, 1980; Wu and Wang, 1989; Wang, 1990). In normal marine conditions the, pH value exceeds 8 and the water is normally saturated with calcium carbonate at shallow depths. However, pH varies considerably in estuaries, and low pH values may prohibit the formation of calcareous tests by

foraminifers. The foraminiferal fauna was dominantly arenaceous in the South Alligator mangrove sediment (e.g. the upper intertidal zone at Appletree traverse), which has high organic content, a relatively low seawater influence and low pH, whereas sites directly influenced by seawater with pH > 8 were dominated by calcareous forms.

5. Taphonomy

Palaeoenvironmental interpretation of foraminiferal faunas not only requires knowledge of their ecology, but also of their taphonomy, which is affected by post-mortem transport and preservation conditions. We now describe the observations of these factors and their effects in the South Alligator environment.

5.1. Transport

Where tidal currents are weak, as in microtidal or diurnal mesotidal estuaries, foraminiferal faunas in the bottom sediments are generally autochthonous (Wang and Murray, 1983). The transport of foraminiferal tests in estuaries has been reported from macrotidal or semidiurnal mesotidal estuaries with strong tidal flows, e.g. from the Severn (Murray and Hawkins, 1976) and Humber Rivers (Brasier, 1981) in the UK, the Elbe River in Germany (Wang, 1983a), and the Qiangtan and Yangtze Rivers in China (Wang, 1983b; Wang et al., 1985). In such systems, marine foraminifers are carried and deposited up the estuary, particularly those that tend to float. Transport in suspension is indicated by the occurrence of benthonic foraminiferal tests in the water column in the Elbe and Yangtze Rivers with species compositions comparable with that in the surface sediment beneath (Wang, 1983a; Cheng, 1987). Together with resuspension from the sediment, foraminifers in macrotidal estuaries tend to become size-sorted (Wang, 1990).

Transport and sorting occur in the South Alligator River. Efficient transport is revealed by the plankton samples taken in February and May, 1986, all of which contained small marine foraminifers, mostly hyaline forms prone to floating such as *Shackoinella globosa* and globigerinids. The sediment samples throughout the tidal river were similar. Due to tidal transport and resuspension, almost all foraminiferal thanatocoenoses in the river contain many exotic, small marine forms, while the percentage of relatively large and heavy marine elements, such as *Quinqueloculina philippinensis* and *Q. ferrusaccii*, decreases upstream. Furthermore, the distribution pattern in the South Alligator River contrasts with that in diurnal mesotidal rivers in tropical northern Australia. The diurnal mesotidal McArthur River, which flows into the Gulf of Carpentaria, was

Table 2
Variation of estuarine foraminiferal assemblages

Estuary type	Salt-wedge or stratified	Well mixed
Tidal regime and tidal range ^a	Micro/mesotidal <SD 2 m-D 2 m	Macrotidal SD 4 m or greater
Forams in suspension	no	yes
Live & dead assemblages	similar	different
Thanatacoenoses	indigenous, euryhaline	many exotic, open marine
Sorting	no sorting, uncorrelated with sediment grain size	Sorted and correlated with sediment grain size
Examples ^b		
Asia	Pearl R., Shuantaizi R.	Yangtse R., Qiangtan R.
Europe	Christchurch Harbour	Elbe R., Ems R.
Australia	McArthur R., Hopkins R.	S.Alligator R., Daly R.

^a Notes: SD = semi-diurnal; D = diurnal.

^b Sources: Wang (1990), Wang et al. (1985).

sampled in January 1986: the surface-sediment foraminiferal fauna is basically autochthonous in origin, brackish-water in nature and normal in size. There is no indication of significant tidal transport of tests, and marine foraminifers were not found in plankton samples within the tidal river (Wang, 1990). The important differences between foraminifer assemblages of mesotidal estuaries and those of macrotidal systems such as the South Alligator are summarised in Table 2.

5.2. Preservation

The potential for preservation varies with foraminiferal characteristics and with the depositional environment, particularly its chemical properties. Occurrence in surface sediments does not imply subsequent preservation. Preservation of calcareous fauna is affected by pH, which varies with the depositional environment and can change after burial. For example, living specimens of the calcareous foraminifera *Elphidium* can withstand a slightly acid environment (Schafer, 1970, reports *Elphidium* in pH 6.7), and in the South Alligator area, living *Elphidium* were found together with an arenaceous fauna in low pH mangrove muds, but their tests dissolved after death in the same sediment and no dead specimens were found. A similar postmortem dissolution in a marsh environment was also reported from Europe (Murray, 1973).

Chemical reactions that occur after burial in estuarine sediments can severely affect the preservation of foraminifers. Pyritisation by bacterial reduction occurs after burial of saturated organic, fine-textured marine and estuarine sediments such as mangrove mud (Breen, 1988), and pyritisation can also occur in the chambers of foraminifer tests in non-reducing sediments, when protoplasm degrades (Jorgensen, 1983). If the pyrite is subsequently oxidised, through partial aeration of the sediment, low-pH sulphate acidification develops (Dent, 1986), leading to carbonate dissolution.

This can occur in the field, through water table lowering by drainage, falling sea level or tectonic uplift, and can also occur during laboratory storage. We observed that foraminifers may disappear if a sulphitic mangrove sediment is exposed at room temperature for a few days.

Four different states of foraminifer preservation, most notably with calcareous forms, were observed in core and sediment samples from the South Alligator River: (1) fresh tests, with the transparent appearance of thin-walled hyaline forms; (2) opaque tests of forms originally with transparent walls, sometimes partly dissolved; (3) light orange to dark brown iron-stained tests, sometimes etched; (4) black or black-striped tests filled with or replaced by pyrite. These states reflect different diagenetic conditions. Pyritised tests indicate pyritisation in reduced organic mud; an orange-brown staining may be from FeSO₄ or Fe(OH)₂ derived from the oxidation of FeS₂, while opaque tests indicate etching of calcite microcrystal edges in the test under low pH conditions. The more resistant species dominate foraminiferal assemblages where diagenetic acidification slowly affects the host sediments.

Dissolution and iron staining of foraminifers was investigated experimentally. To summarise the results, transparent tests of *Ammonia beccarii* s.l. became opaque after 4 h in a buffer solution of pH 6.0, and the calcareous parts were completely dissolved after 70 h. Dissolution was found to vary with species. After 40 h of immersion at pH 6.0, arenaceous tests were not damaged; resistant calcareous species like *Triloculina tricarinata*, *Reussella spinulosa* and *Shackoinella globosa* became opaque, fragile forms such as *Fissurina* sp. and *Lagena* sp. were mostly dissolved, while *Scutularis* sp. disappeared completely. The iron staining process was simulated by immersing foraminifers in ferrous sulphate solution. All calcareous species became stained orange-brown, while diatoms, sponge spicules and some arenaceous foraminifers remained unstained. A very similar pattern of differential staining was observed

amongst foraminifers, diatoms and spicules in mid-Holocene clay/sand laminated channel deposits from the South Alligator River. No attempt was made to replicate pyritisation.

6. Foraminifers in the Holocene sediment tract

Microfossils in two drill cores from contrasting environments were studied systematically: one from the coastal plain (SAH29: site A, Fig. 1), the other from the estuarine plain 50 km upstream (SAH40). Sedimentary facies (Woodroffe et al., 1986, 1989) and pollen analyses from these cores (Chappell and Grindrod, 1985; Grindrod, 1988) have been described previously. Samples from four other cores in the estuarine plain (SAH50, SAH67, SAH72, SAH92 contained no or few foraminifers (core locations, Fig. 1). All cores were taken in 1983. SAH29 and SAH40 contained useful foram faunas (including a few taxa not found in the modern sediment-surface samples) and are described below, but cores that yielded few or no foraminifers are not discussed further, except to note that sponge spicules and brackish-water diatoms such as *Campylo-discus* were found in SAH67. Three laminated mud/sand samples from SAH72 contained rich foraminiferal faunas of mainly small-sized iron-stained specimens of forms prone to floating, similar to assemblages in the modern South Alligator channel.

6.1. Core SAH29

This 9.6 m core was taken from an upper intertidal salt mudflat inland of the mangrove fringe on the coastal

plain (location, Fig. 1). Full seawater persists at the nearby coast for most of the year, although salinities between 15–25 ppt occurred during wet-season floods in March 1984. Samples taken at 30 cm intervals from the core were analysed for foraminifers; rich faunas were found in the upper 750 cm. Fig. 6 shows down-core percentage variations of 13 major species in the faunas and Fig. 7 summarises the principal elements, and their palaeoenvironments. The following four zones with different foraminiferal assemblages were recognized.

Zone 29/1: 0–140 cm. Brown clay with a well-preserved foraminiferal fauna of low diversity and relatively low concentration (2.3 specimens per millilitre). Two species adapted to a wide salinity range, *Quinqueloculina seminula* and *Elphidium hughesi* comprise over 90% of the fauna; the balance includes other brackish-water species such as *Pseudogyroidina sinensis*, *Elphidium hispidulum*, *E. kiangsuensis* and *Rectoelphidiella lepida*. A similar *Q. seminula* - *Elphidium hughesi* fauna occurs today in the supra-tidal zone at Brook Creek, near the river mouth. The fauna indicates a brackish intertidal environment, becoming hyperhaline at the core top sample where *Quinqueloculina seminula* dominates. The exclusively calcareous tests of the fauna imply a rather high pH (>8) in the sediment.

Zone 29/2: 140–170 cm. Light brown-grey organic clay with a poor foraminiferal fauna. Calcareous tests are partially dissolved; their concentration is low (0.4 per c.c.), and the fauna is characterised by the arenaceous form *Trochammina inflata*, accompanied by *Ammonia beccarii* s.l., *Elphidium hughesi* and *E. hispidulum*. This fauna is consistent with an upper intertidal mangrove forest of intermediate salinity and low pH in the sediment. Consistent with this, Grindrod (1988)

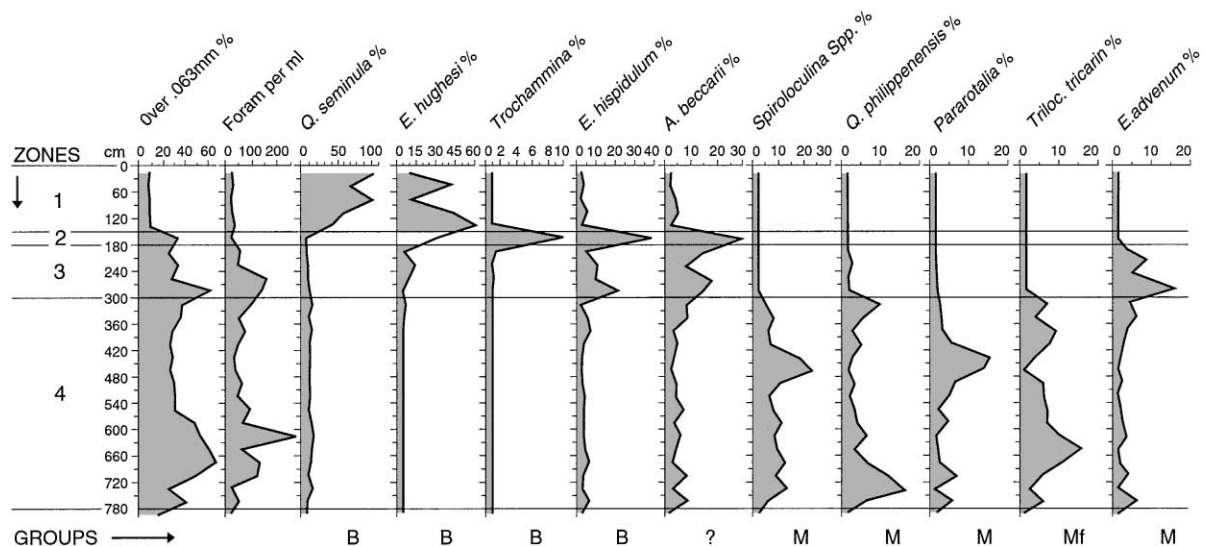


Fig. 6. Down-core variations of foraminiferal concentrations and selected taxa in core SAH29. Note: ordering of taxa chosen to show down-core progression of faunal associations.

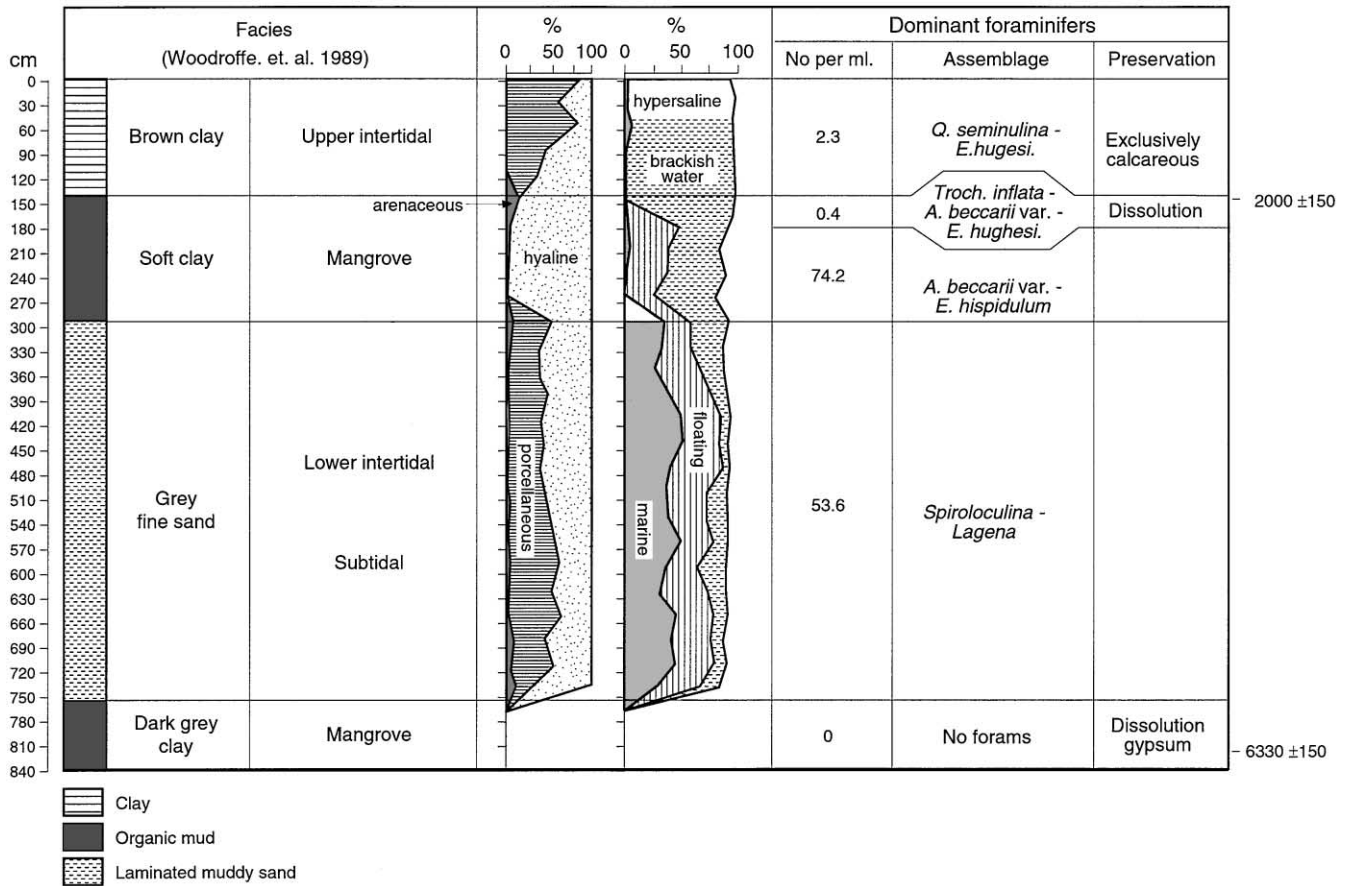


Fig. 7. Summary of sedimentary facies, foraminiferal concentrations, preservation characteristics and major test types and affinity groups in core SAH29. Facies (left columns) after Woodroffe et al., 1989. Note: radiocarbon ages from SAH29 at right.

found a rich rhizophoraceous mangrove pollen flora in this zone of core SAH29.

Zone 29/3: 170–290 cm. Mildly organic grey fine sandy clay with a rich, well preserved fauna (74 specimens per cc), almost exclusively of hyaline forms including species of brackish affinity and types prone to floating. The assemblage contains > 30 taxa: the main elements are *Ammonia beccarii* s.l., *Elphidium hispidulum*, *Lagena* spp. and *Shackoinella globosa*. The combination of brackish-water forms with floatable marine forms indicates an estuarine intertidal environment of intermediate salinity. The zone contains a poorly-preserved mangrove pollen flora (Grindrod, 1988); and the indicated pH is higher than in Zone 2.

Zone 29/4: 290–760 cm. Blue- and brown-grey fine sandy clay with shell hash and a rich, well-preserved foraminiferal fauna (> 53 specimens per cc), with over 40 taxa dominated by marine forms, both hyaline and porcellaneous, and relatively few brackish-water forms. *Spiroloculina communis*, *Lagena* spp., *Pararotalia venusta*, *Quinqueloculina philippinensis*, *Shackoinella globosa*,

Triloculina tricarinata are the most common. A large number of small-sized specimens indicates a strong allochthonous factor, and a subtidal, open coastal environment is indicated. Peak percentages of large-sized full-marine species (*Spiroloculina* spp., *Pararotalia venusta*) in fine-grain horizons in the middle of this zone (e.g. at 420–450 cm) reflect maximum seawater influence, presumably corresponding to the peak of the post-glacial marine transgression at this site. The paucity of organic fragments and good preservation of the calcareous fauna also indicates a high pH subaqueous environment. Below 760 cm, the core consisted of dark gray clay with abundant wood fragments and mangrove pollen, but no foraminifers were found.

6.2. Core SAH40

This 14.7 m core from the estuarine plain, about 50 km upstream, was sampled at 30 cm intervals and analysed for foraminifers. Specimen abundance, test size and preservation vary significantly. In general, the fauna is poorer and smaller in size than in Core SAH29, and is

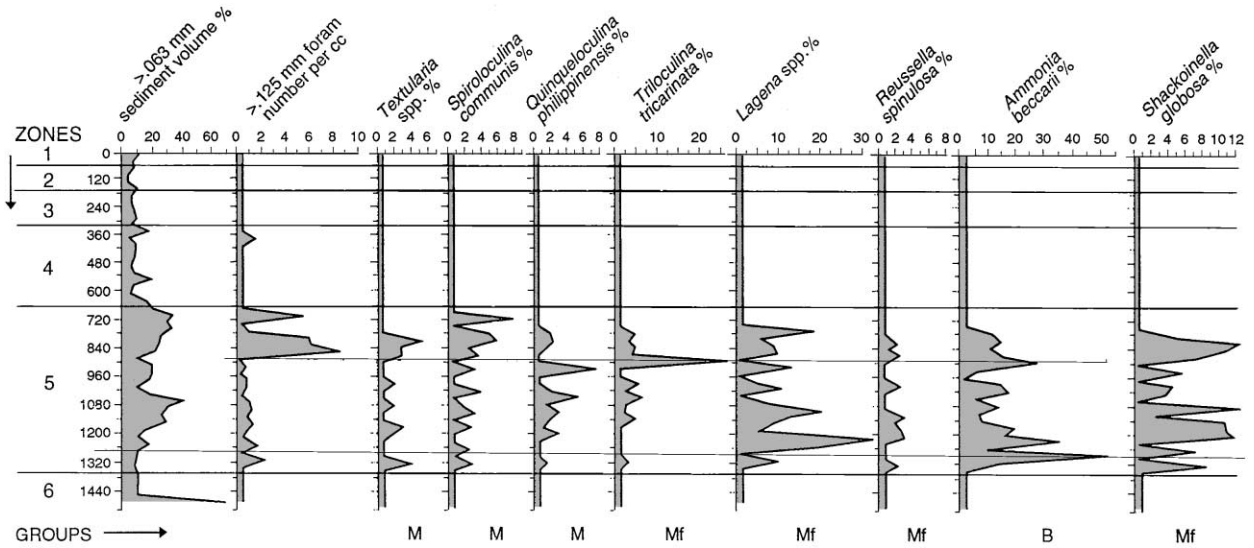


Fig. 8. Down-core variations of foraminiferal concentrations and selected taxa in core SAH40. Ordering of taxa chosen to show down-core progression of faunal associations.

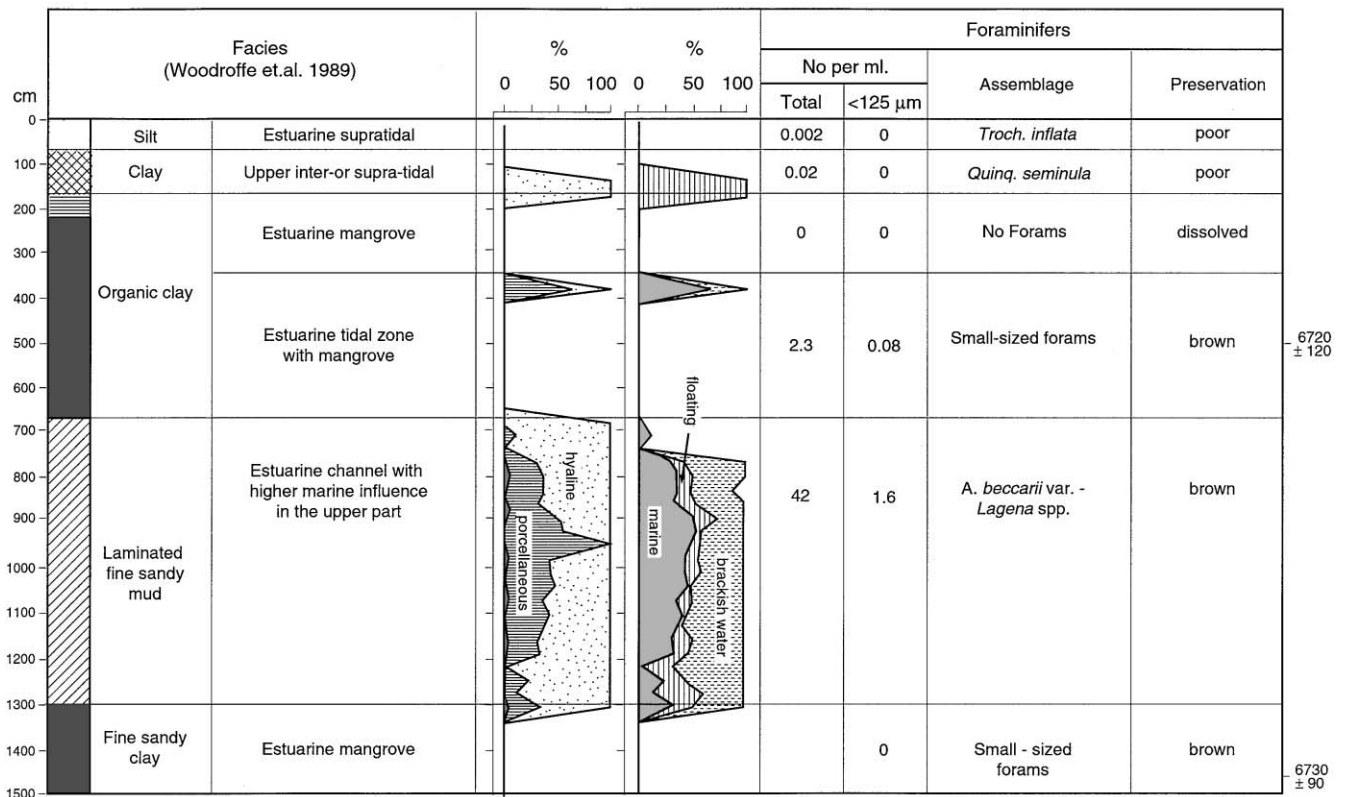


Fig. 9. Summary of sediment facies, foraminiferal concentrations, preservation characteristics and major test types and affinity groups in core SAH40. Facies (left columns) after Woodroffe et al., 1989. Note: radiocarbon ages from SAH40 at right.

completely absent in some sections (eg. 160–320 cm, 1300–1470 cm). Fig. 8 summarises downcore variations of foraminiferal number and percentages of 8 common species, and Fig. 9 summarises the principal elements

and their palaeoenvironments. The following 6 zones are recognised.

Zone 40/1: 0–40 cm. Dark brown earthy clay with very sparse foraminifers and diatoms. Only one

specimen of *Trochammina inflata* was found, smaller than 125 µm, which is characteristic of the estuarine uppermost intertidal zone. Relatively low salinity and low pH of the sediment are indicated.

Zone 40/2: 40–160 cm. Stiff grey clay with orange mottling and ferruginous nodules, contains rare foraminifers with heavy traces of dissolution, which fall into two groups: (i) white small-sized specimens of brackish-water *Pseudononionella variabilis*, *Stomoloculina lingulata*, and *Quinqueloculina seminula*, and (ii) brownish-orange small-sized marine species prone to floating, such as *Shackoinella globosa* and *Fissurina laevigata*. Black uncalcified oogonia of charophytes were also found. The fauna implies estuarine upper to uppermost intertidal environment with lowered salinity and pH.

Zone 40/3: 160–340 cm. Grey clay with abundant organic fragments; no foraminifers were found but there were small brown lumps that may be the remains of dissolved tests. Pollen analysis shows that the sediments were deposited in an estuarine full mangrove environment (Chappell and Grindrod, 1985). Microscopic pyrite seen in the sediment and low pH, inferred from the total absence of foraminifers, may have developed by pyrite oxidation during storage of the core.

Zone 40/4: 340–680 cm. Blue- to dark-grey compact organic mud with a sparse foraminiferal fauna (2.3 specimens per cc), predominantly small-sized iron-stained specimens of forms prone to floating (e.g. *Shackoinella globosa*, globigerinids and lagenids), with very rare specimens > 150 µm of estuarine species (e.g. *Elphidium hughesi*). The fauna, together with mangrove pollen (Chappell and Grindrod, 1985), indicates estuarine intertidal mangrove. pH of the sediment is higher than in Zone 3.

Zone 40/5: 680–1300 cm. Grey laminated fine sand and mud contains a good foraminiferal fauna (42 per cc), dominated by small-sized iron-stained specimens (specimens > 150 µm average only 1.6 per cc). Marine forms, mostly those prone to floating, dominate the fauna, with accessory brackish-water taxa. The most common species > 150 µm are *Ammonia beccarii* s.l., *Lagena* spp., *Triloculina tricarinata* and *Shackoinella globosa*. The fauna resembles that in modern channel deposits of the South Alligator River and indicates an estuarine channel environment. The proportion of marine species is highest around 780–840 cm core depth and suggests maximum seawater influence at that level. The calcareous nature of the foraminiferal fauna and iron staining implies a high pH of the estuarine water, but a strong dissolution of many tests indicates subsequent acidification of the sediment.

Zone 40/6: 1300–1470 cm. Blue-grey fine sandy clay contains only small-sized iron stained foraminifers of allochthonous origin. Organic fragments and pollen indicate a mangrove estuarine environment.

6.3. Discussion: post-depositional degradation

Foraminifera evidently have been degraded or lost from our South Alligator Holocene sediment cores, particularly in organic muds that were shown by Woodroffe et al. (1986, 1989) to have been deposited within mangroves. Surface samples from present-day mangrove sediments at the Appletree traverse are quite rich in foraminifers (Fig. 5) but similar sediments in the cores are less rich or are barren. An occurrence of corroded tests indicates acid conditions, as noted above. The question of when acidification occurs is important for future research with similar materials.

Measurements of South Alligator water, including intertidal surface water, show neutral to alkaline pH at all seasons throughout the tidal river (Chappell and Ward, 1985; and unpublished data). Mangrove soil sediments (1 : 5 aqueous extracts from sealed 30 cm cores measured within 24 h of collection) show pH of 6.0–7.5 but extracts from similar cores that had been aged for several months routinely showed pH from 3.0–6.0 (Dr M.Melville, pers.comm.). The widespread occurrence of iron-stained tests in our cores indicates reducing (Fe²⁺) conditions and is consistent with weak acidity in the mangrove mud. Some dissolution probably occurred within the Holocene sediments prior to coring; however, we consider that a major loss occurred when cores were allowed to dry during laboratory storage at room temperature, and we strongly recommend that sampling and pre-treatment for foraminiferal analysis be done during core recovery.

7. Palaeoenvironmental significance of fossil foraminifera in cores 29 and 40

Although constrained by poor foraminiferal preservation in some zones of cores SAH29 and SAH40, our results improve the palaeoenvironmental reconstructions made previously from pollen and sedimentary analyses, including palaeo-tidal reconstruction. Previous data from over 40 radiocarbon-dated cores show that the South Alligator estuarine plain developed after rising sea level invaded the prior valley, about 8000 radiocarbon years ago, and that mangrove soon became widely established throughout the system. Sedimentation under the mangroves kept pace with the rising sea level, supplied by the sediment moving into the palaeo-estuary from the seaward direction (Woodroffe et al., 1986; Chappell and Woodroffe, 1994). The tidal conditions at the time, which numerical modelling shows to be critical for the sediment transport processes (Wolanski and Chappell, 1996), have been reconstructed for the high-tide level from mangrove pollen data (Chappell and Grindrod, 1985) but not for the low tide level.

Core SAH29 is from the prograded coastal plain at the South Alligator mouth. Sediment and pollen analyses show basal mangrove sediments below 760 cm, overlain by subtidal marine sediment to 290 cm, overlain in turn by mangrove sediments with shallowing-upward succession of mangrove passing from *Rhizophora* through *Ceriops/Bruquiera* to *Avicennia* (Grindrod, 1988). Not only are the foraminiferal assemblages entirely consistent with this, but also, they reveal the transition between intertidal and subtidal more clearly (Fig. 7). Core SAH40 shows similar consistency between methods and, despite poor foraminiferal preservation in the mangrove sediments, the foraminifera show differences between the mid-Holocene coastal and estuarine environments, more clearly than is indicated by the mangrove pollen. The uppermost mangrove sediments (Zone 40/2: 40–160 cm) contain a significantly different fauna from the mangrove zone of core SAH29. Brackish-water types *Bullosatura australiensis*, *Pseudonionella variabilis* and *Stomoloculina multiangula* in SAH40 contrasts with the diverse fauna in the mangrove sediments of SAH29, where many of the brackish-water types have marine affinities (*Quinqueloculina seminula*, *Shackoinella globosa* etc.).

Our foraminiferal data suggest that the previous reconstructions of the mid-Holocene South Alligator estuary at the SAH40 site should be modified. Below the mangrove sediments in SAH40 (i.e., below 680 cm), the foraminifera indicate near-marine conditions similar to those seen in SAH29, rather than subtidal river channel sedimentation as inferred by Woodroffe et al. (1986). The “near marine” sediments in both the cores have similar proportions of marine, floating and brackish species (cf. Fig. 7, 300–750 cm, and Fig. 9, 700–1100 cm), while the >125 µm class is characterised by *Quinqueloculina philippinensis*, *Spiroloculina* spp. and *Triloculina tricarinata* in both the cores. Proportions of porcellaneous to hyaline tests are similar (about 45:55) in both and resemble the ratio in surface samples from near the river mouth, rather than values around 15:85 that occur in the river near core 40 today (Fig. 3). We conclude that estuarine conditions resembling those near the present mouth prevailed at the SAH40 site 6700 years ago, when the series of laminated sediments accumulated. It is likely, therefore, that the very broad funnel-shaped estuary of the lower tidal river (cf. Fig. 1) extended further upstream at that time.

8. Conclusions

Foraminifera provide new information about Holocene palaeoenvironments of the South Alligator River, not available from sedimentology or pollen analysis. In

particular, palaeosalinities can be estimated from the assemblages of brackish and marine taxa. This may be surprising, because *a priori* it would seem unlikely that usefully distinct thanatocoenoses would be preserved in the macrotidal South Alligator River sediments, with its strong tidal currents, extreme seasonal variations of salinity, and possible occurrences of low pH in the deposits themselves. Palaeosalinity can be gauged quite accurately in microtidal and diurnal mesotidal estuaries with weak seasonal variations of salinity. However, the data presented here show that foraminifera provide useful palaeoenvironmental information even for the South Alligator River, and we expect that the same will hold for other tropical estuarine sediment tracts.

Palaeotidal and palaeosalinity data from foraminifera complement those derived from pollen. Quantitative analysis of preserved mangrove pollen is an accurate guide to mid- to upper-intertidal zones in tropical coastal and estuarine sediment bodies (Chappell and Grindrod, 1984, 1985; Grindrod, 1988) but up-river palaeosalinity has not been identified successfully from mangrove pollen in northern Australia, because the taxa that favour low salinity sites (*Xylocarpus*, *Acanthus*, *Heritiera*) are poorly represented in the palynoflora, even though they may be dominant in the local forest. Furthermore, although mangrove pollen assemblages clearly vary with habitat within the mangrove zone, they do not differ much between the intertidal and subtidal realms. Foraminifera are excellent indicators of both habitat and palaeosalinity because of the many species with different estuarine adaptations; our results show that indications of both habitat and salinity are preserved even in tidally mixed faunas of the South Alligator River.

Finally, our observations show that palaeoenvironmental interpretation rests on recognition of both the foraminifer assemblage and its taphonomy in each sedimentary environment. Results also show that many foraminifera degrade rapidly in samples from the field, unless rapidly and correctly treated. However, the taphonomic status of different taxa in a thanatocoenosis is a very useful guide to the original conditions of transport and deposition, and to diagenetic conditions after burial.

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Appendix A

List of fauna in present-day surface sediments of the South Alligator River

Generic determinations are mostly based on Loeblich and Tappan (1988). The name used here is followed by the original name (synonym). Many of the species are illustrated in Albani (1979), Haynes (1973), and Baker (1960). Notes: (1) * denotes the occurrence of living specimens in South Alligator samples (2) Habitat affinities: B = brackish, M = marine, Mf = dominantly marine forms whose relatively small tests tend to be carried out in suspension.

Arenaceous

Thurammia ? limnetes Scott and Medioli, 1980 (B)
Textularia conica d'Orbigny, 1839 (M)
T. oceanica Cushman = *T. foliacea* Heron-Allen & Earland var. *oceanica* Cushman, 1932 (M)
T. lata Germeraad, 1946 (M)
Pseudoclavulina sp.
 **Trochammia inflata* (Montagu) = *Nautilus inflatus* Montagu, 1808 (B)
 **T. squamata* Parker & Jones, 1860 (B)
T. ochracea (Williamson) = *Rotalina ochracea* Williamson, 1858 (B)
Arenoparella mexicana (Kornfeld) = *Trochammia inflata* (Montagu) var. *mexicana* Kornfeld, 1931
Arenoparella asiatica (B)
Eggerella australis Collins, 1958 (M)
Protoschista ? sp.
Gaudryina sp. (M)

Porcellaneous

**Lituola salsa* (Cushman & Brönimann) = *Ammobaculites salsus* Cushman and Brönimann, 1948 (B)
 **Miliammia fusca* (Brady) = *Quinqueloculina fusca* Brady, 1870 (B)
Spiroloculina communis Cushman & Todd, 1944 (M)
S. bradyi Barker, 1960
Spiroloculina sp. A (M)
Quinqueloculina philippinensis Cushman, 1921 (M)
Q. seminula (L.) = *Serpula seminulum* L., 1758 (B)
Q. contorta d'Orbigny, 1846 (M)
Q. poeyana d'Orbigny, 1839 (M)
Q. polygona d'Orbigny, 1839 (M)
Q. lamarckiana d'Orbigny, 1839 (M)
 **Q. ferrusacii* d'Orbigny, 1826 (M)
Q. cf. ferrusacii d'Orbigny
Q. akneriana rotunda (Gerke) = *Miliolina akneriana* d'Orbigny var. *rotunda* Gerke, 1952 (B)
Triloculina tricarinata d'Orbigny, 1826 (Mf)
Triloculina sp. (M)

Edentostomina cultrata (Brady) = *Miliolina cultrata* Brady, 1879 (M)
Edentostomina spp. (M)
Scutuloris spp. (M)
Pyrgo spp.
Miliolinella spp. (M)
Vertebralina sp. (M)
Massilina sp. (M)
Articulina sp.

Hyaline

Lagena spp. (Mf) *Fissurina* spp. (Mf)
Oolina spp. (Mf)
Glandulina spp. (Mf)
Guttulina spp. (Mf)
Polymorphina sp.
Reussella spinulosa (Reuss) = *Verneuilina spinulosa* Reuss, 1850 (Mf)
Trimosina sp. (Mf)
Trifarina spp. (Mf)
Uvigerina spp. (Mf)
Neouvigerina ampullacea (Brady) = *Uvigerina asperula* Czjzek var. *ampullacea* Brady, 1884
Bulimina sp.
Bolivina spp. (Mf)
Brizalina striatula (Cushman) = *Bolivina striatula* Cushman, 1922 (Mf)
B. earlandi (Parr) = *Bolivina earlandi* Parr, 1950 (Mf)
Loxostomum convallarium (Millett) = *Bolivina convallaria* Millett, 1900
Fursenkoina sp. (Mf)
Laterostomella sp. (Mf)
Rectobolivina sp. (Mf)
Chrysalidinella sp. (Mf)
Spirillina sp. (Mf)
Patellina corrugata Williamson, 1858
Schackoinella globosa (Millett) = *Discorbina imperatoria* var. *globosa* Millett, 1903 (Mf)
Ammonia beccarii (L.) s.l. = *Nautilus beccarii* L., 1758 (B)
 ?*Ammonia convexidorsa* Zheng, 1978 (Mf)
Pseudoeponides spp. (B)
Helenina anderseni (Warren) = *Pseudoeponides anderseni* Warren, 1957 (B)
Schwantzia elegantissima McCulloch, 1977 (B)
Pararotalia venusta (Brady) = *Rotalia venusta* Brady, 1884 (M)
Rosalina spp. (Mf)
Gavelinopsis sp. (Mf)
Hanzawaia spp.
Cibicides lobatulus (Walker & Jacob) = *Nautilus lobatulus* Walker & Jacob, 1798 (M)
Cibicidina spp.
Poroeponides spp. (M)
Eponides ? sp.

Cancris auriculus (Fichtel & Moll) = *Nautilus auricula*
Fichtel & Moll, 1803
Cymbaloporetta bradyi (Cushman) = *Cymbalopora poeyi*
(d'Orbigny) var. *bradyi* Cushman, 1915 (M)
Planorbulina variabilis (d'Orbigny) = *Truncatulina*
variabilis d'Orb., 1826
Planorbulinella larvata (Parker & Jones) = *Planorbulina*
larvata Parker & Jones, 1865 (M)
**Stomolocolina lingulata* (Collins) = *Munkiella lingulata*
Collins, 1981 (B)
**Pseudononionella variabilis* Zheng, 1978 (B)
**Pseudononionella* sp.
Bisaccioides cuspatus Collins, 1981 (B)
“*Nonionella*” *excavata* Collins = *Nonionella excavata*
Collins, 1981 (B)
Gen. et sp. nov. A
Elphidium simplex Cushman, 1933 (B)
E. excavatum (Terquem) = *Polystomella excavata*
Terquem, 1875 (B)
E. hispidulum Cushman, 1936 (B)
E. advenum (Cushman) = *Polystomella advena*
Cushman, 1922 (M)
E. discoidale (d'Orbigny) = *Polystomella discoidale*,
d'Orbigny, 1839
E. kiangsuensis (Ho, Hu et Wang) = *Cribrononion*
kiangsuensis Ho, Hu et Wang, 1965 (B)
Elphidium spp.
Cribrononion hawkesburiensis Albani, 1974 (Mf)
?*C. oceanicum* (Cushman) = ?*Elphidium oceanicum*
Cushman, 1933
Nonion ? spp. (Mf)
Rectoelphidiella lepida Ho, Hu et Wang, 1965 (B)
Trichohyalus tropicus (Collins) = *Discorbinopsis tropica*
Collins, 1958 (B)
Globorotalia sp. (Mf)
globigerinids (Mf)

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