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Evidence of a Mid-Holocene Sea Level Highstand from the Sedimentary Record of a Macrotidal Barrier and Paleoestuary System in Northwestern Australia

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ABSTRACT

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This study addresses the mid- to late Holocene stratigraphy and sea level history of a macrotidal barrier and paleoestuary system located along the relatively unstudied northwest coast of Australia. Thirty-nine shallow cores were obtained from three transects perpendicular to the barrier and paleoestuary axis. Seven sedimentary facies were identified on the basis of sediment texture, carbonate content, and foraminifera assemblages: slope, upper intertidal mud, upper intertidal sand flat, lower intertidal sand flat, barrier, estuarine beach, and flood tide delta. The sedimentary infill reveals a fining upward succession of marine sediments up to 6 m thick, mostly along a regressive sequence. All facies are of Holocene age and started to be laid down when sea level was approximately 3 m below present elevation. A radiocarbon date from the topmost sedimentary facies (upper intertidal mud) indicates that relative sea level was at least 1 m higher than today by 2720 years BP. At this time, the estuary was at the final stages of sedimentary infill, with tidal inundation reduced to a minimum. Further evidence of a higher relative sea level during the Holocene is in the form of estuarine beach deposits found at the back of the paleoestuary at an elevation above the present day beach/dune interface. Net nearshore transport in the area, driven by tidal current asymmetry, is northward, and it is proposed that this has significantly influenced the alongshore component of the barrier progradation and evolution of the barrier estuary.

ADDITIONAL INDEX WORDS: *Sea level, marcotidal barrier, Western Australia.*

INTRODUCTION

Mid- to late Holocene sea level curves in the Southern Hemisphere are invariably characterized by either a falling or a fluctuating trend (Pirazzoli, 1991). Throughout this region, a 1–5-m higher-than-present mean sea level appears to have occurred at the end of the postglacial marine transgression (PMT), with the age of this sea level maximum decreasing toward the equator (Isla, 1989). In Australia, geomorphological evidence has been used to propose a 2 m higher mid-Holocene sea level in several coastal sectors spanning clockwise from the Gulf of Carpentaria to southwest Western Australia. A large number of investigations have provided evidence of a mid-Holocene highstand in Queensland (Beaman, Larcombe, and Carter, 1994; Chappell, 1983; Larcombe *et al.,* 1995; Woodroffe and Chappell, 1993) and southwest Western Australia (Searle and Woods, 1986; Semeniuk, 1996; Semeniuk and Searle 1986; Semeniuk and Semeniuk, 1991). Furthermore, Woodroffe *et al.* (1995) and Baker and Haworth (2000) have changed the long-accepted view that there has been 6000 years of sea level stabilization in southeast Australia by publishing evidence of a higher sea level in New South Wales, as have Belperio *et al.* (1984), Hails, Belperio, and Gostin (1984), Belperio, Harvey, and Bourman (2002), and Harvey *et al.* (2002) in South Australia. This evidence supports Lambeck and Nakada's (1990) results of a glacio- and hydroisostatic model showing mid-Holocene sea level varying 1–3 m above present around most of the Australian coast, including Exmouth in Western Australia (23° S).

The arid regions of northwestern Australia are still remote, and only a few sections of the coastline have been the subject of geomorphological research. Investigations of the Holocene geology of several macrotidal, tide-dominated, incised valley estuaries in the Northern Territory revealed that coastal progradation and alluvial plain formation was preceded by widespread mangrove swamp sedimentation at the end of the PMT (Chappell, 1993; Chappell and Woodroffe, 1994; Wolansky and Chappell, 1996; Woodroffe, Mulrennan, and Chappell, 1993). Coring of the mangrove deposits

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provided a C^{14} age distribution with depth that showed a consistent sea level rise until around 6000 years BP (CHAPPELL, 1993). No data exist, however, for the last five millennia; as a result, the northwest of Australia is the only sector of the Australian coastline lacking sound evidence of higher sea level during the mid- to late Holocene.

The behavior of sea level over the last millennia is important for understanding the evolution of a coastal region and its recent trends. A fall of sea level, for instance, speeds up the infilling of estuaries and lagoons by reducing the accommodation space and might, given relatively small alongshore sediment imbalances, provide the bulk of sediment for shoreline progradation (DOMINGUEZ, MARTIN, and BITTENCOURT, 1987; DOMINGUEZ and WANLESS, 1991; ROY *et al.,* 1994). The correct chronological interpretation of sedimentary deposits is central to long-term sediment budget calculations (COWELL, ROY, and JONES, 1995; MASSELINK and LESSA, 1995), as well as for calibrating isostatic models.

Buckley's Plain is a flat, 5-km-wide grass-covered back-barrier feature on the macrotidal Broome coast in northwestern Australia (Figure 1). According to Department of Urban Development of Western Australia (DPUD, 1993), most of the barrier is of Pleistocene age. This suggestion, however, should be considered tentative given the limited nature of research on which it was based and because the distinction between "Pleistocene" and "Holocene" deposits was merely based on different degrees of staining of the sediments that composed the barrier system. Coastal erosion is presently an important subject in areas in which indurated sediments and a shallow substrate curtail the availability of sand (DPUD, 1993). The aim of this investigation is to identify the sedimentary facies underlying Buckley's Plain and to investigate the associated morphostratigraphy to determine (1) the nature of the back-barrier region and its infilling history, (2) the evolution of the barrier on this macrotidal coast, and (3) the sea level trend during the last millennia. The results of this study provide evidence of a mid-Holocene sea level highstand along the northwestern coast of Australia.

STUDY AREA

The study area comprises a barrier and back-barrier system and occupies an 11-km-long coastal section just north of Broome (Figure 1). The barrier detaches from the mainland at Bali Hai and finishes at a creek outlet (considered the remnant of an apparent old estuary) named Coconut Wells. The barrier is approximately 2 km wide in the south, where it encroaches against the mainland, and thins down gradually toward the north, reaching about 100 m in width at Coconut Wells. Landward of the barrier lies Buckley's Plain, an elongated, flat, and grass-covered topographic depression with a maximum width of 5 km in the southern end. The northernmost part of the plain is still inundated by the tides, forming a small (2.5 km long) system of tidal channels always exposed at low tide. Most of Buckley's Plain might therefore be considered a relict estuary.

A Cretaceous siltstone overlain by a ferruginous (laterite) conglomerate and a heavily oxidized desert-dune sand (locally known as "pindan") forms the continental substrate for the marine sedimentation (DPUD, 1993). The barrier is subdivided into Pleistocene and Holocene on the basis of the sediment color (DPUD, 1993). White sand is interpreted as Holocene, whereas Pleistocene sands are supposed to be pink, red, and brown. According to DPUD (1993), the Holocene barrier in Cable Beach forms a thin veneer (1–3 m thick) over the Pleistocene dunes (pink in color) and the pindan basement. A shallow substrate is also indicated by LEWIS (1988), who conducted a number of auger drillings on Cable Beach South (Figure 2). Two morphostratigraphic cross sections are presented by LEWIS (1988), both indicating the presence of pindan at an elevation of 4 m above mean sea level several hundred meters landward of the present beach. The cross sections also suggest the existence of Pleistocene and Holocene barriers, again on the basis of color difference (white to light

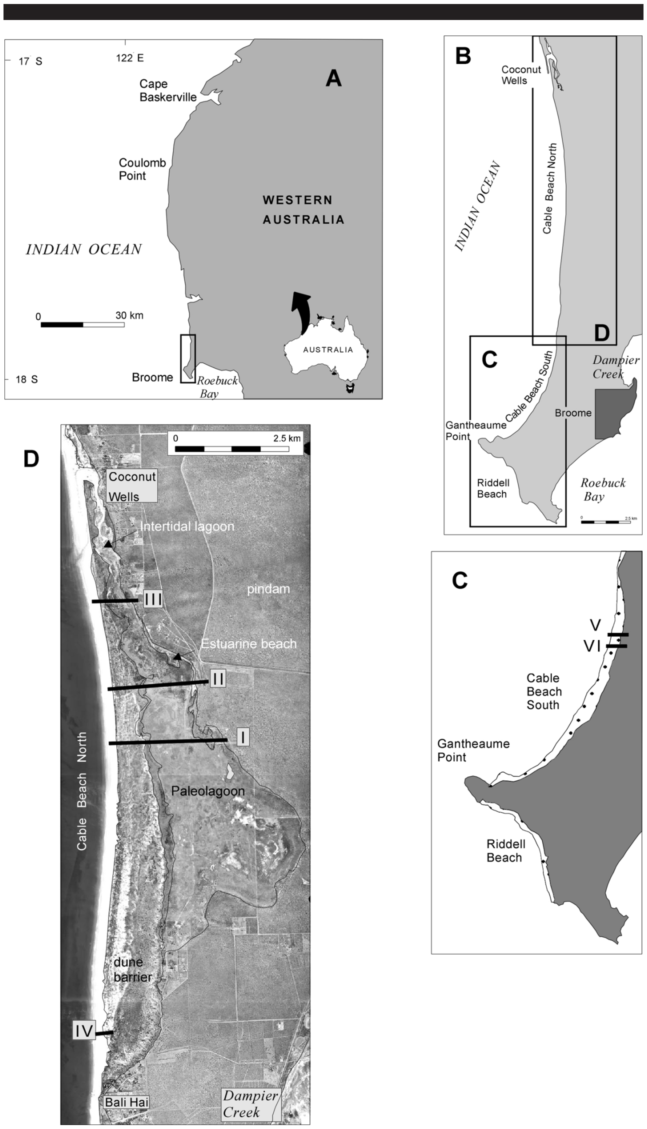

Figure 1. Location map and aerial photograph of the study area. Profiles I–III are shown in Figures 3 and 7, profile IV is shown in Figure 5, and profiles V and VI are shown in Figure 2.

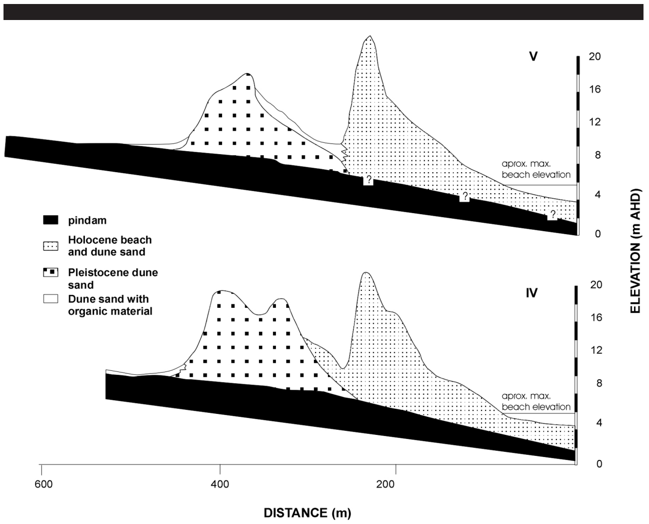

Figure 2. Geological profiles perpendicular to Cable Beach South (see Figure 1 for location), pointing out a shallow pindan substrate and suggesting the existence of two dune barriers of different age (modified from Lewis, 1988). The elevation of the profiles is in Australian Height Datum (AHD), which is approximately mean sea level.

brown compared with reddish brown) and an apparent evidence of soil formation.

Broome experiences a semiarid, tropical monsoon climate characterized by a humid winter and a dry summer. An atmospheric high-pressure cell positioned over the continent in winter induces dry, offshore winds and a mean rainfall of only 6 mm in July. During summer, with winds changing to west–northwest, more humid conditions prevail, and mean rainfall in January (the wettest month) is 163 mm.

The coast is macrotidal, with mean spring and neap tide ranges of 7.7 and 1.8 m, respectively, according to the tidal constituents. A 13-year water level record (August 1991 to May 2004) shows a maximum spring tide range of 10.06 m. Calculated inundation frequencies indicate that the water level exceeds 2, 3, and 4 m (relative to mean sea level) for 20%, 9%, and 2% of the time, respectively. Mean wave energy varies between winter and summer in response to monsoon activity; winter offshore winds maintain low wave energy conditions, whereas summer westerlies create moderate wave energy conditions. Reported wave heights and peak wave periods are 0.5–1.2 m and 9–13 seconds for the summer (Wright *et al.,* 1982). Wave heights are expected to be smaller during winter when offshore winds prevail.

Broome is located within an area prone to summer cyclones, and wave energy is expected to increase significantly during these events. Unfortunately, no wave data are available to confirm this. Between 1909 and 1990, 40 cyclones passed within 150 km of Broome, 16 of which made landfall (DPUD, 1993). Between 1991 and 2004, a time series of the hourly atmospheric pressure in Broome showed another eight events during which the pressure dropped below 995 mbar. During the storm event of 8 December 2000, a daily mean pressure low of 886 mbar produced a storm surge that superelevated the mean sea level by 0.64 m, resulting in the largest anomaly recorded in the 13-year record.

Sediment transport on the upper shoreface (including intertidal zone) is driven by a combination of waves and tidal currents. Masselink and Pattiaratchi (2000) demonstrated that waves, especially those associated with wave groups, entrain and suspend sediments, which are then subsequently advected by tidal currents. Wright *et al.* (1982) recorded shore-parallel current velocities over the subtidal zone fronting Cable Beach. They found that north-flowing currents around high tide (maximum velocities 0.4 m s^{-1}) occurred over a longer duration and were stronger than the south-flowing currents around low tide (maximum velocities 0.2 m s^{-1}). Consequently, net northward tide-driven sediment transport is likely to prevail.

METHODS

Thirty-nine cores were obtained from three transects spanning the entire width of the paleoestuary (Figure 1). Unfortunately, it was not possible to gain access to the southern half of the study area because of the sacred status of this region, locally known as the "Hidden Valley." Coring was initiated with a hand auger to break through either root mats or an indurated sediment layer about 1 m below the ground surface. While augering, sediment was inspected and logged at 0.1-m intervals, and samples were taken for laboratory analysis when significant changes in color, texture, or composition were observed. When feasible, a vibracorer was employed to obtain undisturbed samples at greater depths. In total, 15 core holes were vibracored.

Topographic cross sections of the barrier and Buckley's Plain, as well as the ground elevation of coring locations, were obtained with a TOPCON total survey station. Elevation was corrected to the Australian Height Datum (AHD; approximate mean sea level) with the use of an official benchmark located on Bali Hai (Figure 1). Also, 18 topographic profiles spaced at 500 m across the beach and foredune were surveyed to obtain an estimate of the elevation of the contact between the beach and dune facies.

In the laboratory, the vibracores were cut in 0.5-m lengths, split, logged, and photographed. Subsamples were taken from each identified sedimentary unit for textural analysis. Grain size distribution was determined by converting sediment fall velocity obtained with a 2-m-long settling tube into sediment size with Hallermeier's (1981) equations. Sand/mud ratios and carbonate content were determined by standard procedures. Sixteen samples were selected for analysis of foraminifera content and general morphoscopic appearance to assist with the characterization and differentiation of the sedimentary facies (Figuerêdo *et al.,* 1999). Sediments were wet-sieved with a 62-µm mesh and the retained material dried at 25°C. Tetrachloride was used to separate the foraminifera tests from the rest of the sediment. The specimens were classified by genera in all samples to define the depositional environment, whereas a classification by species was performed in nine samples from the paleoestuary (samples from cores 2, 2/3, and 25/26).

The amount of dateable organic material in the sediments

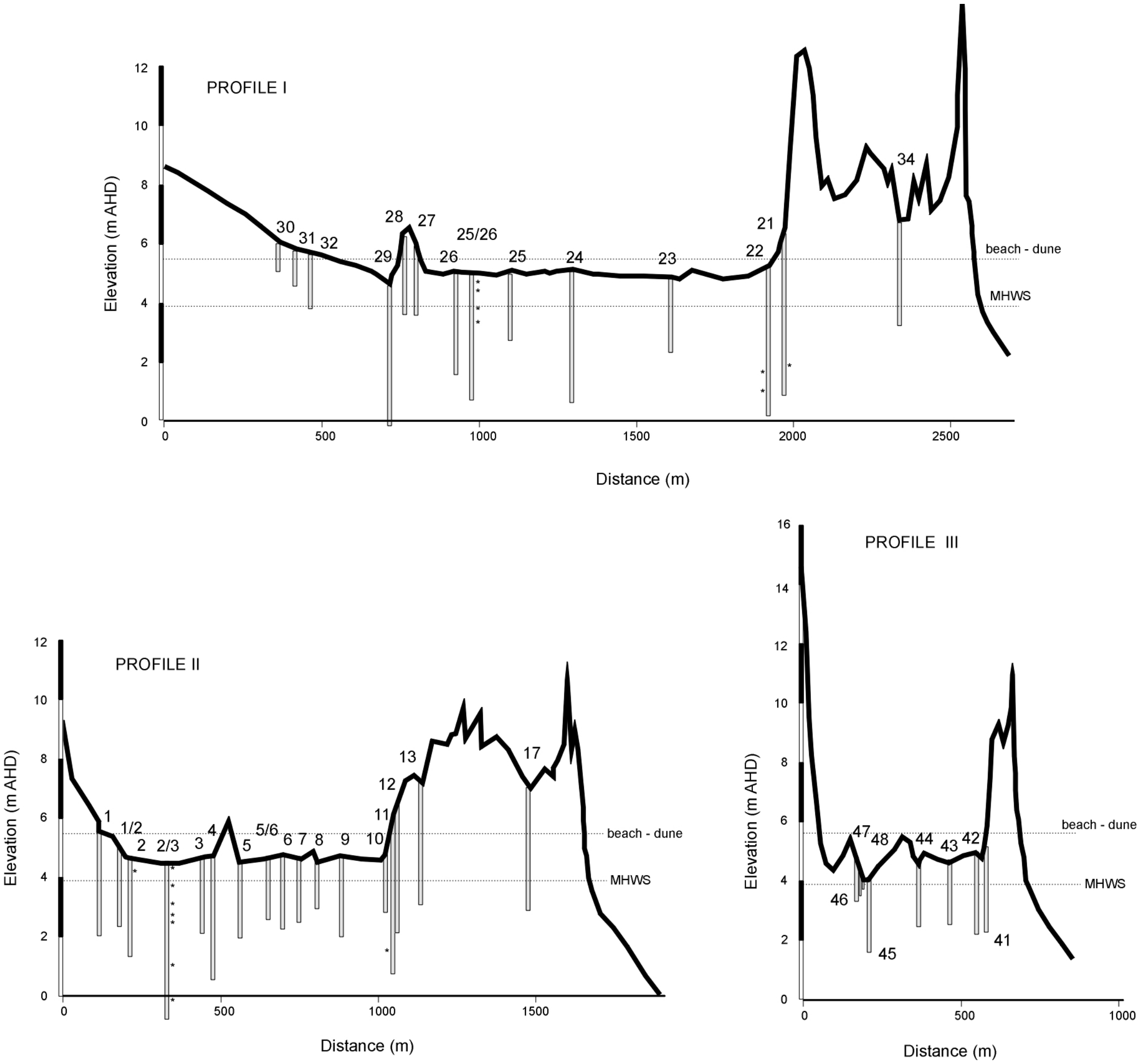

Figure 3. Topographic profiles perpendicular to the coastal plain behind Cable Beach North with the location and length of the cores (see Figure 1 for location). Samples analyzed for their foraminifera content are indicated with an asterisk. The elevation of mean high spring tide level and the average elevation of the beach-dune transition are also given.

was limited, and only two samples were selected for radiocarbon dating: (1) plant fragments from core 25/26, located at +1.42 m AHD, and (2) articulated and disjointed bivalve shells from core 26, located at +4.5 m AHD. Ages were converted to calendar years with the computational routine of STUIVER *et al.* (1998). A dated sample obtained during a previous field campaign in the area (SHORT, personal communication) was also considered.

RESULTS

Topography

Three topographic sections through the coastal plain of the northern half of the barrier estuary system and the associated core locations and lengths are shown in Figure 3. It is evident that the large majority of the cores did not reach AHD, except cores 29 and 2/3, which reached a minimum elevation of −0.9 m AHD (*i.e.,* still in the intertidal zone). The maximum elevation of the dunes is 22 m along Cable Beach South (LEWIS, 1988) but is only 14 m along Cable Beach North. Higher elevations are associated with the seawardmost dunes and these tend to display sharper crests.

The surface of the back-barrier plain is flat and horizontal but is occasionally interrupted by subdued sandy hills. The elevation of the plain is about 5 m AHD in profiles I and II, and slightly lower in profile III (average elevation 4.8 m AHD). Mean high water spring level is 3.9 m AHD, which is located at least 1 m below the surface of the back-barrier plain. Therefore, tidal inundation only occurs under extreme tide conditions, generally with a spring high tide coinciding with a storm surge. Over the available 13-year-long tidal record, the water level only exceeded 5 m AHD for 14 hours.

The mean elevation of the transition between beach and dune (*i.e.,* the upper limit of the shoreface) is an important geomorphological parameter because it indicates the landward limit of wave action (ROEP, 1986). It can be determined in the field by investigating morphology (break in slope), sedimentology (presence of shells), and dune vegetation. None of the beach-dune profiles showed evidence of wave action above 6 m AHD, and the seaward edge of the dune vegetation is generally located below 6 m AHD. It was inferred that the transition between beach and dune occurs at an elevation of +5.5 m AHD (*i.e.,* approximately 1.5 m above mean spring high tide level).

Foraminifera Content

Among the 16 samples analyzed, only one (the lowermost sample in core 2/3; see location in Figure 3) did not contain foraminifera. This sample was composed of polished, well-rounded quartz grains with no bioclasts. In the remaining samples, 24 foraminifera genera were identified, namely *Ammonia, Amphistegina, Archaia, Articulina, Bolivina, Borelis, Bulimina, Cancris, Cassidulina, Cassidulinoides, Cibicides, Cornuspira, Discorbis, Eggerella, Elphidium* (including *E. galvestonensis*), *Eponides, Fisherina, Globigerina, Hanzawaia, Hastegerina, Heterostegina, Lagena, Miliolinella, Neovigerina, Nonion, Peneroplis, Planorbulina, Planulina, Poroeponides, Pyrgo, Quinqueloculina, Reusella, Rolshausenia, Sigmavirgulina, Sigmoilina, Spiroloculina, Textularia, Triloculina, Uvigerina, Wiesnerella.* The more frequent genera (*i.e.,* each accounting for more than 10% of the total number of individuals in the sample), in descending order, were *Elphidium* (excluding *E. galvestonensis*), *Triloculina, Ammonia, Eponides,* and *Quinquelocunlina.* These genera are all characteristic of marine environments, with the exception of *Ammonia,* which can also live in euryhaline environments, and *Triloculina* and *Quinqueloculina,* which are also characteristic of hypersaline shallow seas (MURRAY, 1991). Few typical euryhaline species were observed. These species were *Elphidium galvestonensis, Cibicides lobatulus, Bulimina marginata,* and *Thretomphalus bulloides.* With the exception of *E. galvestonensis,* they were observed in only one sample, and their occurrence can be regarded as accidental. This suite of genera suggests that marine conditions prevailed inside the paleoestuary during the sediment infill process.

The samples for which foraminifera species were identified were derived from the upper mud flat unit (see “Upper Mud Flat” section). The samples had 330 specimens on average, were essentially muddy, and presented more than 50% of the tests well preserved, especially those associated with young specimens. The largest number of badly preserved tests was found in core 25/26, of which 37% showed signs of reworking, 7% were broken, and 5% oxidized (FIGUERÊDO *et al.,* 1999). Oxidized tests, with up to 10% of relative abundance, were observed in all samples. With no exception, all species can be encountered in muddy substrates, and given the overall high degree of well-preserved tests in the samples, it can be suggested that these species were autochthonous.

Radiocarbon Dating

The sample from core 25/26, with the largest mass (plant residuals), underwent standard radiocarbon dating (CENA422), was normalized with $\delta^{13}C$ (−26.8%), and was dated at 10,600 ± 90 C^{14} years BP (12,731 Cal BP). Bivalve shells from core 26 underwent AMS dating (Beta 168228) but did not have enough mass for $\delta^{13}C$ measurement. This sample was dated at 2,720 ± 40 C^{14} years BP (2,790 Cal BP). Because the majority of the data referred to in the discussion do not use the calendar correction, the conventional C^{14} age will be mentioned henceforth.

Sedimentary Facies

On the basis of color, texture, elevation distribution, foraminifera content, and morphoscopy, seven sedimentary facies were identified. Figure 4 shows the distribution of the sedimentary facies across each profile and their vertical distribution.

Upper Mud Flat

This unit is characterized by a prevailing white color, makes up more than 50% of fines (>62 μm), and has a carbonate content of up to 77%. The sediment contains a significant amount of marine foraminifera with well-preserved tests. It is the topmost sedimentary unit observed in the majority of the paleoestuary cores and, as such, possesses varying degrees of soil development that lends a brown color to the upper 1 m of the sediment package. Because of the high calcium carbonate content, a highly indurated surface with traces of iron staining has developed between 3.0 and 4.0 m AHD. Average maximum (top) and minimum (base) elevation for this facies is 5.0 and 2.8 m AHD (lowest elevation of 1.0 m AHD in core 29), respectively, and the maximum thickness is 2.5 m (except core 29 in which this facies is 3.6 m thick, and the color of the sediment varies from light to dark gray). This facies represents the topmost sedimentary unit throughout the back-barrier plain, except for the higher cores in profile III and over the sand ridges in profile II (cores 27 and 28). It always overlies a lower sandy facies (Upper Sand Flat) in a gradual contact. It is interpreted as a high intertidal deposit on the basis of sediment texture, composition, and its stratigraphic position, and in accordance with the radiocarbon-dated sample Beta 168228, it was formed in the late Holocene (around 2720 C^{14} y BP). Another occurrence of muddy sediment was observed at the base of core 25/26, between 1.67 and 0.74 m AHD. The color was dark gray, indicating enrichment by organic matter. The overlying unit has richer sand content, and the contact is highlighted by an accumulation of pebbles and shells. This deposit is also interpreted as high intertidal, but apparently was laid down in the early Holocene during transgression, as suggested by a radiocarbon date of 10,600 C^{14} years BP (CENA422).

Upper Sand Flat

This facies is composed of fine, relatively well-sorted sands, light gray to brownish yellow in color, with tints of white from the mixing in of carbonate-rich mud from the Upper Mud Flat

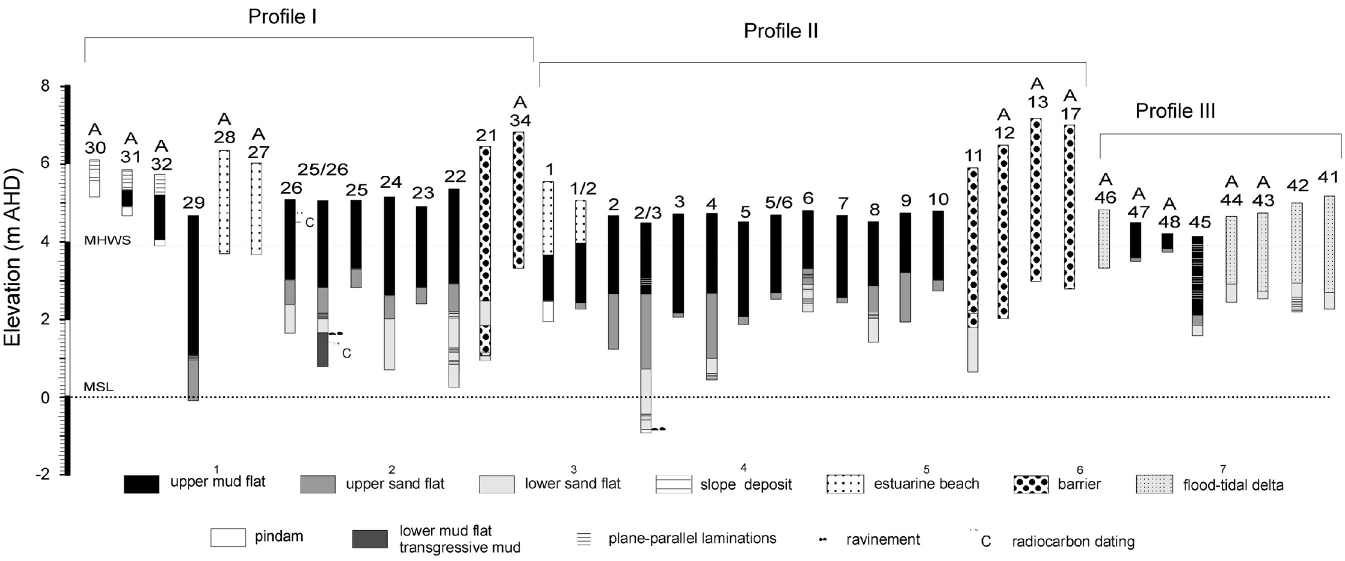

Figure 4. Core elevations and interpretation of sedimentary facies.

facies. Intercalated layers of mud are occasionally observed. Mean sediment size varies between 0.1 and 0.22 mm; average carbonate concentration is 39% (standard deviation of 13%), but values as high as 71% can be observed. The majority of the carbonate comes from sand-sized calcareous fragments made of thorns of echinoderm, pteropoda, ostracoda, algae, molluscs, and foraminifera (whole shells or large pieces of it are not frequently observed). The average concentration of fines is 5% but can be up to 26% of the total sample weight. Heavy minerals are common, and in some of the cores, small pebbles of white mud were present. Sedimentary structures are occasionally observed and are characterized by horizontal, parallel laminations highlighted by differences in sediment texture. This facies was observed in the majority of the cores from the back-barrier plain, spanning between 0.7 and 3.4 m AHD, with a maximum thickness of 1 m (once again, core 29 is an exception, with a minimum elevation of 0 m AHD). In cores in which this facies was completely cored, it always overlaid the Tidal Channel facies with a usually gradual contact. On the basis of its stratigraphic position, texture, and composition, this facies is interpreted as an intertidal, low-energy sand flat of Holocene age.

Lower Sand Flat

This unit was observed in most of the deepest cores taken from the back-barrier plain. The unit comprises a light to medium gray, medium to coarse sand grading downward into pebbles (lithic, coral, and gray mud clasts), large fragments of calcareous shells, and pieces of wood. The mean grain size varies from 0.2 to 0.4 mm, and the average carbonate and fines content is 20% and 1.5%, respectively. Most of the carbonate content appears to come from fragments of mollusk shells and microgastropodes. Subhorizontal, plane-parallel laminations (highlighted by texture and differences in shell fragment content) and intercalation of medium and coarse sand layers with a higher content of shell fragments are common. Some of the plane-parallel laminations in the upper limit of the facies (cores 8, 22, and 25/26) show differences in the lamination thickness, perhaps suggesting an incipient formation of tidal bundles. Heavy minerals are present, but not in great abundance. With the exception of the sample taken from core 2/3, which was deprived of bioclasts, the foraminifera content in this facies is mostly characterized by the genera *Ammonia, Eponides,* and *Bolivina,* whose tests show signs of intense reworking. The maximum elevation of this facies is 3.0 m AHD in profiles I and II and 4 m AHD in profile III. Minimum elevation is −1.0 m AHD, and maximum thickness is approximately 2 m. This facies represents the lowermost estuarine deposit, and its lower boundary, when identified, is characterized by an erosive contact. The erosive character is recognized by (1) an accumulation of pebbles and large fragments of mollusk shells at the base of core 25/26 where this facies overlies a medium to dark gray mud and (2) a rather irregular contact between this unit and a dark, thin, organic-rich sand layer that sits on top of core 2/3. This unit underlies both the Upper Sand Flat facies and the Flood Tidal Delta facies with a gradual contact. On the basis of texture, composition, and elevation, this facies is interpreted as being formed in a broad intertidal channel, exposed to a relatively higher energy level in the mid-Holocene.

Slope Deposit

This facies composes very fine to fine sand, with a varying content of silt, mostly brown to red brown in color, eventually presenting fragments of roots and other organic matter. It was augered in cores 30, 31, and 32; therefore, sediment structures were not identified. The facies was only identified in the mainland margin of profile I at elevations spanning between 8.6 and 5.3 m AHD and maximum thickness of 0.6 m. The facies overlies both pindan and Upper Mud Flat, apparently in a gradual fashion. On the basis of elevation, stratigraphic position (above an estuarine facies and intercalated with pindan), color, and sediment texture, the facies is interpreted as continental slope deposit, laid down as wash load by pluvial water running down the slope.

Estuarine Beach

This facies is composed by fine sand with varying content (up to 24%) of mud, dark brown or yellow red in color, with carbonate content between 7% and 43% and rare occurrence of disarticulated shells. It was encountered in the mainland border of the estuary, in cores 1 and 1/2 in profile I and cores 27 and 28 in profile II. It was the topmost sedimentary unit in the cores and, when completely cored, overlaid the Upper Mud Flat. Maximum and minimum elevations were 7.7 m (core 28) and 6.3 m AHD (core 1), and maximum thickness was 1.8 m. Its texture, elevation, and stratigraphic position allows for the interpretation of a beach deposit, perhaps with an aeolian capping, apparently associated with a time when the estuary had a broad mouth and was more exposed to wave action during high tide (as discussed later). It is also possible that this facies formed simultaneously with the Upper Sand Flat, the former encroached against the mainland, influenced by the tides and waves and possessing higher elevation, and the latter mainly driven by tides at a lower elevation.

Barrier

This facies is a composite facies, consisting of both beach, dune, and possibly overwash deposits laid down behind the estuary mouth. Because of the similarities between these facies (and lack of primary sedimentary structures present), differentiation between them becomes rather tentative. The dune facies tends to be composed of fine and very fine well-sorted sand, yellow-orange in color, with carbonate content of up to 44%. The beach facies comprises moderately-sorted medium sand, with carbonate content of up to 80%, depending on the presence of shelly layers, and is orange in color. Mean grain size and standard deviation are 0.34 and 0.13 mm, respectively. The maximum and minimum elevation of this unit are 7.2 and 1.8 m AHD, respectively, with a maximum thickness of 5.4 m. However, given that the cores were obtained from the deepest troughs of the profiles, maximum facies thickness is expected to exceed 10 m.

Flood Tidal Delta

This unit is composed of very well sorted fine to very fine sand, with color tones varying among yellow, gray, and white, implying that a varying degree of oxidization has occurred. Mean grain size and sorting are 0.18 and 0.05 mm, respectively, with carbonate content ranging from 27% to 60%. The facies was identified in most of the cores in profile. Maximum and minimum elevation was 5.2 and 2.6 m AHD, respectively, with a maximum thickness of 3.9 m in core 21. The distinction between the Barrier facies and this unit was based on the presence of shells, resulting in an increase in the carbonate content. On the basis of the geographical location of the cores, it is proposed that this facies is associated with the influx of sand driven by tides and waves refracted around the estuary mouth. In such an environment, interfingering of this facies with the underlying Lower Sand Flat facies can occur, as suggested by some sections of the cores from profile III, with higher mean grain size (averaging 0.26 mm) and standard deviation (averaging 0.12 mm) values. This facies could also be interpreted as a more recent analog of the Upper Sand Flat facies, given similarities in the environment of deposition. The reason this facies stands alone is because of its higher elevation, lack of muddy sediments, and slightly higher concentration of shells. Besides, the Flood Tidal Delta facies is not overlain by another facies.

On the basis of the sedimentary facies and geomorphology, the back-barrier plain (Buckley's Plain) is interpreted as a paleoestuary. This will be further discussed in the next section.

DISCUSSION

Age of the Barrier and Paleoestuary System

DPUD (1993) suggested that in the Broome region, Pleistocene as well as Holocene barrier (dune and beach) deposits are present. This notion is solely based on the color difference that exists between sediments close to the present coastline (*i.e.,* Holocene deposits) and those more inland (*i.e.,* Pleistocene deposits). The former sediments are supposed to be white in color, whereas the latter sediments would possess a pink or brown hue. The white Holocene sand would, then, form a thin (<1 m) veneer over older deposits on the barrier along Cable Beach.

A coral sample was collected from an auger hole at the top of the active beach 500 m to the north of the southern end of Cable Beach (Figures 1 and 5). The hole had 0.1 m of "dune" sand, overlying 1.5 m of white, then reddish sand, before it encountered beach rock, where the coral was obtained. The sample was dated at 3180 ± 90 C^{14} years BP (SUA-1722; sample collected and dated by Prof. A.D. Short, University of Sydney). Because the coral sample is overlain by pink sand, it is clear that the latter is of Holocene age. Therefore, the distinction between Pleistocene and Holocene sediments on the basis of color differences appears to be incorrect, and it is proposed that the whole barrier abutting Buckley's Plain is of Holocene age.

A Holocene age for the barrier also agrees with the radiocarbon dating result (10,600 y BP) obtained for a sample from the mud deposit at the base of core 25/26, which gives the maximum possible age for this facies. The base of this core was 0.74 m AHD and represents one of the lowest elevations reached during this project. Moreover, the dated mud deposit was overlain by three of the most prevalent back-barrier facies, namely Upper Mud Flat, Upper Sand Flat, and Lower Sand Flat. This clearly indicates that the sedimentary infill of Buckley's Plain is Holocene in age.

Sea Level History

The elevation of the mean high water spring tide in Broome is close to 3.9 m AHD, which is 1 m below the mean elevation

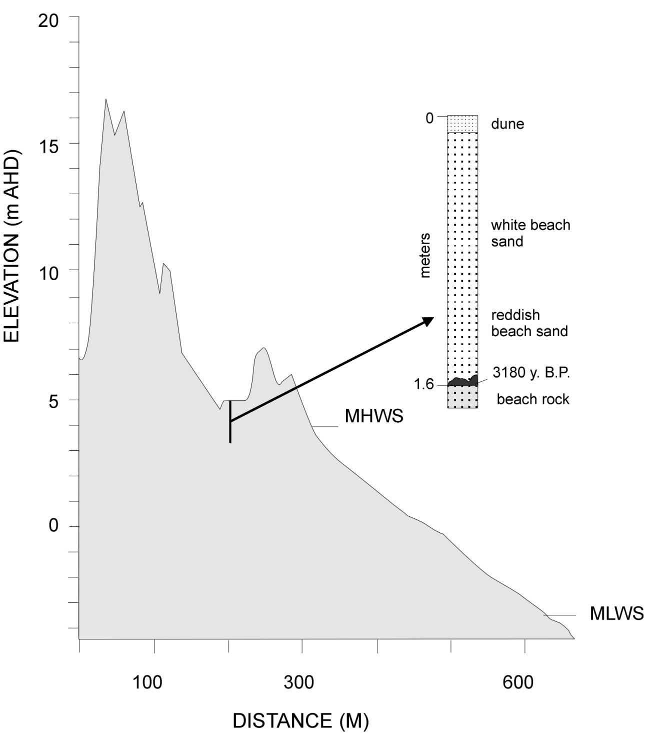

Figure 5. Cross section profile of the barrier north of Bali Hai (see profile IV in Figure 1 for location), showing the position of the auger hole from which the dated coral fragment was obtained. The core shows a thin (*ca.* 10 cm) layer of dune sand followed by 1.5 m of white and then reddish sand and finally beach rock (Andrew Short, Sydney University, personal communication).

of Buckley's Plain. Inundation of Buckley's Plain by seawater requires a rather high storm surge, or the coincidence of storm surges with equinoctial spring high tides, which is a rare event. The highest measured sea level in the last 10 years was 5.27 m AHD and was associated with a low pressure cell of 886 mbar that passed over the region during an average tide (9 m range) in December 2000, producing a storm surge of 0.64 m. Analysis of a 13-year-long sea level record from Broome (1991–2004) shows that inundation at +5 m AHD occurred only 0.013% of the time (*i.e.,* only about 14 h within that time interval). Considering the elevation of the surface of the back-barrier plain and the frequency of tidal inundation, it is inferred that the Upper Mud Flat facies dated at 2720 C^{14} years BP formed with sea level at least 1 m above the present level. Because a time lag can be expected between the complete sedimentation of the Upper Mud Flat facies and the sea level maximum of the mid-Holocene, it is possible, if not likely, that the relative paleo–mean sea level around Broome reached an even higher elevation when maximum postglacial sea level was attained (close to 6000 C^{14} y BP). A higher mid-Holocene relative sea level in this section of the coast is in accordance with relative sea level trends reported from most studies conducted along the Australian coast and substantiates LAMBECK and NAKADA's (1990) model results on the hydroisostatic adjustment of the Australian continental shelf to the PMT. The model predicted the postglacial sea level maximum to occur around 6000 BP, reaching an elevation of 2 m in Exmouth (located 1200 km SW of Broome) and 4 m in the South Alligator River (located 1200 km NE of Broome). Differences in elevation between the two coastal locations are explained by differences in shelf width. There is, however, no paleo-sea level study to validate the model result in the Northern Territory, and it could be overestimated (mismatches between model results and field evidence have been pointed out by LAMBECK and NAKADA [1990]). A possible exception is the report by WRIGHT, COLEMAN, and THOM (1972) of intertidal deposits 2 m higher than present tide level in Ord River, related by the authors to the seaward displacement of the tidal limit with delta sedimentation.

It appears that an elevated mid-Holocene sea level was sustained until around 2500 C^{14} years BP. This is in accordance with data presented by BEAMAN, LARCOMBE, and CARTER (1994), CHAPPELL (1983), FLOOD and FRANKEL (1989), and LARCOMBE *et al.* (1995), both in Queensland and New South Wales, which indicate that sea level was still high as recently as 1800 C^{14} years BP. It is also in agreement with vermitid data along the Brazilian coast (ANGULO, LESSA, and SOUZA, 2005). Therefore, it seems likely that the emergence of Buckley's Plain must have occurred only within the last 2000 years.

The intertidal mud sample dated at 10,600 C^{14} years BP points to an unrealistic mean sea level. The deposit is about 0.9 m thick, with an average elevation of 1.2 m. Assuming that the tidal range around the Pleistocene/Holocene boundary was the same as today and that this sample represents the upper intertidal region, mean sea level would be about −3 m. This elevation is far too high to be associated with a sea level 10,000–11,000 years ago. Eustatic sea level curves established for eastern Australia point to a mean sea level between −50 m and −40 m around this time (CHAPPELL and POLLACH, 1991; LARCOMBE *et al.,* 1995; THOM and ROY, 1983). This indicates that the plant remains must have been reworked from an older deposit, terrestrial or marine, and incorporated into the tidal flat. However, despite being useless as an indicator of paleo–sea level, the sample does allow the determination of a minimum age for the back-barrier plain.

The Evolution of Cable Beach Barrier

In spite of the limited amount of data and the difficulties in distinguishing internal barrier facies, it is likely that a transgressive barrier unit exists in the sedimentary record. Barrier retrogradation would have displaced the back-barrier estuary in a landward direction, at least during the last 1000 years of the marine transgression, as suggested by the dark-gray mud in core 25/26. During this process, the estuary would have narrowed as it backed up against the mainland in a process similar to that described by FINKELSTEIN and FERLAND (1987) for the East Coast of the US. As the onshore migration of the barrier was halted by the hills around Broome, its northern part would have isolated the present-day paleoestuary (Buckley's Plain). It is possible that erosion

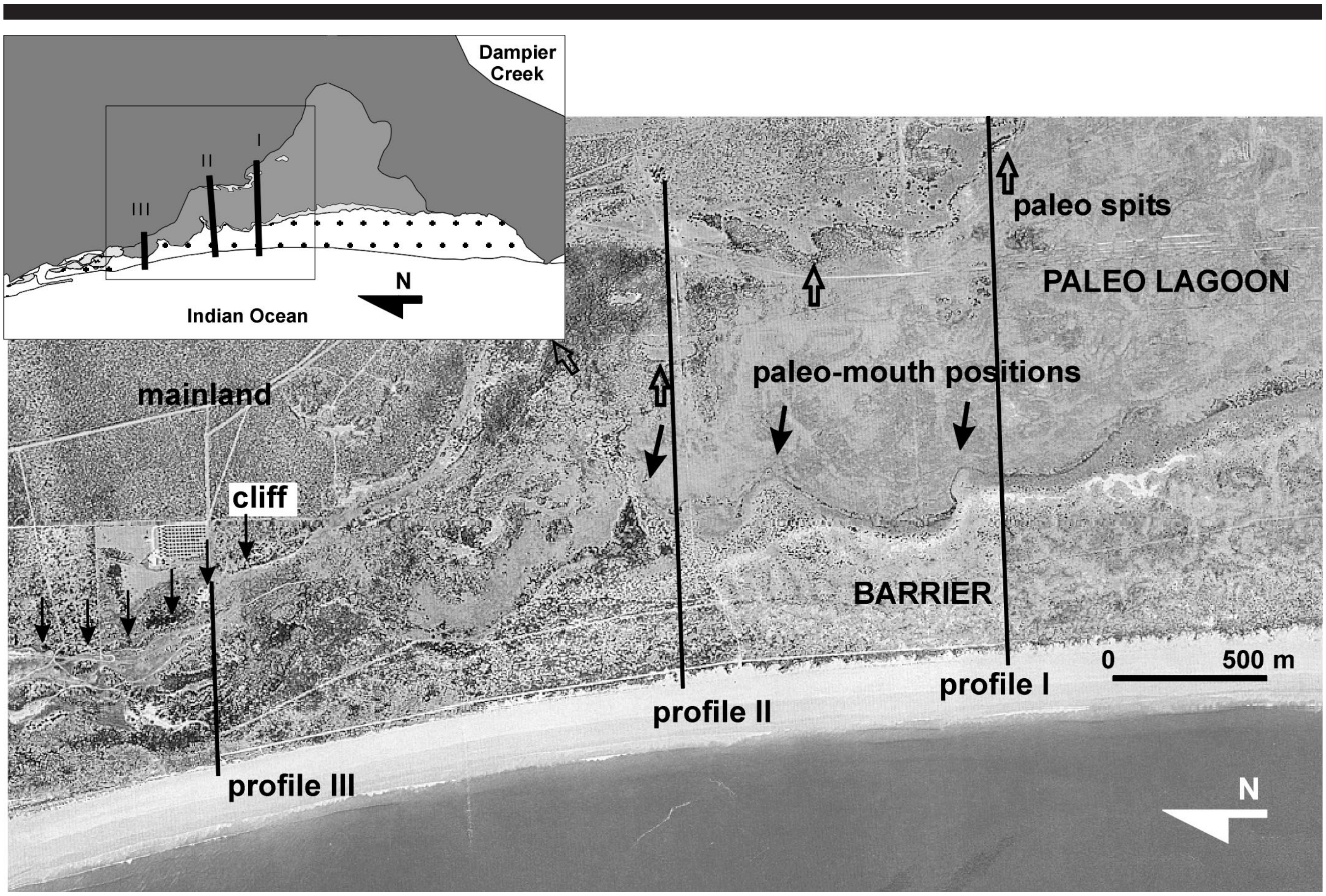

Figure 6. Aerial photograph of Cable Beach and Buckley's Plain showing relict curved spits in the estuary.

of the shallow pindan substrate during the transgression could have lent the pink color to the inner barrier sediments.

Sediment transport studies on Cable Beach (Masselink and Pattiaratchi, 2000; Wright *et al.,* 1982) have demonstrated a strong tidal asymmetry in the longshore current, within and beyond the surf zone, promoting net sediment transport toward the north. Geomorphologic evidence of this net transport direction is also given by the orientation of other estuarine inlets up the coast, besides Coconut Wells. Because neither climate (and wind direction) nor tidal circulation is expected to have significantly changed in the last 5000 years, it is suggested that this net transport direction could have persisted throughout the Holocene. Therefore, the development of the barrier-estuarine system must have had a significant lateral component from south to north.

A model for longshore barrier growth (or spit growth) and associated development of an estuary is known for both transgressive and regressive coasts (Almeida, 2001; Hine, 1979; Redfield, 1967; van Heteren and van de Plassche, 1997). Sediment transported alongshore is driven inward at the estuary mouth by wave refraction, depositing sediment in a wave swash ramp. The sediment can then be conveyed into the estuary by flood tide currents. Barriers having curved endings are therefore a common feature on coasts in which longshore sediment transport is voluminous, and as the barrier grows, several fossil curved features could be left behind, pinpointing previous estuary mouth positions (Hayes, 1980). An examination of aerial photographs of Buckley's Plain reveals some relict features that could be associated with successive steps of longshore progradation (Figure 6).

It is likely that longshore barrier growth coincided with shore-normal coastal progradation; otherwise, the barrier could not have attained a width of 2 km at its southern end. Evidence of shore-normal and shore-parallel barrier growth is given by van Heteren and van de Plassche (1997) in Cape Cod (US), where the effect of sea level rise is apparently counteracted by a positive sediment budget. Given that sea level has apparently stood high until late in the Holocene, shore-normal coastal progradation might have been a more recent trend.

The effect of cyclones on barrier morphology and stratigraphy warrants some discussion. A morphostratigraphic study in macrotidal barriers in Mackay (northeast Australia), where on average, five cyclones make landfall per decade (Beach Protection Authority of Queensland, unpublished data), showed little evidence of major erosion episodes in the Holocene (Masselink and Lessa, 1995). This also appears to have been the case in this investigation: no major erosive contact was observed in the back-barrier cores or in the estuary. One could argue that the potential effect of cyclone activity on coastal morphology is limited in macrotidal regions because there is relatively little chance of cyclone landfall coinciding with high water level. A cyclone that hit the Broome region on 19 April 2000 did, however, coincide with spring tides. This event caused the second-highest water level in 13 years of tide gauging, when mean sea level reached 5.1 m AHD (just above the average elevation of the paleoestuary). The southern part of Cable Beach was stripped bare of sand, leaving the underlying rocks exposed, but the beach recovered in a few weeks. It thus appears that the role of cyclones in affecting the long-term macrotidal beach/barrier morphology and morphostratigraphy is limited.

Estuary Stratigraphy and Evolution

The sedimentary infill identified in the paleoestuary reveals a fining upward succession of marine sediments, with the Flood Tidal Channel facies succeeded by the Lower Sand Flat facies and the Upper Mud Flat facies (Figure 7). The whole succession is about 6 m thick, mostly comprising a regressive sequence (shallowing vertical succession of environments). An exception to this is the existence of dark-gray mud in core 25/26. This deposit was laid down apparently as a transgressive, intertidal sedimentation during the late to mid-Holocene sea level rise, with mean sea level at *ca.* -3 m AHD. The organic content of this transgressive mud is not observed in the regressive succession, implying that a change in the environment of deposition might have occurred.

Although the regressive sedimentary facies were all laid down in an intertidal environment, there was a somewhat energetic condition established in the early stages of the paleoestuary, when medium to coarse sand was deposited within channels. The sand source was the nearshore, and the environment of deposition was clearly marine, as indicated by the foraminifera content. At the end of the PMT, with seas at least 1 m above present elevation, the barrier would have been shorter and the estuary mouth wider. The tidal currents associated with this phase were apparently able to partially erode a transgressive mud deposit (identified in cores 25/26 and 29) and the pindan (core 2/3), leaving behind a tidal ravinement surface (Figure 4).

Relatively thick sand accumulations occur locally at paleospits at the landward (west) border of Buckley's Plain (Figures 6 and 7). Given the textural and compositional similarities, the intertidal sand facies has apparently been reworked by waves at high tide and helped to form spits and estuarine beaches. Another sediment source for these supratidal sand deposits appears to have been the erosion of the continental deposits exposed in paleocliffs in the northern extreme of the Buckley's Plain (see profile III in Figures 3 and 6). With a broader estuary entrance located farther to the south, these paleocliffs could have been exposed to wave action at high tide. The morphology of the spits suggests that the sediments were transported from north to south all along the eastern estuarine border. Spit breaching and segmentation is also suggested by low sandy hills inside the estuary, interpreted as remnants of previous spits (see profile II in Figure 7).

The development of a large flood tide delta deposit in the northernmost profile is explained by a smaller tidal prism and tidal current energy in the paleoestuary in more recent times. With a less energetic environment inside the estuary, sediment conveyed to the mouth by waves and tides were less prone to advection and gave rise to a higher flood tide delta. Ground surface sediments in profile III is thus mostly sand because the flood tide delta was not covered by intertidal mud. Development of the flood tide delta might also be related to the change in the type of estuary from tide to wave dominated during the course of the estuarine evolution. It is possible that small macrotidal estuaries are initially tide-dominated systems, but develop into wave-dominated systems as soon as a barrier estuary develops and closes off most of the estuary. It is also only when the barrier is well-developed and a relatively narrow estuarine mouth is present that a proper flood tide delta develops (DALRYMPLE, ZAITLIN, and BOYD, 1992).

Buckley's Plain was a shallow estuary that evolved on a relatively featureless, low-lying coastal plain, with no incised valley. Because of a small accommodation space, sediment thickness within shallow estuaries is generally smaller than 10 m, regardless of the tidal range (FINKELSTEIN and FERLAND, 1987; LESSA and MASSELINK, 1995; REDFIELD, 1967; VAN HETEREN and VAN DE PLASSCHE, 1997). Along regressive coastlines, shallow estuaries tend to disappear relatively fast because of the combination of lowering sea level and bottom aggradation. The maximum depth of the continental substrate under Buckley's Plain seems to be shallower than 10 m, as indicated by core 2/3 inside the estuary and augering on the beachface (DPUD, 1993). Nevertheless, Buckley's Plain still required around 3000 years after the postglacial sea level maximum to be completely infilled. This contrasts with the rather prompt infilling of deeper macrotidal estuaries in the Northern Territory, where infilling was finalized around 5000 years BP, with the switch between mangrove "big swamp" to freshwater estuarine plain (CHAPPELL and WOODROFFE, 1994; WOODROFFE, MULRENNAN, and CHAPPELL, 1993). The infilling of the Northern Australian estuaries was mostly promoted by mangrove mud deposition, with the excess sediment apparently transported from the sea (CHAPPELL, 1993). The slow infilling rate of Buckley's Plain might reflect both a reduced availability of suspended sediments in the coast and less efficiency in transporting them into a shallow and intertidal estuary.

CONCLUSIONS

Buckley's Plain is the remnant of a Holocene, shallow, macrotidal estuary infilled with at least 6 m of marine sediments. The estuary developed behind an onshore-migrating sand barrier under the influence of a rising sea level, which first isolated the southern half of a 10-km-long embayment, and then by lateral barrier progradation driven by the littoral drift. Barrier retrogradation is indicated by the presence of an estuarine intertidal mud deposit associated with a paleo–sea level at least 2 m below the present one. The elevation of the sedimen-

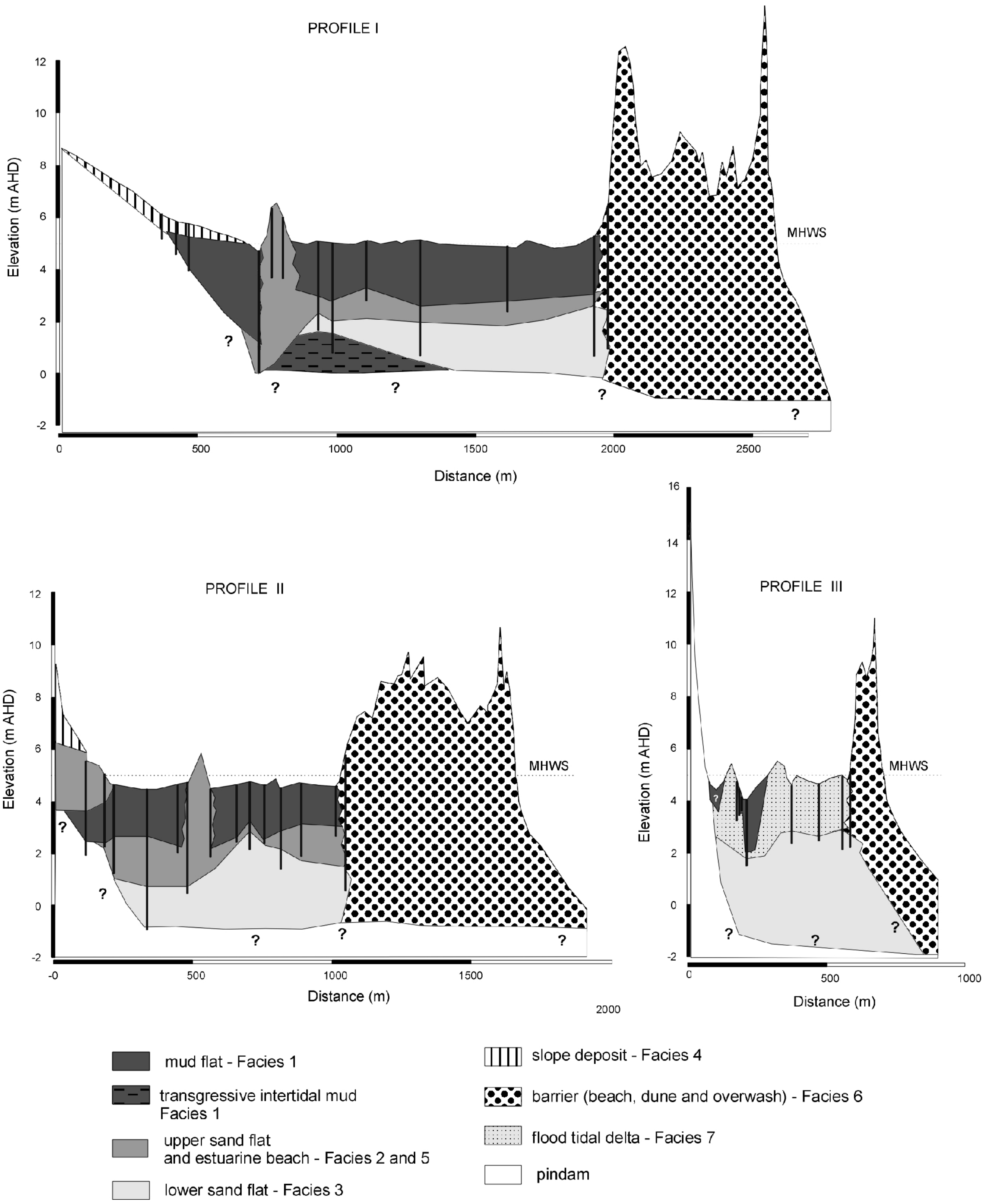

Figure 7. Stratigraphic framework for the three cross sections across the paleoestuary. Flood Tide Delta facies has been incorporated into the barrier facies in profiles I and II because of its limited extent.

tary facies inside the paleoestuary indicates that relative sea level was at least 1 m higher at the end of the PMT, which is in accordance with several other higher mid-Holocene sea level studies published in Australia, as well as with hydroisostatic models. Sea level was apparently held up until as late as 2720 years BP, which is also consonant with similar findings elsewhere in Australia. The effect of cyclones on coastal sedimentation was not observed in the collected cores and suggests that sedimentation on macrotidal coasts is less prone to cyclone activity than that on microtidal coasts.

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