Mid-Holocene Development of Mangrove Communities Featuring Rhizophoraceae and Geomorphic Change in the Richmond River Estuary, New South Wales, Australia

TAKEHIKO R. HASHIMOTO[1]*, NEIL SAINTILAN[2] and SIMON G. HABERLE[3], [1]**Department of Primary Industries, PO Box 344, Hunter Region Mail Centre, NSW 2310, Australia. Corresponding author. Email: riko.hashimoto@dpi.nsw.gov.au;* [2]*Centre for Environmental Restoration and Stewardship, Australian Catholic University, North Sydney, NSW 2059, Australia;* [3]*Research School of Pacific and Asian Studies, Australian National University, Canberra, ACT 0200, Australia*

Received 8 March 2005; Revised 7 July 2005; Accepted 6 December 2005

Abstract

This paper describes the hitherto unreported occurrence of mid-Holocene mangrove deposits in the Richmond River estuary, southeastern Australia, thereby providing evidence for changes in the distribution and composition of mangrove communities within a subtropical estuarine system during the Holocene. Stratigraphic, radiocarbon and palynological evidence indicates that widespread development of mangrove communities took place in the upstream reaches of the Richmond River estuary during the period 7000 to 6000 years BP. These communities maintained their habitat through substrate aggradation under the conditions of a moderate sea-level rise, in contrast to other estuaries within the region, which generally experienced the submergence of intertidal substrates. Mangrove species belonging to the family Rhizophoraceae, most likely *Bruguiera gymnorrhiza* and *Rhizophora stylosa*, dominated these communities, in strong contrast to contemporary communities, which are dominated by *Avicennia marina*. Moreover, these mid-Holocene communities were located a considerable distance upstream of the contemporary occurrences of Rhizophoraceae species within the estuary. The changes in the spatial distribution and composition of mangrove communities parallel the large-scale evolution of the estuary driven by sea-level variation. Shallow, buried Pleistocene terraces probably contributed to the regionally unique aggradational response of the mangrove communities and their substrates to a sea-level rise during mid-Holocene times.

KEY WORDS *sedimentation; palynology; sea-level change; estuary evolution; coastal wetland*

Introduction

Environmental changes associated with Quaternary sea-level fluctuations have had a profound impact on the distribution of mangrove habitats at both local and regional scales. During the Holocene, regionally synchronous phases of mangrove expansion and contraction appear to have taken place in estuaries of northern Australia (Thom *et al*., 1975; Woodroffe *et al*., 1985; Crowley, 1996) and on tropical carbonate reefs in the Pacific and the Florida-Caribbean region (Woodroffe and Grindrod, 1991). Such

doi:10.1111/j.1745-5871.2006.00360.x

changes have been attributed to fluctuations in the availability of suitable substrates, controlled by the interplay between deposition and sea-level behaviour (Woodroffe and Grindrod, 1991; Grindrod *et al.*, 1999).

Changes to mangrove habitats during the Holocene have not been confined to their spatio-temporal distribution. In some cases, evidence suggests that the composition of the mangrove communities also changed, with certain species being more dominant at specific periods during the Holocene. In particular, the increased representation of mangroves belonging to the family Rhizophoraceae during the mid-Holocene transgression has been documented from widely separated parts of the world, including northern Australia (Woodroffe *et al.*, 1985; Crowley *et al.*, 1990; Crowley and Gagan, 1995) and the tropical Americas (Bartlett and Barghoorn, 1973; Tissot, 1980).

Along the coast of eastern Australia, species diversity within contemporary mangrove communities declines with increasing latitude (Wells, 1983), possibly in response to changes in the mean temperature of the coldest month and frost incidence (Saenger and Moverley, 1985). The coast of northern New South Wales represents a transitional zone, in which the southern distributional limits of three tropical mangrove species, *Bruguiera gymnorrhiza* (L.) Lamk., *Excoecaria agallocha* L. and *Rhizophora stylosa* Griff. are reached, and southward of which the mangrove communities are generally dominated by the species *Avicennia marina* var. *australasica* (Wells, 1983; West *et al.*, 1984). At the regional scale, mangroves along the southeast Australian coastline occur in discontinuous pockets in wave-sheltered environments, such as estuaries and deltas, bays, tidal inlets and coastal creeks.

Although a considerable body of research documents the Holocene dynamics of mangrove habitats and communities in the tropics and warm subtropics (for example Parkinson *et al.*, 1994; Crowley, 1996; Fujimoto *et al.*, 1996; Miyagi *et al.*, 1999; Ellison, 2000; Iselbe and Sanchez, 2002), few studies have been carried out in cooler subtropical and warm temperate settings, such as those of southeastern Australia. The limited evidence available suggests that mangrove species in some of these areas have experienced substantial changes in their regional spatial distribution during the Holocene (Mildenhall and Brown, 1987; Mildenhall, 1994).

Although much research effort has been directed at the determining and predicting mangrove response to sea-level rise at a general level (namely regions and communities), the effects of local-scale factors, including the variability in substrate conditions, have received far less attention.

This paper documents the occurrence of mid-Holocene mangrove deposits in the lower Richmond River, northern New South Wales, southeastern Australia, and explores the relationship between mangrove habitat, sea-level change, and estuarine-deltaic evolution.

The study area

Coastal geomorphology

The microtidal coast of northern New South Wales is characterised by a series of bedrock-bound embayments filled with unconsolidated sediments of mainly Pleistocene to Holocene age (Roy and Boyd, 1996; Roy, 1998: Figure 1). The estuarine-deltaic lowland of the Richmond River is located in the largest of such embayments of the region. Much of the embayment is filled with relict Pleistocene alluvial and coastal deposits, and the Holocene sediments occupy a

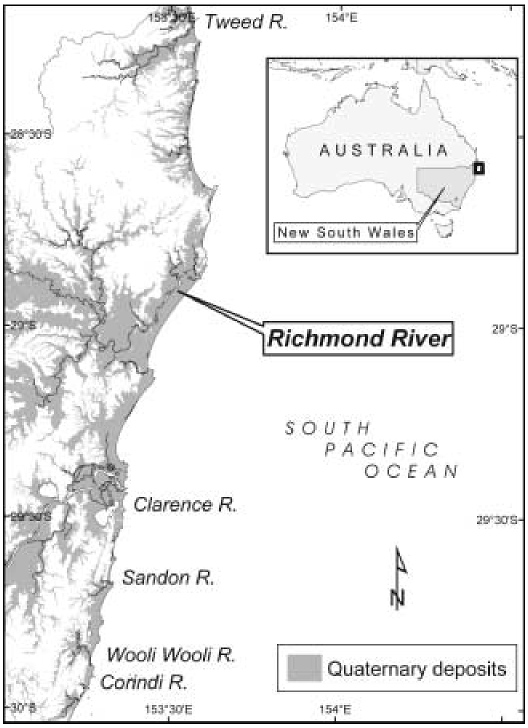

Figure 1 The northern New South Wales coast showing the distribution of Quaternary deposits.

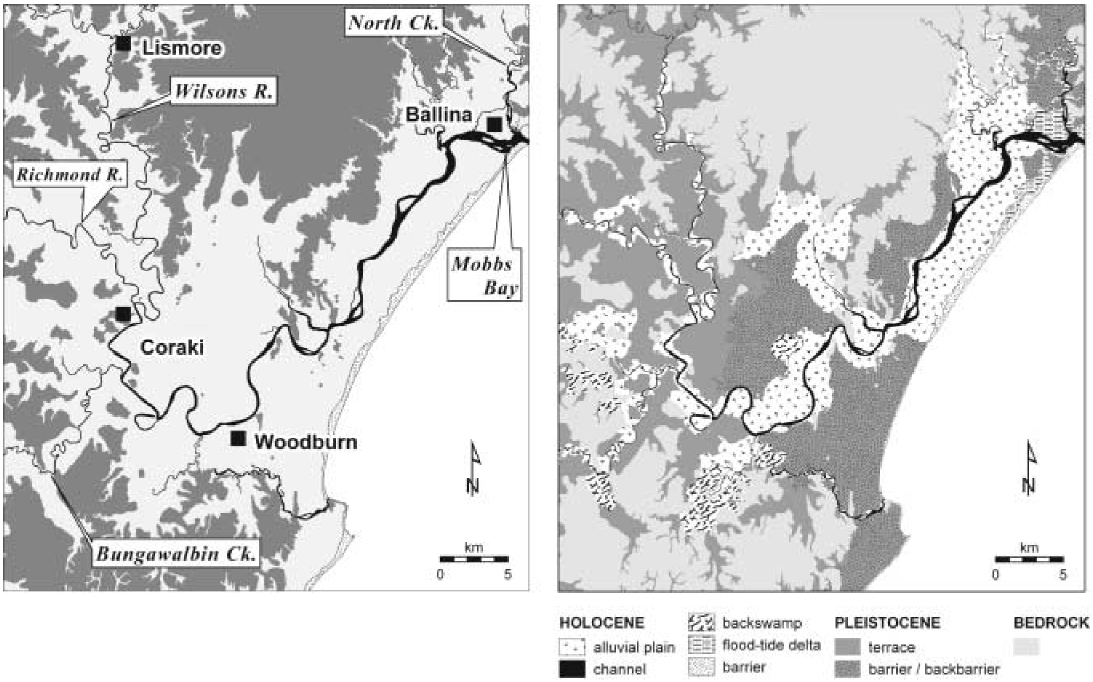

Figure 2 Richmond River area, New South Wales, showing its general configuration (left) and Quaternary geology (right).

relatively narrow inset valley incised into this material (Figure 2). The location of the upstream boundary between the Holocene lowland and the Pleistocene deposits, in the vicinity of the confluence of the main channel and Bungawalbin Creek, is obscure at the surface, as Holocene sediments thinly and discontinuously mantle the older deposits over extensive areas. On the seaward side, the Holocene deposits are separated from the ocean by a composite Pleistocene/ Holocene coastal barrier and flood-tide delta system (Drury, 1982).

The present-day configuration of estuarine-deltaic lowlands in southeastern Australia has been largely attained through the infilling of estuarine basins enclosed on their seaward side by coastal barrier systems during the Holocene marine transgression and highstand. The rate of sea-level rise was rapid (*ca*. 0.01 m yr^{-1}) in the early part of the transgression to approximately 8000 years BP, then slowing down to approximately half this rate prior to attaining the present level at 6500–6000 years BP (Roy and Boyd, 1996). Highstand conditions have essentially prevailed since that time, although there is growing evidence that a higher sea level of up to 2 m above the present level may have been attained at some stage during the mid- to late-Holocene (Flood and Frankel, 1989; Baker and Haworth, 1997).

In the larger estuarine systems, such as that of the Richmond River, two main depositional mechanisms have been important in their infilling process: the vertical aggradation of the estuarine basin floor with fluvially derived, suspended-load sediments (dominated by clay- and silt-sized particles), and the lateral (downstream/seaward) expansion of a mixed-load (sand, silt and clay) fluvial delta into the basin (Roy, 1984). Infilling of the estuarine basin was a highly heterogeneous process due to differences in sedimentation rates across the fluvial delta (Hashimoto, 2003: Figure 3). The establishment of a subaerial delta plain was rapid proximal to the mouth of the deltaic distributaries, while subaqueous conditions persisted for a longer period in distal areas. Cut-off and inter-channel bays thus evolved from the unfilled remnants of the original estuarine basin in channel-distal areas, which commonly continued to persist even after the full expansion of the delta across the estuarine basin to the ocean. The contemporary Richmond River lowland represents a well-developed stage of estuary infilling, characterised by extensive estuarine-deltaic plains traversed by a channel system with a meandering to straight morphology.

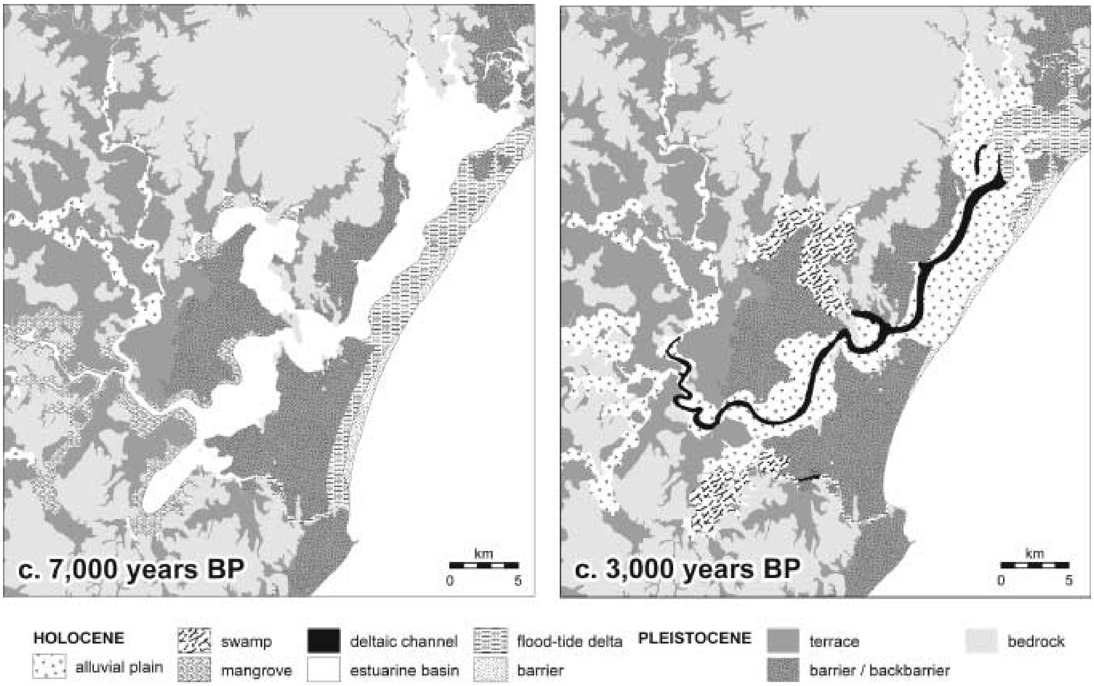

Figure 3 Holocene evolution of the Richmond River estuary and deltaic lowland.

Terrestrial and freshwater swamps, with original vegetation dominated by subtropical rainforest, *Eucalyptus*, *Melaleuca* and *Casuarina* species, prevail over most of the plains. Intertidal environments, featuring mangrove and saltmarsh vegetation, are restricted to narrow strips fringing channels and to the more extensive areas within the North Creek sub-catchment.

Climate

The climate of coastal northern New South Wales is humid subtropical with a distinct summer to autumn maximum in rainfall. The regional climate is strongly influenced by the El Niño-Southern Oscillation (ENSO), which results in large interannual variability in rainfall (Sturman and Tapper, 1996). Mean temperatures in the lower Richmond River catchment, in the vicinity of Ballina, vary from daily maxima of 27–31°C in January to daily minima of 6–12°C in July. Frosts are experienced every winter in the inland parts of the catchment, but are rare at the coast. Mean annual rainfall decreases from over 1400 mm along the coast to 1100 mm in the western parts of the coastal lowlands.

Hydrology and tides

The Richmond River is one of the largest coastal drainage systems of New South Wales, with a catchment area of *ca.* 6900 km^2 and a mean annual discharge of 1 920 000 ML (Richmond Catchment Management Committee, 1995). Two major tributaries, Wilsons River from the north and Bungawalbin Creek from the south, merge with the main channel in the vicinity of the geographical centre of the Quaternary depositional basin (Figure 2). Downstream of Woodburn (*ca.* 40 km from the mouth), the Richmond River increasingly assumes an estuarine character in its hydrology and geomorphology. At its mouth, the Richmond River is joined by North Creek, a southward-trending estuarine tributary, prior to discharging to the sea. Most of the annual discharge (90%) and flood events occur during the summer-autumn wet season (Sinclair Knight and Partners, 1980; Hossain *et al.*, 1997), when the river may completely freshen to its mouth for periods of up to a few weeks (Eyre *et al.*, 1997). During dry periods, saline conditions extend considerable distances upstream, as evidenced by the occurrence of mangroves (*Avicennia marina* and *Aegiceras corniculatum* (L.) Blanco) over 40 km from the river mouth. Tidal influence extends along most of the lowland reaches of the Richmond River, reaching 120 km upstream of the mouth along the Wilsons tributary (Department of Land and Water Conservation, 2000). Tidal range within the channel decreases rapidly with increasing upstream distance, from the open ocean range of approximately 2 m at the mouth to 0.5–0.8 m in the upper estuarine reaches.

Contemporary mangrove occurrence in the Richmond River

Most of the approximately 5 km^2 of mangrove in the Richmond River today occurs within the downstream 10 km of the main channel and in North Creek (West *et al*., 1985). Mangrove species richness is highest in this farthest downstream segment of the estuary, with all of the five species previously identified from the estuary being represented; namely *Rhizophora stylosa, Bruguiera gymnorrhiza, Excoecaria agallocha, Aegiceras corniculatum* and *Avicennia marina* (West *et al*., 1984; Youseff and Saenger, 1999).

Throughout the estuary, *Avicennia marina* and *Aegiceras corniculatum* are the dominant species, and they are the only species present in the more upstream locations to the limit of mangrove growth at Woodburn, approximately 45 km from the river mouth. *Rhizophora stylosa* is confined to a small stand in Mobbs Bay at the river mouth (Youseff and Saenger, 1999), and was not identified in the previous surveys of Wells (1983) and West *et al*. (1984). Individuals of *Bruguiera gymnorrhiza* may be found over 10 km upstream of the river mouth, but their principal distribution is also in the lower estuary, specifically in North Creek and near the river mouth.

Methods

Sediment sampling and analysis

As part of a more general study on the evolution of the Richmond River estuarine-deltaic lowland, sediment samples were collected from 119 locations in the Richmond River estuarine-deltaic lowland. At most locations, hand ('Dutch') augers were employed to collect samples to a maximum depth of 2 to 8 m below ground level. Sediment samples were collected from auger holes when changes in texture, colour and/or organic matter content were observed. When the sediments were loose and waterlogged, steel casings were employed to prevent the collapse of the hole upon extraction of the auger head. Ground elevations at the augering sites are generally 1 to 3 m above AHD (Australian Height Datum), and were determined from published sources or through topographic surveys using a Topcon laser level.

The organic matter content of the sediment samples was determined by combusting oven-dried (90–100°C for 24 hours) and disaggregated sediment in an electric furnace at 430°C for 24 hours, then measuring weight loss. The results were expressed as a percentage of the pre-combustion dry mass. Sediment texture was analysed by wet-sieving the sediment through a 63 μm-mesh sieve (Gale and Hoare, 1991), and comparing the pre- and post-sieving dry sediment mass to yield the percentage proportions of sand-, clay- and silt-sized particles.

At twelve of the augering sites, located in the upstream part of the lowland, organic-rich sediments were identified in the lowland subsurface. Dark grey matrix colour, enrichment with macro-organic matter (particularly root matter and wood fragments), the presence of pyrite and/or jarosite, and their elevation relative to the present-day sea level indicated a high likelihood that they were originally deposited within an intertidal, mangrove swamp environment. Sediment samples from these sites were selected for further analyses (described below), and form the basis for the discussion presented in this paper.

Pollen analysis

Pollen assemblages in 15 sediment samples from six of the augering sites were analysed in order to detect the presence of mangroves. Samples were selected on the basis of their likely origin within a mangrove environment (as outlined in the preceding paragraph). In addition, sediment samples of the overlying backswamp or the underlying estuarine basin facies were analysed at three sites for comparison.

Extraction of pollen and spores from sediment samples followed standard procedures (Faegri and Iversen, 1989). Pollen and spore identification was assisted by regional reference collections held at the School of Geography and Environmental Sciences, Monash University, and the Department of Archaeology and Natural History at the Australian National University. Pollen and spore counts are expressed as percentages of the total pollen and spore sum, which reaches a minimum of 200 in all samples.

Radiocarbon dating

Organic material in five sediment samples from four of the auger sites (3, 6, 9 and 10: Figure 4) was dated using radiocarbon methods. Sample selection was guided by the availability of easily dated material, such as coarse wood fragments or peat. Two samples were dated at auger site 9,

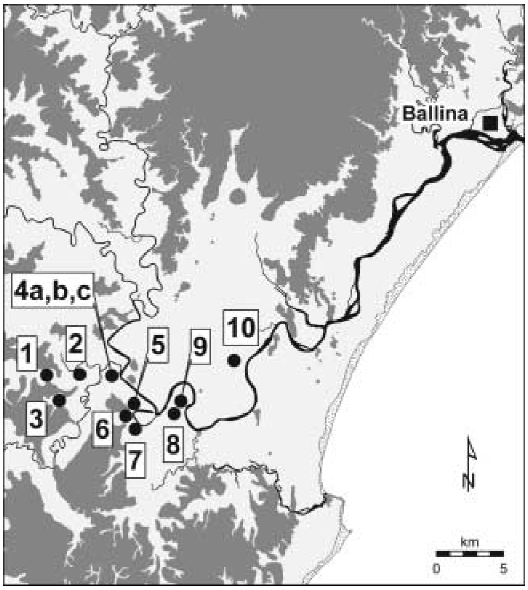

Figure 4 Auger-hole sites encountering mangrove facies sediments in the subsurface, Richmond River lowland.

where the (suspected) mangrove deposit attained a particularly great thickness, in order to gauge the rate of its deposition. All samples were dated by the conventional method at the University of Waikato Radiocarbon Dating Laboratory, Hamilton, New Zealand, except for Sample 5 at Site 9 (Sample 9/5), which was dated by the AMS (accelerator mass spectrometry) method at Rafter Radiocarbon Laboratory, Lower Hutt, New Zealand. The organic material was pretreated with a hot acid/alkali/acid wash, and then dried, prior to age determination. All ages are quoted as conventional radiocarbon ages, with correction for isotopic fractionation applied (Keith *et al.*, 1964; Aitken, 1990).

Results

Distribution of mangrove sediments in the subsurface of the Richmond River lowland

Organic-rich sediments of likely mangrove origin were encountered at twelve of the 119 drill-holes within the Richmond River estuarine-deltaic lowland. All of the occurrences were located at in the upstream part of the Holocene lowland, mostly at distances of 40 to 55 km from the river mouth along the present-day channel (Figure 4). The occurrences also extend considerable distances into some tributary valleys, such as those of Bungawalbin and Sandy Creeks. The present-day surface geomorphology of the areas underlain by the organic-rich deposits is typically dominated by low-lying backswamps and distal sections (backslopes) of levees bordering the channels. The deposits appear to be absent from the more channel-proximal parts of the levees. In the remaining part of this paper, these deposits will be collectively referred to as the *mangrove facies* sediments.

Sediment characteristics and stratigraphy

Sediments of the mangrove facies are variable in texture, colour and organic matter content. They range from reddish brown fibric peat to dark brown to dark grey organic-rich silty clay, commonly with woody organic fragments. The total organic matter content commonly ranges from 15 to 40% dry weight. The matrix sediment is fine-grained (sand content values are generally less than 10%), and in some cases entirely composed of silt- and clay-sized particles (Figure 5). The thickness of the facies is highly variable, ranging from less than 0.5 m to more than 3.8 m at the sites considered in the study. At more than half of the sites it exceeds 1.5 m. The upper elevational limit of these deposits lies at or near the present-day local high-tide level, whereas their lower limit is generally located at depths below the present-day low-tide level, in some cases by as much as 2–3 m.

The organic matter content and texture of the mangrove facies vary with depth within the stratigraphic profile (Figure 6). Typically, organic matter content decreases with increasing depth. At some sites, the mangrove facies grades

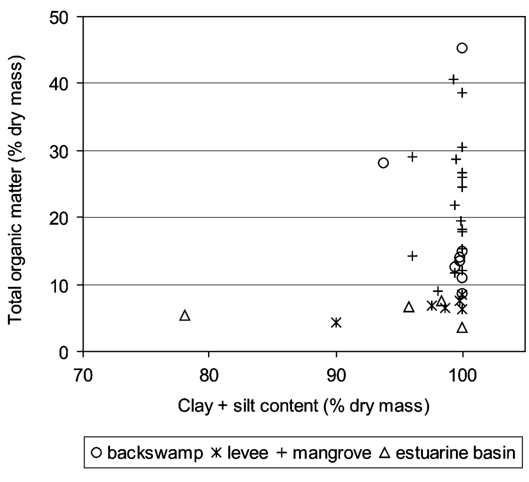

Figure 5 Organic matter and combined silt/clay content of mangrove facies and associated Holocene sediments, Richmond River lowland.

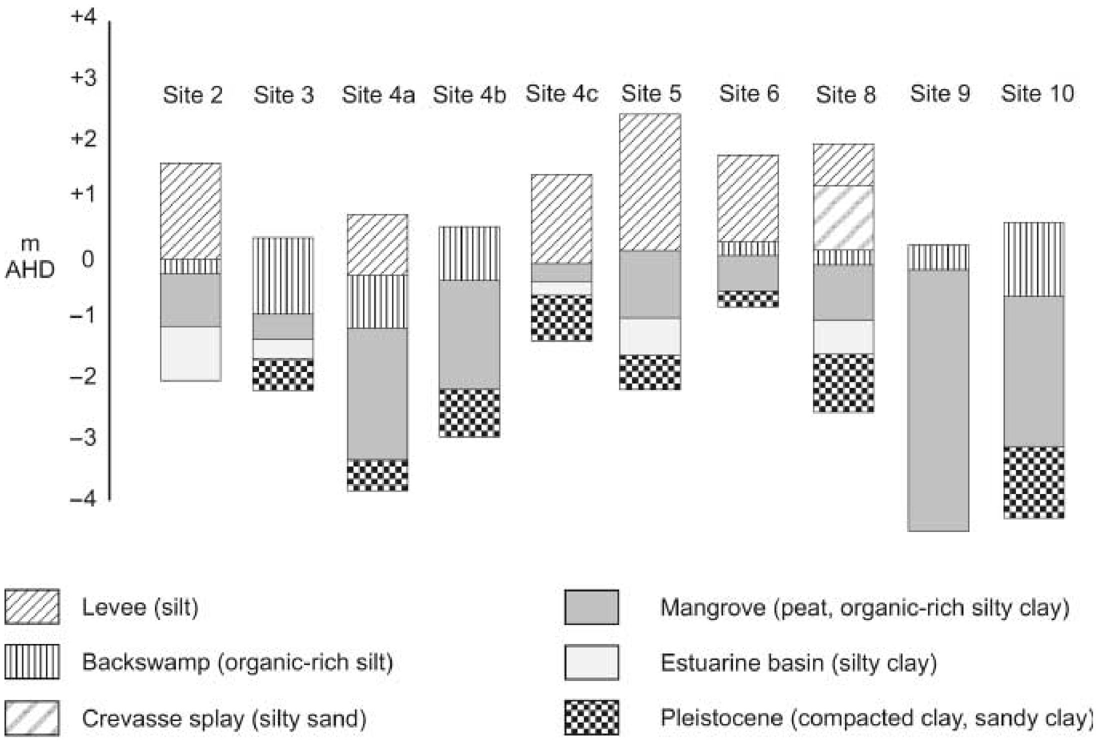

Figure 6 Stratigraphy of mangrove facies and associated sediment, Richmond River lowland. Auger-hole logs are arranged according to their geographic location from upstream (left) to downstream (right).

downward into predominantly clastic (<10% organic matter) dark grey silty clay, which is inferred to have been deposited under subaqueous estuarine basin conditions. On the other hand, at Site 9, the upper organic mangrove facies-rich unit attains an exceptional thickness (approaching 4 m) and an underlying estuarine basin facies was not reached by the base of the auger hole. At most sites, the mangrove facies sediments are directly or indirectly underlain by compacted and partly oxidised clayey sediments of late Pleistocene age at a depth of 2 to 4 m below the lowland surface (Figure 6). This implies that the Holocene-Pleistocene contact at these sites is considerably shallower than at the axial and downstream parts of the estuary, where it commonly lies at depths in excess of 10–15 m beneath the surface (Drury, 1982). At Sites 2 and 9, the contact was not reached by the base of the auger hole, but both sites are located close to outcrops or shallow subcrops of Pleistocene sediments.

Radiocarbon dating

Radiocarbon dates indicate that most of the mangrove facies sediments in the upper Richmond River lowland were deposited during the period 7000 to 6000 years BP (Table 1). There

Table 1 Radiocarbon ages of mangrove facies sediments, upper Richmond River lowland.

Site/sample	Depth (m below surface)	Material	Conventional C14 age (years BP)
3/4	0.9	Wood	6558 +/– 150 (Wk-9774)
6/5	2.1 – 2.2	Wood	6117 +/– 186 (Wk-9773)
9/5	1.8 – 2.5	Peat	6096 +/– 59 (NZA 9737)
9/6	4.5 – 4.8	Peat	6990 +/– 130 (Wk-8315)
10/5	2.5 – 2.7	Peat	6993 +/– 52 (Wk-9776)

appears to be little spatial pattern in age variability between the sites. Samples collected from greater depths within the stratigraphic sequence, such as 9/6, 3/4, and 10/5, returned greater ages than those collected at shallower depths, as might be expected. However, the difference between the former and the latter is relatively small, with those from the greatest depths returning ages of *ca*. 7000 years BP.

Palynology

Mangrove pollens belonging to the taxa Rhizophoraceae and *Avicennia* were detected at all auger-hole sites selected for detailed palynological analysis of the sediment (Table 2). They were present in varying quantities in all samples representing the mangrove facies, but were absent from samples representing the backswamp (4b/2, 9/2) and estuarine basin (5/6) facies. At some sites (2, 8, 9 and 10) the representation of Rhizophoraceae and *Avicennia* varies considerably at different stratigraphic levels within the mangrove facies (Table 2). In the upper parts of the facies, there is a tendency for the overall representation of mangrove taxa within the pollen assemblage to be low, and the mangrove pollens to be dominated by *Avicennia*. At lower stratigraphic levels, the representation of Rhizophoraceae (and consequently, of total mangrove pollen) increases, often quite dramatically (Table 2 and Figure 7). It is interesting to note that *Avicennia* does not always follow this trend, and, at some sites, actually decreases with increasing depth. The result of multiple sample analyses at Site 9, where the mangrove facies is particularly thick, indicates that relatively high *Avicennia* and low Rhizophoraceae values only prevail in the uppermost part of the mangrove facies, and the representation of Rhizophoraceae pollen far outweighs that of *Avicennia* throughout most of the facies (Figure 7). A sharp decline in mangrove pollen representation is apparent about the upper stratigraphic contact of the mangrove facies with the overlying backswamp sediments, and the pollen assemblage becomes dominated by *Casuarina*, and certain other freshwater and dryland taxa such as Myrtaceae at Site 9, and Graminae (Poaceae) at Sites 2 and 8.

The results also suggest some geographic variation in the representation of mangrove pollen taxa. In the comparatively downstream locations (Sites 5, 8, 9 and 10), Rhizophoraceae is the dominant or co-dominant taxon within the pollen assemblage (30–55%) of the mangrove facies, together with *Casuarinaceae* (Table 2). In the upstream areas, the relative importance of Rhizophoraceae within the pollen assemblage, and that of mangrove pollens in general, declines considerably (Table 2). At Site 2, mangrove pollen comprises up to 12% (of which Rhizophoraceae constitutes over 10%) of the total pollen assemblage, wheras at Site 4b, only traces of Rhizophoraceae and *Avicennia* were detected. At these upstream sites, the pollen assemblage within the mangrove facies and the overlying sediments is dominated by *Casuarina* and/or fern spores.

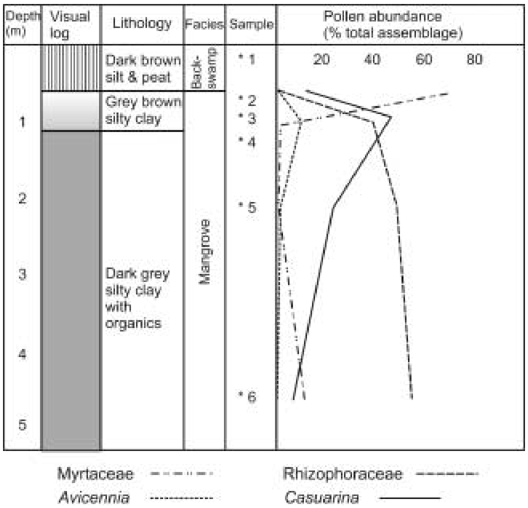

Figure 7 Stratigraphy and palynology of Holocene sediments at site 9, Richmond River lowland.

Geographic and stratigraphic variations are also apparent in the relative proportions of *Rhizophora*-type and *Bruguiera*-type within the Rhizophoraceae pollens present in the mangrove facies (Table 2). Generally, the *Bruguiera*-type is dominant over the *Rhizophora*-type, but the relative importance of the latter tends to increase in the downstream direction. In the upstream sites (2, 4b, 5), *Rhizophora*-type pollens are absent, but they constitute maxima of 42% and 74% of all Rhizophoraceae pollens at Sites 9 and 10. Furthermore, an increase in the *Bruguiera*-type pollen and a compensatory decrease in the *Rhizophora*-type are apparent in the upper stratigraphic levels of the mangrove facies at these two sites; at Site 9, the proportion of *Bruguiera*-type within the Rhizophoraceae pollens increases from 58% at the bottom to 68% at the top of the mangrove facies, and at Site 10, from 26% to 80%.

Table 2 Pollen assemblages within the the mangrove facies and associated sediments, upper Richmond River lowland. The variable *Rhizophora*/*Bruguiera* refers to the percentage proportions of *Rhizophora*- and *Bruguiera*-type grains within the total Rhizophoraceae pollen count. Locations of the augering sites are shown in Figure 4.

Site / sample	2/4	2/6	4b/2	4b/3	5/4	5/6	8/6	8/8	9/2	9/3	9/4	9/5	9/6	10/3	10/5
n	308	386	225	232	261	234	218	315	237	223	371	220	212	200	456
Sampling depth (m)	2.8–2.9	3.8–3.9	1.0–1.1	1.5–1.6	3.2–3.3	3.6–3.7	2.1–2.2	2.8–2.9	0.7–0.8	0.9–1.0	1.0–1.3	1.8–2.5	4.5–4.8	2.1–2.2	3.5–3.7
Organic matter (%)	12.2	7.5	15	24.5	14.3	3.6	40.6	28.7	14.1	18.3	17.8	19.4	21.9	25.9	26.6
Rhizophoraceae	0.3	10.4	0	1.7	34.1	0	0	33.3	0	17.5	31	45.9	54.7	41.5	45.6
(*Rhizophora*/*Bruguiera*)		(0/100)		(0/100)	(0/100)			(21/79)		(32/68)		(31/69)	(42/58)	(20/80)	(74/26)
Avicennia	0.6	1	0	0.4	0.8	0	4.6	0	0.4	4.9	3.5	2.3	0	5	0
Casuarina	7.1	26.7	38.2	40.5	35.2	17.5	46.8	27.3	10.5	45.7	29.4	23.2	7.1	29.5	38.6
Myrtaceae	0.3	9.3	1.8	3	4.2	1.7	11	11.4	69.6	2.7	3.2	0.5	10.4	6.5	7
Pandanus	0	0	0	0	0.8	0	0	0	2.1	0	0	0	0	0	0
Palmae	0	0	0	0.9	0	1.3	0	0	0	3.1	0	6.4	0	0	0
Other Tricolporate[1]	0.3	4.4	4	10.8	3.1	0.4	0.5	3.8	1.3	3.1	3.2	4.5	9.4	3	0
Gramineae	29.5	4.7	1.3	2.2	2.7	0	20.2	1.9	0	2.7	0.8	1.4	4.2	1	2.2
Asteraceae	1.6	0	0	0	1.9	0	0	1.6	0.4	0	0	0	0	0	0
Chenopodiaceae	1.6	0	0.4	0	0	0	0	0	0.4	0	0	0	0	0	0
Cyperaceae	5.8	0	3.1	0	0.8	0	0	11.1	1.3	1.8	0	0	0.5	0	0
Typha	11.4	0	1.3	0	0	0	0	0	0	0.9	0	0.5	0	0	0
Fern spores	41.2	39.1	38.2	12.5	16.1	78.2	12.8	8.6	6.8	8.1	16.2	11.4	6.6	13.5	6.6
Other[2]	0	4.4	11.6	28	0.4	0.9	4.1	1	7.2	9.4	12.7	4.1	7.1	0	0
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

1 Other Tricolporate includes all pollen grains with tricolporate structure (not ascribed to any known taxonomic group).
2 Other includes all pollen grains that could not be ascribed to any known taxonomic group.

Discussion

Development of mangrove communities under transgressive conditions in the mid-Holocene
Sedimentological, palynological and radiocarbon data indicate that mangrove communities developed in the upstream parts of the Richmond River estuary during mid-Holocene times, 7000 to 6000 years BP, leading to the locally widespread deposition of organic-rich sediment. Furthermore, the apparently uninterrupted deposition of these mangrove sediments within the stratigraphic sequence, from subtidal elevations upward to around the present-day high-water mark, suggests that these communities were able to keep pace with the slowing sea-level rise in the latter part of the post-glacial marine transgression through the synchronous aggradation of their substrates. Radiocarbon dates from Site 9 suggest a vertical accretion rate of the substrate in the order of 3.0 to 5.4 mm yr^{-1}, which is comparable to the approximate rate of sea-level rise in southeastern Australia during the period 8000 to 6500 years BP (about 5 mm yr^{-1}: Roy and Boyd, 1996), and also to the maximum long-term rates of mangrove sedimentation under Holocene transgressive conditions in the humid tropics, for example in northern Australia (Woodroffe, 1990, 1992), Micronesia and the Philippines (Miyagi *et al*., 1995; Fujimoto *et al*., 1996), and in southwestern Thailand (Miyagi *et al*., 1999). Thus, they appear to have maintained their habitat more or less continuously up to the onset of highstand conditions at 6000 years BP, after which they were displaced by freshwater swamp and dryland vegetation communities, such as those dominated by *Casuarina* and Myrtaceae. The high percentage of Gramineae pollen, in conjunction with the presence of Cyperaceae and *Typha* pollen, about the stratigraphic contact between the mangrove and backswamp facies at some sites may indicate the establishment of open vegetation, most likely a grass-dominated swamp.

Rhizophoraceae as a significant component of mangrove communities in the mid-Holocene Richmond River estuary
Mangrove species belonging to Rhizophoraceae appear to have been an important component of the mid-Holocene mangrove communities in the upper Richmond River estuary. The levels of total Rhizophoraceae representation within the pollen assemblage here are comparable to that of *Rhizophora* spp. pollen in the substrate sediments of mangrove forests adjoining a *Rhizophora*-dominated community in tropical northeastern Australia (Grindrod and Rhodes, 1984). *Rhizophora* representation in excess of 50% within a pollen assemblage is generally accepted as being indicative of a significant presence of the genus within the community (Crowley *et al*., 1994; Chappell and Grindrod, 1985; Grindrod, 1985; Clark and Guppy, 1988). On the other hand, the relationship between the representation of *Bruguiera* spp. within existing communities and in the pollen assemblage of the substrate sediment is not well understood. Thus, although *Bruguiera*-type pollen is in most cases dominant over *Rhizophora*-type within the pollen record, it is difficult to ascertain with confidence the relative importance of each genus within the system. Nonetheless, it may be concluded that mangrove species in the Rhizophoraceae appear to have been a major component in the upper Richmond River estuary (if not dominant), between 7000 and 6000 years BP. The upstream decline in the importance of *Rhizophora* relative to *Bruguiera* is likely to reflect the progressive decrease in salinity within the estuary with increasing distance from the estuary entrance, and the consequential loss of species with preference for high salinity levels, such as *Rhizophora stylosa*. Although the species-level identification of Rhizophoraceae pollen is problematic and was not attempted, the *Rhizophora*-type pollen grains are likely to be of *R. stylosa*, and the *Bruguiera*-type pollen those of *B. gymnorrhiza*, given that these species are the only ones present within the region today. The most southerly occurrences of other *Rhizophora* and *Bruguiera* species, namely *R. apiculata* Blume, *R. lamarkii* Montr., and *B. exaristata* Ding Hou, are located in the vicinity of Port Clinton, Queensland (22° 30′S; Wells, 1983), 700 km to the north.

The subtle increase in the representation of *Avicennia* pollen, observed toward the upper stratigraphic limit of the mangrove deposits facies at some of the sites, may also be significant, given that this taxon is commonly under-represented within the pollen record. Crowley *et al*. (1994) note that the relative representation of *Avicennia* pollen within the sediments of modern *Avicennia*-dominated forests is usually below 10%. Thus the *Avicennia* peak of *ca*. 5% in the upper part of the mangrove deposits at Sites 8 to 10 is likely to signify the displacement of Rhizophoraceae and the establishment of an *Avicennia*-dominant mangrove community at the onset of the Holocene highstand.

The apparent existence of mangrove communities featuring Rhizophoraceae species over a period of at least 1000 years in an upstream area of the Richmond River estuary, located a considerable distance from the ocean and near freshwater discharge at the delta, is intriguing, given the present-day restriction of the species to the high-salinity environments of the lower estuary, in the Richmond River and also in riverine estuaries in Queensland (Bunt *et al*., 1982; Bunt *et al*., 1985; Saintilan, 1996, 1997). It may reflect the enhanced upstream penetration of marine water within the estuary under transgressive conditions, further assisted by the likely existence of a second tidal inlet 'upstream' of the main estuary entrance, which has subsequently been abandoned (Hashimoto, 2005). Alternatively, other factors, such as a more favourable (warmer) climate, may have increased the competitive advantage of Rhizophoraceae over the regionally dominant *Avicennia marina* at the time of deposition of the mangrove sediments in the upper Richmond River estuary.

Mangrove response to sea-level change – the role of large-scale forcing and local-scale factors

The ecological changes described in the preceding paragraphs appear to parallel mid-Holocene sea-level changes and the expected resultant geomorphic evolution of the Richmond River estuary and delta. During the latter stages of the Holocene transgression, the aggradation of delta substrates at a rate comparable to that of the sea-level rise permitted the maintaining of intertidal elevations, and thus the continued existence of mangrove communities featuring species of Rhizophoraceae. However, with the onset of highstand conditions, the absence of sea-level forcing allowed vertical accretion to raise the substrate beyond intertidal elevations, and to establish a subaerial estuarine-deltaic plain, which expanded with the downstream progradation of the delta front. Thus, as the substrate accreted to higher intertidal elevations, *Avicennia* may have displaced Rhizophoraceae due to their tolerance of such marginal conditions. Further aggradation resulted in the total displacement of mangrove communities by freshwater backswamp communities dominated by taxa such as *Casuarina* and *Melaleuca*.

Mid-Holocene transgressive mangrove sediments have rarely been described previously from southeastern Australia. In other large estuarine-deltaic systems of the region, such as those of the Tweed and Clarence Rivers, deposits of likely mangrove origin are either absent or very thin (<1.0 m), and do not appear to be enriched in organic matter to the extent of the mid-Holocene deposits from the upper Richmond estuary (Hashimoto, 2005). In most major Holocene estuarine-deltaic lowlands in southeastern Australia, the near-surface alluvial and freshwater sediments are generally underlain by thick clayey to sandy deposits of estuarine basin and delta front origins, suggesting that the Holocene transgression resulted in the expansion of subaqueous environments throughout most of the estuary (Hails, 1968; Walker, 1970, 1972; Lin and Melville, 1993; Roy, 1993; Huq, 1995; Lin *et al*., 1998; Hashimoto, 2005).

Why mangroves could flourish under transgressive conditions in the upper Richmond River estuary during the mid-Holocene, and not in the other nearby estuaries, may partly be attributable to local-scale geological controls. The upstream parts of the estuarine-deltaic lowland of the Richmond River are characterised by the widespread occurrence of Pleistocene coastal barrier, estuarine and fluvial sediments, either as surface outcrops or as buried terraces at shallow depths (generally <4 m) below the lowland surface (Drury, 1982; Hashimoto, 2005). The latter underlie most of the sites where mid-Holocene mangrove sediments were encountered. Such extensive preservation of relict sediments originating from the last interglacial highstand at or near the lowland surface is a phenomenon peculiar to the upper estuary of the Richmond River (Figure 8).

In the other large estuarine-deltaic systems of the southeast Australian region, as well as in the downstream reaches of the Richmond River lowland, such Pleistocene remnants are rare or are mantled by considerable thicknesses of Holocene sediments. The shallow depth, relative to the present-day sea level at which the terraces occur in the upper estuarine-deltaic lowlands of the Richmond River, implies that they were directly affected by rising sea levels only during the latter part of the Holocene marine transgression, at a time when the rate of sea-level rise was rapidly decreasing. Thus, while the terraces themselves provided an extensive, stable and even substrate which the mangroves could easily colonise, the slowing rate of sea-level rise allowed the substrate to aggrade at a comparable rate, permitting the mangroves to maintain their position and preventing their landward retreat or loss through submergence.

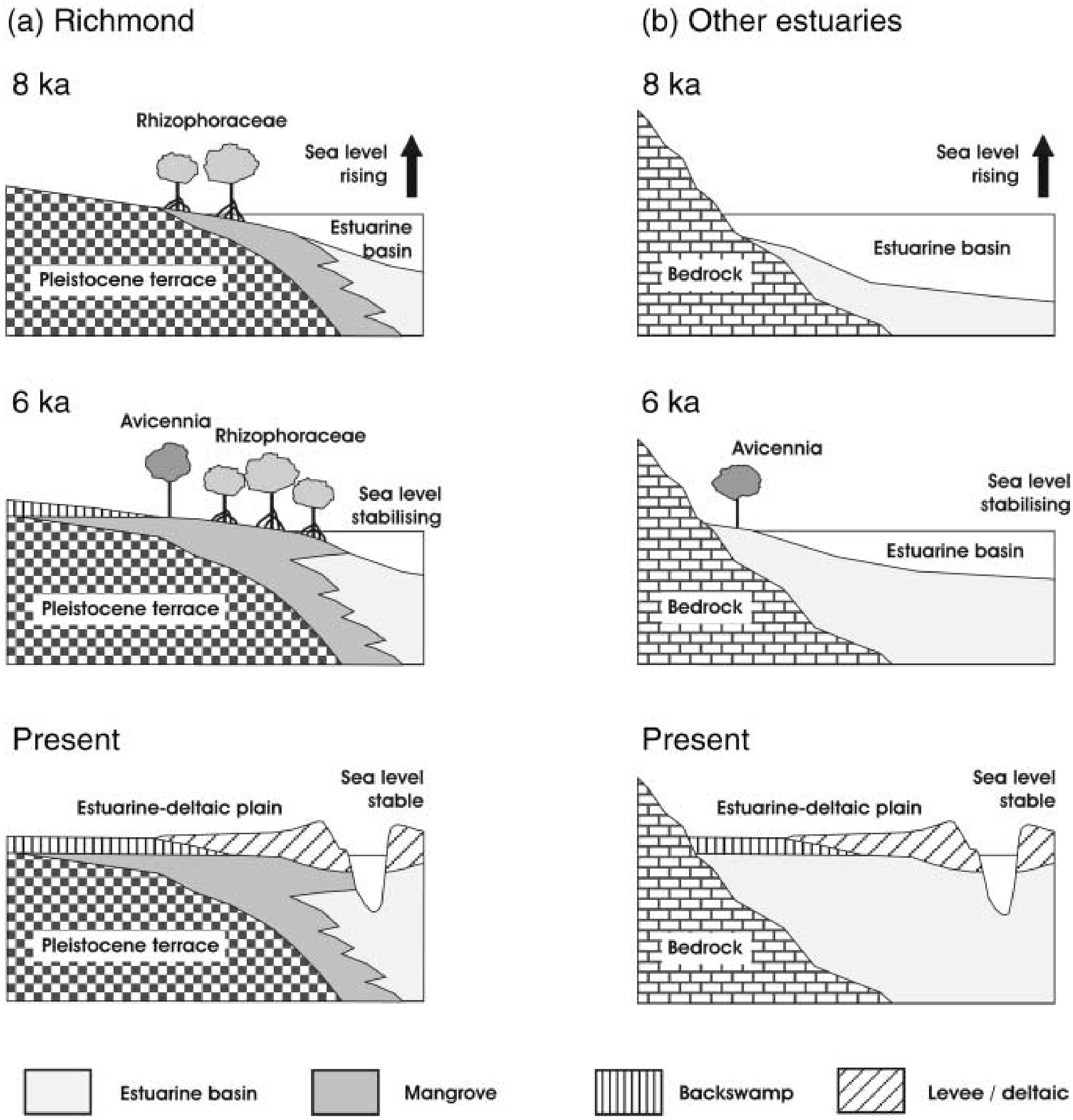

Figure 8 Conceptual model of sedimentation and mangrove habitat development during the mid-Holocene in (a) Richmond River and (b) other estuaries of the region.

Conclusions

Sediment-based evidence indicates that mangrove communities were widely established in the upper Richmond River estuary, southeastern Australia, during mid-Holocene times, *ca*. 7000 to 6000 years BP, in the final phase of the post-glacial marine transgression. These communities were floristically unique, at both regional and local scales, due to the prominence of species belonging to the family Rhizophoraceae, in contrast to most contemporary communities which are dominated by *Avicennia marina*. Moreover, the mid-Holocene mangrove communities are of geomorphic/geological significance, in that they were able to maintain their substrate despite the sea-level rise through vertical accretion, unlike in most other estuaries of the region. This aggradational response resulted in the deposition of organic-rich sediments, which attain thicknesses considerably greater than highstand intertidal deposits in other estuaries of the region. The close association between the spatial distribution of these sediments and areas of shallowly buried Pleistocene terraces suggests that the local-scale geomorphic control played a key role in the establishment of mangrove communities and deposition of associated sediments within the upper Richmond River estuary, in addition to the large-scale control imposed by sea-level forcing. Moreover, the findings suggest that Rhizophoraceae mangrove species in south-eastern Australia were more widespread during mid-Holocene times than today. Their currently restricted distribution in the downstream parts of Richmond River and other riverine estuaries within the region may represent refugia, arising from a progressive contraction in the area of suitable habitats parallelling estuary infilling during the Holocene highstand.

ACKNOWLEDGMENTS

We wish to thank Ursula Pietrzak at the School of Geography and Environmental Sciences, Monash University, for preparing the pollen and spore extractions, and Cathi Greve and Susan Ly, formerly of the Division of Geography, University of Sydney, for their cartographic skills. Nick Wilson, Australian Catholic University, is thanked for his interpretation of biogegraphic data and field assistance. The research was supported by an Australian Catholic University internal research grant for N. Saintilan and an Australian Postgraduate Research Award for T. Hashimoto. Climatic data for the study area were supplied by the Bureau of Meteorology Australia.

REFERENCES

Aitken, M.J., 1990: *Science-based Dating in Archaeology*. Longman, London.

Baker, R.G.V. and Haworth, R.J., 1997: Further evidence from relic shellcrust sequences for a late Holocene higher sea level for eastern Australia. *Marine Geology* 141, 1–9.

Bartlett, A.S. and Barghoorn, E.S., 1973: Phytogeographic history of the isthmus of Panama during the last 12 000 years. In Graham, A. (ed.) *Vegetation and Vegetational History of Northern Latin America*. Elsevier, Amsterdam, 203–299.

Bunt, J.S., Williams, W.T. and Bunt, E.D., 1985: Mangrove species distribution in relation to tide at the seafront and up rivers. *Australian Journal of Marine and Freshwater Research* 36, 481–492.

Bunt, J.S., Williams, W.T. and Clay, H.J., 1982: River water salinity and the distribution of mangrove species along several rivers in north Queensland. *Australian Journal of Botany* 30, 401–412.

Chappell, J. and Grindrod, J., 1985: Pollen analysis: a key to past mangrove communities and successional changes in North Australian coastal environments. In Bardsley, K.N., Davie, J.D.S. and Woodroffe, C.D. (eds) *Coasts and Tidal Wetlands of the Australian Monsoon Region*. Mangrove Monograph No. 1.1, North Australia Research Unit, Australian National University, Darwin, 225–236.

Clark, R.L. and Guppy, J.C., 1988: A transition from mangrove forest to freshwater wetland in the monsoon tropics of Australia. *Journal of Biogeography* 15, 665–684.

Crowley, G.M., 1996: Late Quaternary mangrove distributions in northern Australia. *Australian Systematic Botany* 9, 219–225.

Crowley, G.M., Anderson, P., Kershaw, A.P. and Grindrod, J., 1990: Palynology of a Holocene marine transgressive sequence, lower Mulgrave River valley, north-east Queensland. *Australian Journal of Ecology* 15, 231–240.

Crowley, G.M. and Gagan, M.K., 1995: Holocene evolution of coastal wetlands in wet-tropical northeastern Australia. *The Holocene* 5, 385–399.

Crowley, G.M., Grindrod, J. and Kershaw, A.P., 1994: Modern pollen deposition in the tropical lowlands of northeast Queensland, Australia. *Review of Palaeobotany and Palynology* 83, 299–327.

Department of Land and Water Conservation, 2000: *New South Wales Tidal Planes: Data Compilation*. Department of Land and Water Conservation New South Wales, Sydney.

Drury, L.W., 1982: Hydrogeology and Quaternary Stratigraphy of the Richmond River Valley, New South Wales. Unpublished PhD Thesis, University of New South Wales.

Ellison, J.C., 2000: How South Pacific mangroves may respond to predicted climate change and sea-level rise. In Gillespie, A. and Burns, W.C.G. (eds) *Climate Change in the South Pacific: Impacts and Responses in Australia, New Zealand and Small Island States*. Kluwer, Dordrecht, 289–301.

Eyre, B., McKee, L., Hossain, S., Ferguson, A., Gay J. and Davies, P., 1997: A preliminary conceptual model for northern New South Wales estuaries: implications for management. *Proceedings of the 7th Annual New South Wales Coastal Conference, 12–14th November 1997, Ballina, New South Wales*. Ballina Shire Council and Coastal Council New South Wales, Ballina, 167–171.

Faegri, K. and Iversen, J., 1989: Textbook of Pollen Analysis (revised by K. Faegri, P.E. Kaland and K. Krywinski). John Wiley and Sons, Chichester, 4th ed.

Flood, P.G. and Frankel, E., 1989: Late Holocene higher sea level indicators from eastern Australia. *Marine Geology* 90, 193–195.

Fujimoto, K., Miyagi, T., Kikuchi, T. and Kawana, T., 1996: Mangrove habitat formation and response to Holocene sea-level changes on Kosrae Island, Micronesia. *Mangroves and Salt Marshes* 1, 47–57.

Gale, S.J. and Hoare, P.G., 1991: *Quaternary Sediments*. Belhaven, London.

Grindrod, J., 1985: The palynology of mangroves on a prograded shore, Princess Charlotte Bay, North Queensland, Australia. *Journal of Biogeography* 12, 323–348.

Grindrod, J., Moss, P. and van der Kaars, S., 1999: Late Quaternary cycles of mangrove development and decline on the north Australian continental shelf. *Journal of Quaternary Science* 14, 465–470.

Grindrod, J. and Rhodes, E.G., 1984: Holocene sea-level history of a tropical estuary: Missionary Bay, North Queensland. In Thom, B.G. (ed.) *Coastal Geomorphology in Australia*. Academic Press, Sydney, 151–178.

Hails, J.R., 1968: The late Quaternary history of part of the Mid-North Coast, New South Wales, Australia. *Transactions Institute of British Geographers* 44, 133–149.

Hashimoto, T.R., 2005: Morphostratigraphy and Evolution of Estuarine-deltaic Lowlands along Embayed Wave-dominated Coasts: Holocene Examples from Southeastern Australia. Unpublished PhD Thesis, School of Geosciences, University of Sydney, rev. ed.

Hossain, S., Donnelly, R. and Eyre, B., 1997: Increased suspended sediment transport to the Richmond River estuary since European settlement. *Proceedings of the 7th Annual New South Wales Coastal Conference, 12–14th November 1997, Ballina, New South Wales*. Ballina Shire

Council and Coastal Council New South Wales, Ballina, 70–76.
Huq, N.E., 1995: Clarence River Lowland Floodplain: a Morphostratigraphic Analysis of a Complex Holocene Floodplain. Unpublished PhD Thesis, Australian National University.
Iselbe, G. and Sanchez, O., 2002: History of Late Holocene vegetation at Quintana Roo, Caribbean coast of Mexico. *Plant Ecology* 160, 187–192.
Keith, M.L., Anderson, G.M. and Eichler, R., 1964: Carbon and oxygenisotope composition of mollusk shells from marine and fresh-water environments. *Geochimica et Cosmochimica Acta* 28, 1757–1786.
Lin, C. and Melville, M.D., 1993: Control of soil acidification by fluvial sedimentation in an estuarine floodplain, eastern Australia. *Sedimentary Geology* 85, 271–284.
Lin, C., Melville, M.D., White, I., Wilson, B.P. and Yu, D., 1998: Sedimentary environment and acid potential of the pyritic sediments in a sand barrier estuarine system, eastern Australia. *Geochemical Journal* 32, 91–101.
Mildenhall, D.C., 1994: Early to mid-Holocene pollen samples containing mangrove pollen from Sponge Bay, East Coast, North Island, New Zealand. *Journal of the Royal Society of New Zealand* 24, 219–230.
Mildenhall, D.C. and Brown, L.J., 1987: An early Holocene occurrence of the mangrove *Avicennia marina* in Poverty Bay, North Island, New Zealand: its climatic and geological implications. *New Zealand Journal of Botany* 25, 281–294.
Miyagi, T., Kikuchi, T. and Fujimoto, K., 1995: Mangrove habitat and late Holocene environmental change in the Western Pacific. *Proceedings of the International Symposium on Paleoenvironmental Change in Tropical-Subtropical Monsoon Asia, March 1995*. Research Centre for Regional Geography, Hiroshima University, Special Publication No. 24, Higashi-Hiroshima, 189–199.
Miyagi, T., Tanavud, C., Pramojanee, P., Fujimoto, K. and Mochida, Y., 1999: Mangrove habitat dynamics and sea-level change – a scenario and GIS mapping of the changing process of delta and estuary type mangrove habitat in southwestern Thailand. *Tropics* 8, 179–196.
Parkinson, R.W., DeLaune, R.D. and White, J.R., 1994: Holocene sea-level rise and the fate of mangrove forests within the wider Caribbean region. *Journal of Coastal Research* 10, 1077–1086.
Richmond Catchment Management Committee, 1995: Draft Richmond Catchment Management Strategy. New South Wales, Australia.
Roy, P.S., 1984: New South Wales estuaries: their origin and evolution. In Thom, B.G. (ed.) *Coastal Geomorphology in Australia*. Academic Press, Sydney, 99–121.
Roy, P.S., 1993: *Late Quaternary Geology of the Hunter Delta – a Study of Estuarine Valley-fill Sequences*. Report GS 1993/292, Geological Survey of New South Wales, Department of Mineral Resources, Sydney.
Roy, P.S., 1998: Cainozoic geology of the coast and shelf. In Scheibner, E. and Basden, H. (eds) *Geology of New South Wales – Synthesis. Volume 2: Geological Evolution*. Geological Survey of New South Wales, Memoir Geology 13, 361–385.
Roy, P.S. and Boyd, R., 1996: *Quaternary Geology of a Tectonically Stable, Wave-dominated, Sediment-deficient Margin, Southeast Australia: IGCP Project #367, Field Guide to the Central New South Wales Coast*. Geological Survey of New South Wales, Department of Mineral Resources, Sydney.
Saenger, P. and Moverley J., 1985: Vegetative phenology along the Queensland coastline. *Proceedings of the Ecological Society of Australia* 13, 257–265.
Saintilan, N., 1996: Mangroves of the Mary River. *Wetlands* (Australia) 15, 30–37.
Saintilan, N., 1997: Above- and below-ground biomass of mangroves in a sub-tropical estuary. *Marine and Freshwater Research* 48, 601–604.
Sinclair Knight and Partners, 1980: *Richmond Valley*. New South Wales Coastal Rivers Flood Plain Management Studies, Sinclair Knight and Partners Pty. Ltd. Consulting Engineers, Sydney.
Sturman, A.P. and Tapper, N.J., 1996: *The Weather and Climate of Australia and New Zealand*. Oxford University Press, Melbourne.
Thom, B.G., Wright, L.D. and Coleman, J.M., 1975: Mangrove ecology and deltaic-estuarine geomorphology: Cambridge Gulf-Ord River, Western Australia. *Journal of Ecology* 63, 203–232.
Tissot, C., 1980: Palynologie et évolution récente de deux mangroves du Tamil Nadu (Inde). *Travaux et Documentaries, Centres d'Etude de Géographie Tropicale* 39, 109–214.
Walker, P.H., 1970: Depositional and soil history along the lower Macleay River, New South Wales. *Journal of Geological Society of Australia* 16, 683–696.
Walker, P.H., 1972: Seasonal and stratigraphic controls in coastal floodplain soils. *Australian Journal of Soil Research* 120, 127–142.
Wells, A.G., 1983: Distribution of mangroves species in Australia. In Teas, H.J. (ed.) *Tasks for Vegetation Science, Volume 8*. Dr W. Junk Publishers, The Hague, 57–75.
West, R.J., Thorogood, C.A., Walford, T.R. and Williams, R.J., 1985: *An Estuarine Inventory for New South Wales, Australia*. Fisheries Bulletin 2, Department of Agriculture, New South Wales.
West, R.J., Walford, T.R., Thorogood, C.A. and Williams, R.J., 1984: Mangrove distribution in New South Wales. *Wetlands* (Australia) 4, 2–6.
Woodroffe, C.D., 1990: The impact of sea-level rise on mangrove shorelines. *Progress in Physical Geography* 14, 483–520.
Woodroffe, C.D., 1992: Mangrove sediments and geomorphology. In Robertson, A.I. and Alongi, D.M. (eds) *Tropical Mangrove Ecosystems*. Coastal and Estuarine Studies 41, American Geophysical Union, Washington, 7–41.
Woodroffe, C.D. and Grindrod, J., 1991: Mangrove biogeography: the role of Quaternary environmental and sea-level change. *Journal of Biogeography* 18, 479–492.
Woodroffe, C.D., Thom, B.G. and Chappell, J., 1985: Development of widespread mangrove swamps in mid-Holocene times in northern Australia. *Nature* 317, 711–713.
Youssef, T. and Saenger, P., 1999: Mangrove Zonation in Mobbs Bay – Australia. *Estuarine, Coastal and Shelf Science* 49, 43–50.