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Rapid coastal geomorphic change in the River Murray Estuary of Australia

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Abstract

The River Murray Estuary, a Ramsar Wetland Site, has experienced considerable rapid coastal change during the Quaternary. The interplay of aeolian processes, river flows, tidal oscillations, wave action and variations in relative sea-level due to global sea-level changes and land subsidence, provides the energy for the ongoing dynamism, often accelerated by human impacts. The estuary is the terminus of the Murray-Darling catchment, which covers 1.073 million km^2 of the Australian continent. Terminal Lakes Alexandrina, Albert and the Coorong Lagoon are Holocene features, occupying tectonically subsiding Quaternary interdune areas. They formed in response to eustatic sea-level rise following the Last Glacial Maximum (ca. 20 ka). The last interglacial shoreline (125,000 yr BP) parallels the modern shoreline several kilometres inland. Dislocation of the last interglacial shoreline demonstrates ongoing tectonic subsidence, as does historical seismic activity. The northern half of Hindmarsh Island formed during last interglacial times when it was the sink for dominant longshore transport from the southeast, which pushed the River Murray westward, partly explaining the large bend in the River Murray at Goolwa. The modern coastal barriers of Sir Richard Peninsula and Younghusband Peninsula formed from 7000 yr ago, following glacier melt and sea-level rise. Subsequently, the barriers have migrated landward, sporadically exposing lagoonal sediments on the ocean beaches. Differential loading of the soft lagoonal sediments by advancing dunes, possibly in conjunction with seismic events, has deformed and elevated them to up to 10 m above present sea-level (APSL). During the mid-Holocene an extensive sand flat, with associated dunes, formed immediately inland of the coastal barrier. At least six generations of Late Pleistocene dune systems occur in the region. For example, during last glacial times the climate was drier, colder and windier than at present and a system of parallel, west–east trending, yellow–red desert dunes developed around the lakes. Aeolian processes remain important with occasionally up to 5000 tonnes of sand being in motion along 10 km of the modern shoreline. During mouth migration, dunes up to 2 m high have been formed and vegetated in 12 months, directly inland from the mouth, and replicating the formation of older dunes on Hindmarsh Island. Elsewhere sand blown directly from the barrier system infills channels. Barrage construction on the beach facies of the last interglacial shoreline transformed the estuary into freshwater lakes with permanently raised water levels and reduced the tidal prism by 90%. Increased deposition, upstream and downstream, accompanied barrage construction, as have accelerated lakeshore erosion and the growth and consolidation of the flood tidal delta (Bird Island). These human accelerated changes provide rapidly formed analogues of older Quaternary features, and aid their interpretation. The shape and location of the Murray Mouth is constantly changing, migrating over 1.6 km since the 1830s.

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Migrations of up to 6 km over the past 3000 yr have influenced sedimentation on the landward shore of the back-barrier lagoonal system.

Keywords: River Murray; Estuarine environment; Last Interglacial; Amino acid racemisation; Thermoluminescence; Neotectonics; River regulation; Deltaic sedimentation

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1. Introduction

Australia is often viewed as a very old and stable landscape in which there are extremely low rates of geomorphological change (e.g. Twidale, 1998). Although relict landscape features are preserved in the Australian environment, a significant part of the Australian landscape is of recent origin, the product of rapid geomorphological changes. Bourman (1974) drew attention to the fact that there are many instances of rapid geomorphological change in Australia, especially where humans have impacted on the landscape. For example, the estuary of the lower River Murray is an example of an area undergoing rapid and ongoing geomorphological change. Furthermore, the landforms and sediments resulting from these accelerated changes provide analogues of similar events that occurred throughout the Quaternary.

The former estuary of the River Murray, comprising Lakes Alexandrina, Albert and the Coorong Lagoon is a Holocene feature that developed by submergence of interdunal areas during the sea-level rise that followed the Last Glacial maximum ca 20 ka BP. The estuary is the terminus for the drainage of the Murray-Darling catchment, which covers almost 14% or 1.073 million km^2 of the Australian continent. The location of the estuary has been controlled by regional tectonism since it occupies an area of subsidence in comparison with uplift of the nearby Mount Lofty Ranges and an uplifted coastal plain to the southeast (Fig. 1). The development and functioning of the estuary have been affected by variations in relative sea-level throughout the Quaternary, climatically controlled fluctuations in river flows, oceanic tidal, swell and storm processes, and the role of aeolian processes. Most recently, the impacts of humans have been added to these variables. Originally a vibrant, highly productive estuarine ecosystem of 75,000 ha, characterised by mixing of brackish and fresh water with highly variable flows, barrage construction has transformed the lakes into freshwater bodies with permanently raised water levels; freshwater discharge has been reduced by 75% and the tidal prism by 90% (Bourman and Barnett, 1995; Harvey, 1996).

In this work the geomorphological evolution of the Murray Mouth estuarine setting is considered in the context of rapid coastal change. In particular, the interplay of a range of geomorphological processes such as ongoing neotectonic activity, displayed in basin subsidence and hydro-isostasy, and their relations to other coastal processes is examined. We conclude that even very slow rates of basin subsidence can have a major geomorphological effect on coastal configuration, particularly where sea-level appears to be rising independently.

2. Geological and morpho-dynamic setting

The Murray Estuary is situated in the southwestern corner of the Murray Basin in relatively close proximity to its boundary with the Adelaide Geosyncline rocks of the Mount Lofty Ranges (Fig. 2). The Mount Lofty Ranges comprise folded, deformed and resistant metamorphic and crystalline rock >500 Ma. Granites crop out at Port Elliot and metasandstones occur at, and west of, Middleton Beach. In contrast, the Murray Basin comprises much younger, essentially flat lying Palaeozoic and Cainozoic sediments with the older, basement rocks downfaulted to considerable depths. For example, a bore hole on Hindmarsh Island, not far from the Murray Mouth, penetrated to a depth of 230 m, and ended in Permian glacigene sediments, 280 Ma old, without reaching the older basement rocks. Within the Permian glacial sediments many different rock types occur, having been transported by ice as erratics from distant sources to the southeast of the study site. Consequently, isolated rocks found within this area of the Murray Basin such as pebbles and boulders of granites and Kanmantoo Group metasedimentary rocks have been transported by waves along the present shoreline, former shorelines, or are Aboriginal artefacts.

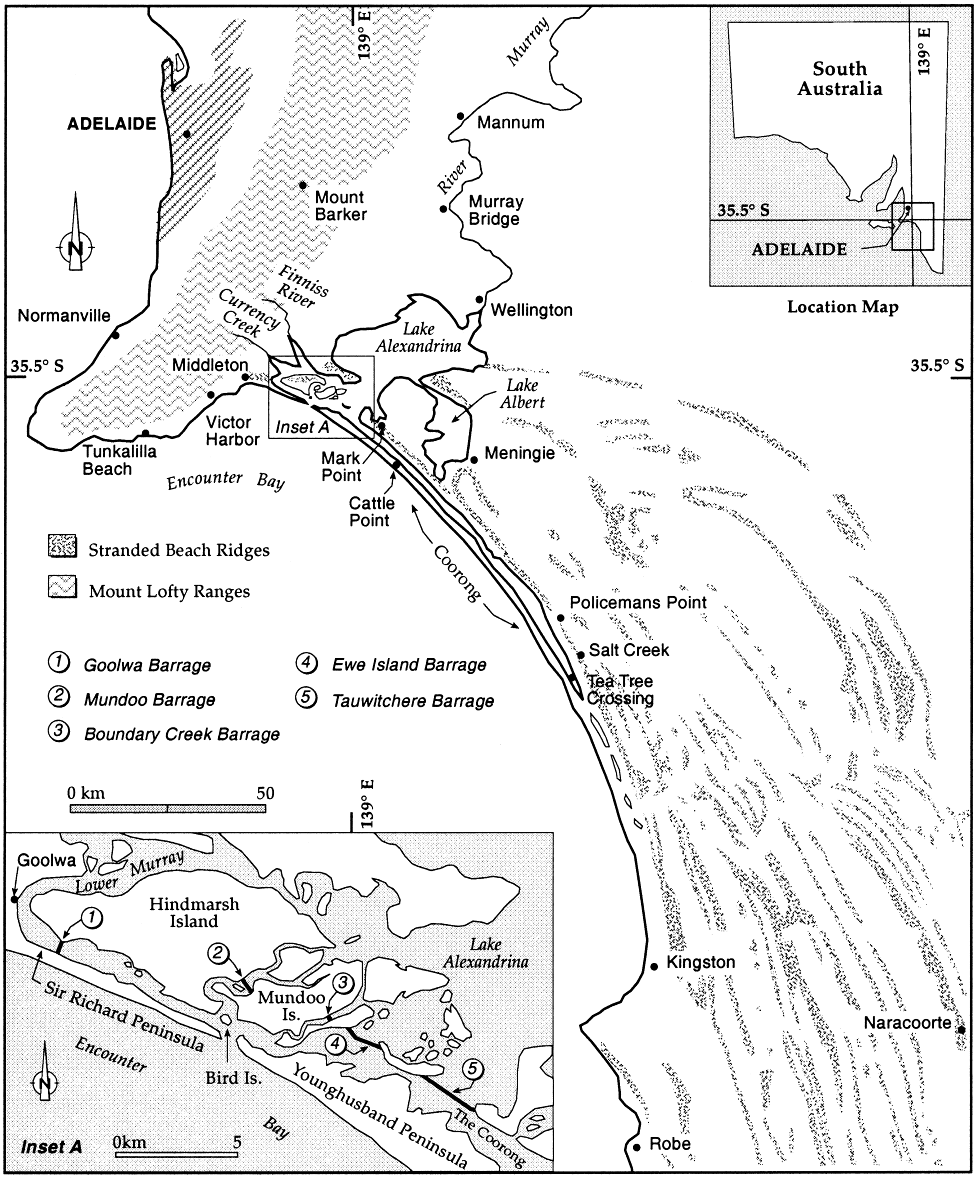

Fig. 1. Location map of the Lower River Murray Lakes and the Upper Coorong Lagoon, South Australia. Inset A shows the location of the barrage system. Construction of the barrages was completed by 1940.

The majority of sediments underlying the Holocene River Murray Estuary are Tertiary and Pleistocene limestones, and associated coastal sediments including aeolian dune deposits (aeolian calcarenites). Many of these coastal sediments are capped by well-developed calcretes, which preserve their morphological forms in the landscape. Repeated marine transgressions and regressions throughout the Quaternary have left a legacy of stranded shorelines on the coastal plain southeast of the Murray Estuary as it was progressively uplifted in response to intraplate volcanism (Murray-Wallace et al., 1996). One of the classic records of Quaternary sea-level fluctuations has thus been preserved.

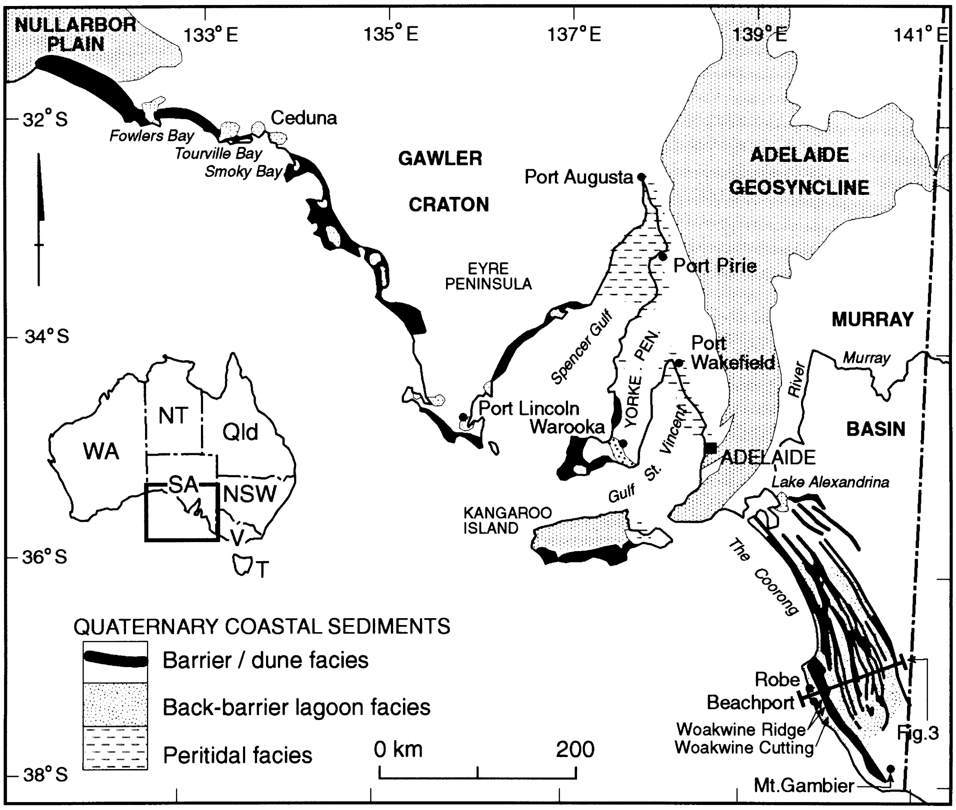

Fig. 2. Quaternary coastal sediments of the South Australian coastline with respect to the major structural settings of the Gawler Craton, gulfs area, Mount Lofty Ranges and the Murray Basin. The location for the cross section in Fig. 3 is shown.

To the southeast of the Murray Estuary, in the Robe–Naracoorte area, at least eight major interglacial coastal-barrier shorelines are preserved by uplift (Fig. 3) and have been interpreted to be the product of eccentricity band Milankovitch changes in insolation and corresponding glacio-eustatic cycles (Hossfeld, 1950; Sprigg, 1952, 1959a; Tindale, 1959; de Mooy, 1959a,b; Blackburn et al., 1965; Cook et al., 1977; Schwebel, 1978, 1983; Huntley et al., 1993; Belperio, 1995).

Coastal plain uplift decreased northwards towards the Murray Estuary, indicated by the successive decrease in elevation of coastal barriers and their attendant sea-level indicators, particularly the diagnostic back-barrier lagoon facies with intertidal indicator faunal assemblages (Sprigg, 1952; Murray-Wallace et al., 1998). As a result of ongoing tectonic tilting, the barrier systems, in plan, converge to the northwest (Fig. 1). For example, the distance between the last interglacial shoreline (Oxygen Isotope Substage 5e) and the penultimate interglacial shoreline (Oxygen Isotope Stage 7) in the Robe area of the southeast is 10 km, whereas at Hindmarsh Island the distance separating them is ~1 km. Similarly, the distance between the last interglacial barrier shoreline (Woakwine Range) and Robe Range, an interstadial composite barrier (ca. 105 ka) near Robe is 10 km, whereas at Hindmarsh Island it is 2 km and west of Goolwa, only 0.5 km.

During the Holocene transgression, by 7 ka, the sea flooded the interdune corridors of pre-existing coastal barriers such as the Late Pleistocene Woakwine and Robe Ranges. To the north, near the present Murray Mouth, the terminal lakes of the River Murray formed; Lake Alexandrina and its smaller appendage Lake Albert (Fig. 1). Lake Albert has no direct access to the sea, although an opening from it to the Coorong Lagoon may have existed previously

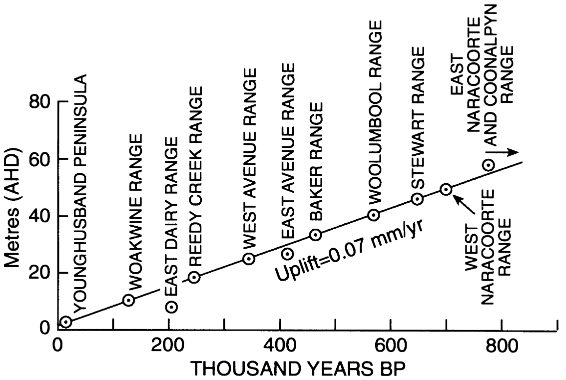

Fig. 3. Uplift of the former coastal barriers along the line from Robe to Naracoorte. Source: Belperio, 1995.

(Taylor and Poole, 1931). During the maximum Holocene sea-level of approximately 7000 to 6000 yr BP extensive sand and mud flats formed in favourable localities on the margins of this lake system, infilling minor embayments. Elsewhere former Holocene shorelines are marked by abandoned cliff lines and fields of recessional beach/dune ridges. The formation of the coastal barriers of Sir Richard and Younghusband Peninsulas (Fig. 1, inset A) was also initiated at this time; they represent modern analogues of the older barriers. Sir Richard Peninsula is composed dominantly of Holocene bioclastic and quartzose sands. Only near its proximal end do older Pleistocene calcreted, calcareous dune sediments crop out.

Younghusband Peninsula has a slightly more complex evolution as the Holocene coastal dune barrier rests on an older, calcreted inlier related to interstadial sea-level stands of 80–100,000 BP (von der Borch, 1975, 1976; Harvey, 1981, 1995). Three postulated phases of pre-historic settlement on the northern part of Younghusband Peninsula provide clues to its geomorphological development (Luebbers, 1978, 1982). The first phase, from 6000–4500 BP, was interpreted to indicate sporadic use of the incipient barrier system when it was a chain of islands (Luebbers, 1982). An early settlement phase between 4500–2000 BP was regarded as significant because it suggests initial colonisation and settlement by cohesive land-using groups. This evidence, together with a change in predominant shell midden type in the southeast, was considered to indicate that the marine influence here ceased as the islands became attached to the mainland around 2000–3000 BP. After this time there was a major settlement phase with large sedentary or semi-sedentary populations on the peninsula; the shellmound at one habitation site contains the refuse from an estimated 9000–150,000 meals (Luebbers, 1982).

The area has only a micro-tidal spring high-water range of 0.8 m at Victor Harbor, although storm surges may raise sea-level by up to 1.5 m above the predicted astronomical tide (Bourman and Harvey, 1983). The tidal range inside the Murray Mouth is considerably less. The extreme tidal ranges are 2.18 m at Victor Harbor (open ocean) and 1.30 m (inside the mouth) (Radock and Stefanson, 1975). The wave climate at the mouth of the Murray is persistently of moderate to high energy and the back barrier lagoon receives significant influxes of marine-derived sands through the mouth (Short and Hesp, 1980). Swell waves with a period of 14–15 seconds roughly arrive parallel to the shore, whereas storm waves with a period of 6–8 seconds generally approach the coastline at an angle from the southwest (Bourman, 1979). The resultant of winds capable of transporting sand also trends from the southwest (see Fig. 6) (Bourman, 1986).

Studies of littoral drift along the Encounter Bay coastline have been generally inconclusive (Bourman, 1979; Chappell, 1991; Harvey and Chappell, 1992; Reissen and Chappell, 1993). Chappell (1991) using meteorological data indicated that there was an average nett littoral drift of 260,000 $m^3 yr^{-1}$ between 1940 and 1990. For 1941 and 1942 a potential westerly movement of over 1,000,000 m^3 was calculated, but the hindcasting reveals major directional shifts in potential sand movement. For example, between 1940 and 1950 the movement was predominantly to the west, between 1951 and 1968 predominantly to the east and between 1969 and 1989, predominantly to the west. Bourman (1979) noted that along Sir Richard Peninsula the sand-sized beach sediments coarsen towards the Murray Mouth, the opposite to that expected for the eastward drift along the peninsula suggested by the direction of its prolongation. However, the pebble-sized materials, based on their provenance, appear to be transported towards the Murray Mouth. Consequently, Bourman (1979) suggested that swell waves may transport fine sediment from near the Murray Mouth, towards Goolwa Beach, but that storm waves may transport all the beach sediment in the opposite direction, so that the nett effect may be to transport the coarser materials in one direction and the finer in the other.

3. Mapping and dating methodologies used

Aerial photographs and topographic maps have been used to map the distributions of various stratigraphic units, and time series aerial photographs were utilised to illustrate changes since European settlement, such as lakeshore erosion and fluctuations in the position of the Murray Mouth and its associated flood tidal delta. Standard levelling techniques were applied to determine the elevations of various shoreline features with respect to modern sea-level.

For age determinations, radiocarbon dating (University of Waikato) was applied to appropriate Holocene materials, aeolian facies were dated by thermoluminescence techniques, carried out at the University of Wollongong, and amino acid racemisation methods were used on shoreline and back barrier facies molluscs. The analytical techniques adopted in this work, for amino acid racemisation, are described in detail elsewhere (Murray-Wallace, 1993). Wherever possible, well-buried molluscs ($\geqslant$1 m) were selected to minimise the influence of diurnal and seasonal temperature changes such that temperatures associated with longer-term climatic change represented the dominant influence on diagenetic racemisation. The hinge region of bivalve molluscs was selected to avoid possible intrashell variations in enantiomeric ratios. Surface encrustations of soil or sediment on the fossil molluscs were removed using dental tools, followed by cleaning in distilled water in an ultrasonic bath. The outer surfaces of the shells were then removed in dilute HCl to remove any recrystallized or chalky layers. Samples were then hydrolysed for 16 h at 110°C in 8 M HCl. Following cation exchange separation of the protein residues, samples were freeze dried and derivatised. Chromatography of the *N*-pentafluoropropionyl D, L-amino acid 2-propyl esters was undertaken using a Hewlett-Packard 5890 Series II gas chromatograph with a 25 m, coiled fused silica capillary column with the stationary phase Chirasil L-Val, flame ionisation detector and helium carrier gas. D/L ratios were determined on the basis of peak area calculations.

4. Last Interglacial shoreline

Between about 132 to 118 ka, during the Last Interglacial Maximum, sea-level was approximately 2 m above present sea-level (APSL) (Murray-Wallace and Belperio, 1991). Last Interglacial shell beds occur sporadically along the western shores of Encounter Bay and form a near-continuous, well preserved fossil shoreline along the coastal plain from Lake Alexandrina to Mount Gambier. Variations in the elevation of the last interglacial shoreline reveal that uplift of the Mount Lofty Ranges, subsidence of the Murray Basin and uplift of the Mount Gambier coastal plain continue today.

Near Goolwa, the shelly foreshore and estuarine facies of the Last Interglacial run across the lower part of the estuary parallel to the modern coastline and approximately 2 km inland. The northwesterly tip of Younghusband Peninsula at the Murray Mouth is a modern analogue of the distal end of the last interglacial (TL age 138 ± 13 ka; Sample W2103; Table 1) barrier preserved on the western end of Hindmarsh Island. The largest accumulation of sand on Younghusband Peninsula occurs a few kilometres southeast of the mouth, where the peninsula is at its highest and widest, due to the accumulation of sand derived by longshore transport from the southeast. During last interglacial times longshore transport was also dominantly from the southeast. Consequently, the last interglacial barrier prograded towards the northwest, forming the northern half of the current Hindmarsh Island. This is represented by a now calcreted succession of dunes and beach ridges, which formed a high barrier and effectively pushed the main channel of the River Murray (the Goolwa Channel) towards the west. Hence, the northwesterly drift of sand along the last interglacial shoreline is partly responsible for the large bend in the River Murray at Goolwa and the western end of Hindmarsh Island (Fig. 1, inset A). Not only did the last interglacial shoreline prograde to the west, but the delivery of sand to the end of the barrier must have been sufficient to cause the seaward progradation of the barrier,

Table 1
Thermoluminescence dates

Laboratory No.	Specimen name	Location: 1:50,000 map reference	TL age (ka)
W2256	H.Is.23	Goolwa 6626-I 3077/60689	> 329
W2346	Clayton 1	Goolwa 6626-I 30118/60695	213 ± 35
W2245	Point Sturt 1	Narrung 6726-IV 3227/60694	229 ± 48
W2347	Boomer Beach	Encounter 6626-IV 2895/60647	266 ± 34
W2348	Surfers Beach	Encounter 6626-IV 2947/60673	103 ± 6
W2258	H.Is 25	Goolwa 6626-I 3097/60658	85 ± 7.1
W2103	H.Is 26	Goolwa 6626-I 3036/60683	138 ± 13
W2254	H.Is 21	Goolwa 6626-I 3037/60687	18.8 ± 1.8
W2257	H. Is 24	Goolwa 6626-I 3054/60654	3.9 ± 0.8

marked by a succession of recurved spits on the southwestern corner of the island. These features are clearly evident on aerial photographs both on Hindmarsh Island (last interglacial age) and on the distal end of Younghusband Peninsula (modern age) (Fig. 4).

All of the barrages except the Goolwa Barrage are built on the shelly beach facies of the last interglacial shoreline. Surveys prior to construction of the barrages revealed that the channels across the fossil shoreline are shallow (1–3.5 m deep) (Oliver and Anderson, 1940). In contrast, unconsolidated sediments underlie the site of the Goolwa barrage, and it was necessary to drive 19 m long piles into the sediments to provide sound footings for the barrage structure. Oliver and Anderson (1940) estimated that during maximum flows up to 70% discharged through the Goolwa Channel, 10% through the Mundoo Channel and the remainder through the Tauwitchere, Boundary Creek and Ewe Island channels. From this it is clear that the Goolwa Channel has been the major channel discharging water from the River Murray since last interglacial times, and that it was excavated well below present sea-level during glacial episodes.

4.1. Aminostratigraphical correlation of the last interglacial shoreline

In this work amino acid racemisation in fossil molluscs has been determined to verify the time equivalence of coastal deposits inferred to be of last interglacial age on the basis of morphostratigraphic evidence. The amino acid racemisation data provide a geochronological framework for the neotectonic interpretations made in this work. Fossil molluscs were selected from estuarine (Chiton Rocks and the Hindmarsh River Valley at Victor Harbor, and the Normanville Embayment) and shallow subtidal foreshore facies (Hindmarsh Island and Mark Point) for amino acid racemisation analysis. The fossils collected for analysis are from deposits interpreted here as correlatives of the Last Interglacial (Oxygen Isotope Substage 5e) Woakwine Range of the Robe area, and the Glanville Formation of Gulf St Vincent (Belperio, 1995; Murray-Wallace et al., 1999) based on the faunal assemblages of the deposits (e.g. presence of the distinctive arcoid bivalve *Anadara trapezia*), their stratigraphic relationships with similar sediments of Holocene age and in some instances their heights above present sea-level.

A high extent of racemisation is evident in the fossil molluscs from the four deposits in the Murray Lakes region (i.e. Chiton Rocks, Hindmarsh River Valley, Hindmarsh Island and Mark Point). The extent of racemisation in these fossils far exceeds that found in Holocene molluscs from southern Australia (Murray-Wallace, 1995). Similarly, the extent of racemisation of amino acids in a specimen of *Donax deltoides* from Sir Richard Peninsula, with a radiocarbon age of 2660 ± 140 yr cal BP (SUA-2881) is significantly lower than observed for the molluscs from the Murray Lakes region (Table 2). Despite the potential sources of uncertainty, such as a genus-effect on racemisation and the shallow burial depth of the *Donax deltoides* at Mark Point, the results suggest a common age for these fossil molluscs. By analogy with the extent of racemisation in fossil molluscs from the reference section of the Glanville Formation of the Adelaide region, and a similar deposit at


a
b

Normanville, a last interglacial age is assigned to the fossil molluscs from the former shoreline underlying the barrages in the Murray Lakes area.

5. Neotectonics

5.1. Neotectonics from Last Interglacial shoreline elevations

Given the above correlation and age assignment, compelling evidence of neotectonic activity in the area is provided by the systematic variations in altitude of the last interglacial shoreline from Mount Gambier to the Mount Lofty Ranges, and comparison with the elevation of the shoreline in the more stable Gawler Craton area of Eyre Peninsula (Fig. 5) (Murray-Wallace et al., 1996; Bourman et al., 1999). The elevation of the last interglacial shoreline in the study area is 6 m AHD (Australian Height Datum) at Victor Harbor, 10 m AHD at Chiton Rocks, 0.9 m AHD on Hindmarsh Island, 2 m AHD at Mark Point, 4 m AHD at Bonney Reserve, 5 m AHD at Salt Creek, 8 m AHD at Robe (Woakwine Range) and 18 m AHD near Mount Gambier. This indicates downtilting towards the Murray Mouth area from both westerly and south-easterly directions. Comparisons with variations in elevation of last interglacial shoreline deposits around the South Australian coastline reveal that the lower Murray Lakes has been subsiding over the past 125,000 yr at a rate of 0.02 mm yr^{-1}.

5.2. Historical seismicity

As well as there being evidence of ongoing tectonic dislocation of last the interglacial shoreline, there are also records of historical seismicity affecting the region, influencing landform evolution by initiating coastal slumping and erosion. Sprigg (1952) reported on three episodes of crustal deformation in the area: the first was of post-Ordovician to pre-Jurassic age; the second a Late Mesozoic-Tertiary phase, marked by undulatory folds and minor faults; and the third of Pleistocene age indicated by regional warping away from the Mount Gambier volcanic region towards the base of the rising Mount Lofty Range, a tendency temporarily reversed during periods of volcanic activity.

Historical seismic events reported include major episodes centred on the Beachport area (Sprigg, 1952), to the southeast of the Murray Estuary. For example, an earthquake occurred on May 10th, 1897, with tremors continuing at intervals for some months. The epicentre was on Beachport (Felt Intensity 9 on the Mercalli Scale) with a Felt Intensity between 8 and 9 at the Murray Estuary reflecting ongoing subsidence. During the earthquake a large mass of aeolianite was split and portions fell into the sea near Cape Jaffa, while northwest of Mount Benson 'travertinised aeolianite' was deeply cracked (Sprigg, 1952). A similar, but less severe, earthquake occurred on 8th April, 1948 with its epicentre beneath the sea 10 miles northwest of Beachport, possibly associated with a submarine volcanic eruption Sprigg (1959b). Sprigg (1952) considered these earthquakes to represent deep basement faulting. An earthquake (September 19, 1902), with its epicentre at Warooka on Yorke Peninsula (Felt Intensity 8) also affected the Murray Lakes region (Felt Intensity 5). Residents of Goolwa town reported a severe tremor associated with this event, which caused cracking of some of the buildings in the Goolwa area (Bourman, 1973, p. 22). Other possible indications of neotectonics in the area include the erosion of Middleton Beach and deformation of soft back-barrier sediments. This evidence will be discussed later.

5.3. Sea-level change and neotectonic factors

Records of sea-level for Victor Harbor, nearby to the Murray Mouth, have been monitored and analysed by the National Tidal Facility (NTF) at Flinders University in South Australia. South Australian sea-level trends based on tide gauge data (Mitchell, 1991) have been adjusted by Harvey and Belperio (1994) by exclusion of neotectonic factors from the tidal data. The calculated sea-level trend for Victor Harbor of +0.6 mm yr^{-1} (Mitchell, pers. comm., 1994), has been revised downwards to 0.5 mm yr^{-1} to exclude

Fig. 4. Photographs of the recurved spits on the distal ends of the modern Younghusband Peninsula (A) and the last interglacial barrier on Hindmarsh Island (B). Source: Mapland, South Australia.

Table 2

Extent of amino acid racemisation (total acid hydrolysate) in fossil molluscs from the Murray Lakes region and other Late Quaternary deposits in South Australia (Amino acids: ALA–alanine; VAL–valine; LEU–leucine; ASP–aspartic acid; PHE–phenylalanine; GLU–glutamic acid. Current mean annual air temperature: 16°C (Murray Lakes region); 17°C (Dry Creek, Adelaide))

Locality	Species	Depth of burial (m)	Amino acid D/L ratio					
			ALA	VAL	LEU	ASP	PHE	GLU
Chiton Rocks, Watson Gap, Victor Harbor	*Anadara trapezia*	2	0.56 ± 0.004	0.29 ± 0.004	0.42 ± 0.001	0.50 ± 0.001	0.42 ± 0.01	0.31 ± 0.01
R. Hindmarsh Valley, Victor Harbor	*Anadara trapezia*	2	—	0.28 ± 0.04	0.45 ± 0.05	—	—	—
Hindmarsh Is. borrow pit (Murray Lakes)	*Mactra australis*	1	0.65 ± 0.02	0.26 ± 0.005	0.36 ± 0.01	0.55 ± 0.01	0.41 ± 0.04	0.34 ± 0.03
Mark Point (Murray Lakes)	*Donax deltoides*	0.3	0.59 ± 0.01	0.31 ± 0.01	0.42 ± 0.01	0.59 ± 0.01	0.49 ± 0.03	0.34 ± 0.003
Normanville Embayment	*Mactra australis*	2.6–3.5	0.63 ± 0.02	0.28 ± 0.01	0.27 ± 0.01	0.59 ± 0.01	0.36 ± 0.03	0.33 ± 0.007
Dry Creek, Adelaide, Glanville Fm. (125 ka)	*Anadara trapezia*	1.5	—	0.31 ± 0.01	—	0.61 ± 0.01	—	—
Sir Richard Peninsula, 2660 ± 140 yr BP (SUA-2881)	*Donax deltoides*	Surface recently exhumed midden	0.13 ± 0.02	0.07 ± 0.01	—	0.19 ± 0.01	—	0.12 ± 0.005

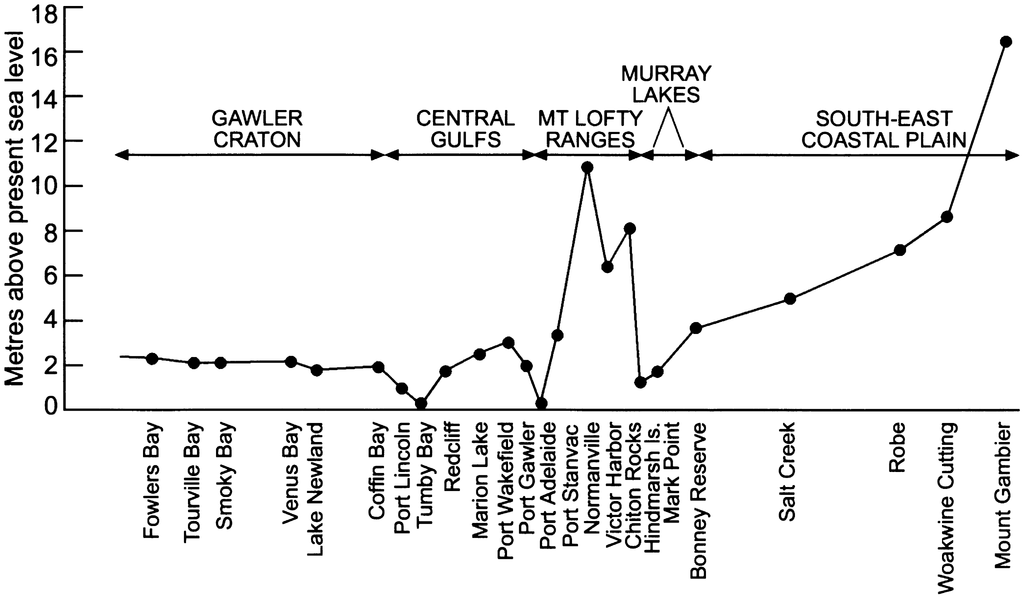

Fig. 5. Variations in elevation of last interglacial shoreline deposits around the South Australian coastline which reveals that the lower Murray Lakes has been subsiding over the past 125,000 yr. Source: Bourman et al. (1999).

known neotectonic overprinting in the region (Harvey and Belperio, 1994).

6. Aeolian processes and deposits

Aeolian processes are intimately associated with the formation of coastal barriers, as well as their ongoing modification. At least six generations of Late Pleistocene dune systems have been recognised on Hindmarsh Island. These have been distinguished by thermoluminescence dating and they have distinctive characteristics such as calcrete carapaces, included shell fragments, carbonate free dunes and various degrees of iron and organic contents. The oldest dunes in the area are all calcareous and calcreted, and relate to former Pleistocene shorelines. Due to the progressive Quaternary uplift of the coastal plain in the southeast and the subsidence at the Murray Mouth the fossil barrier shorelines converge in a northwesterly direction as shown on Fig. 1. Resulting from this, elements of older barriers occur on Hindmarsh Island over which younger barriers are draped. For example, a sample collected from a quarry exposure on the north central part of Hindmarsh Island returned a TL age greater than 329 ka (W2256) (Table 1). Remnants of the Penultimate interglacial occur nearby at Clayton (W2346 TL age 213 ± 35 ka), Point Sturt (W2345 TL age 229 ± 48 ka) and west of Middleton at Port Elliot (W2347 TL age 266 ± 34 ka, isotopic substage 7e). Substage 5c elements are being eroded at the coastline east of Middleton (W2348 TL age 103 ± 6 ka), while substage 5a relicts (W2258 TL age 85 ± 7.1 ka) occur on Hindmarsh Island overlying eroded last interglacial deposits as well as forming the core of Sir Richard Peninsula at its proximal end. All of the Pleistocene relict dunes are heavily calcreted.

6.1. Last Glacial Maximum desert dunes

East–west oriented, sub-parallel, unconsolidated and non-calcareous sand dunes also occur in the Murray Lakes region. The quartzose sand is distinctively red to yellow in colour due to thin coatings of iron oxides and the dunes characteristically rest on older consolidated, calcareous aeolianites. The quartzose dunes occur on Hindmarsh Island and in areas surrounding Lakes Alexandrina and Albert. Thermoluminescence dating indicates that this dune

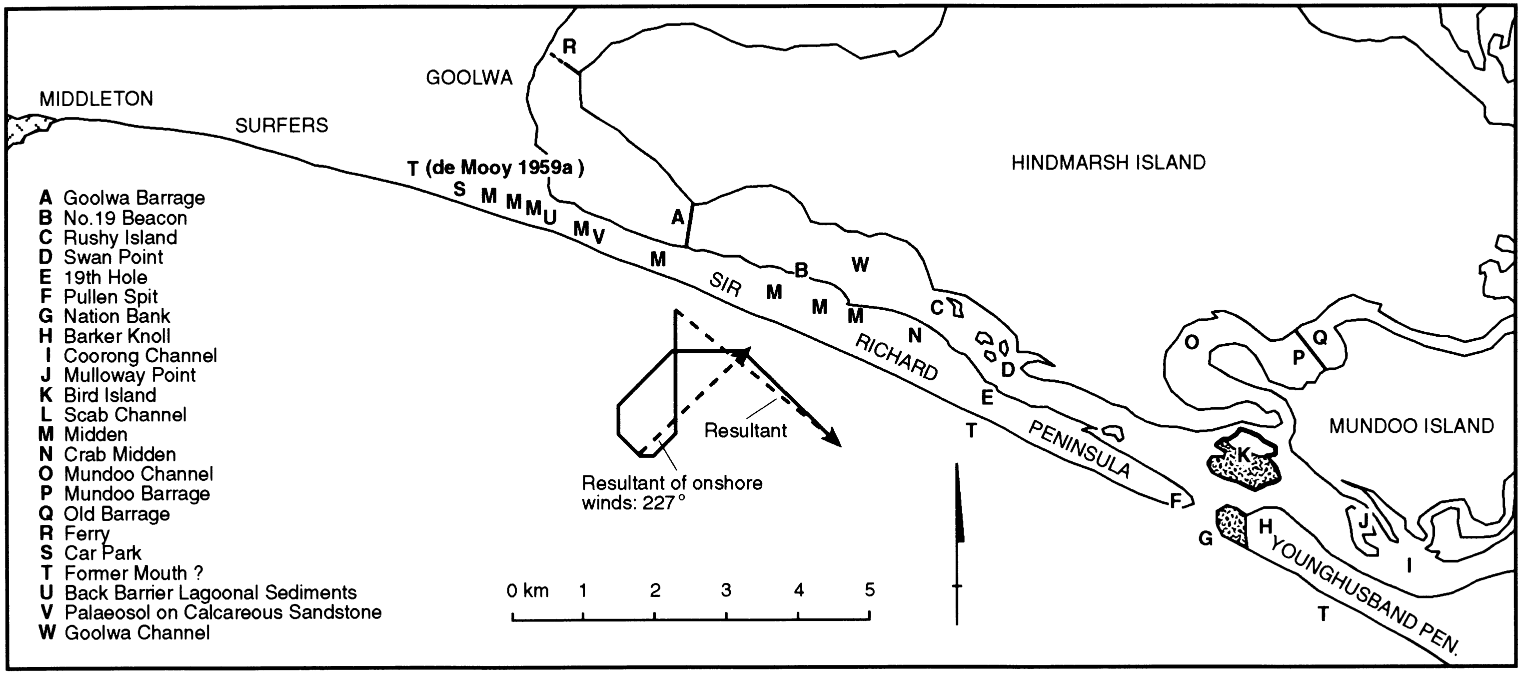

Fig. 6. Map of Sir Richard Peninsula, a Holocene coastal barrier, showing the locations of Aboriginal middens (M). They only occur on the proximal half of the barrier. A vegetated flood tidal delta, Bird Island (K) occurs inland from the Murray Mouth, with postulated former flood tidal deltas occurring at D (Swan Point) and J (Mulloway Point). The wind resultant diagram shows local winds at Victor Harbor (>28.8 km hr^{-1}) effective in initiating longshore transport on Sir Richard Peninsula.

Fig. 7. Aboriginal midden consisting of the Goolwa cockle (*Donax deltoides*) on the coastal barrier of Sir Richard Peninsula.

formation occurred ca 16000 to 18000 yr ago, during the late stage of the Last Glacial Maximum (18.8 ± 1.8 ka, W2254, Table 1). At this time the shoreline was some 180 km further to the southwest and up to 120 m lower than present, with the River Murray extended across the continental shelf (Sprigg, 1979). A land bridge to the site of the current Kangaroo Island also existed. At this time the climate was much colder, drier and windier than at present (Belperio, 1995) and distinctive red–yellow desert dunes extended over much of Australia (Jennings, 1968), including the Murray Estuary (Sprigg, 1979) and, possibly, the exposed continental shelf. In the study area these former desert dunes appear to have been favoured sites for Aboriginal occupation, possibly because they were relatively high and well drained sites. They are very prone to sand drift if overgrazed, indicating their fragility, but several reactivated areas on Hindmarsh Island have been stabilised by grass plantings and stock exclusion.

6.2. Holocene coastal barrier system

Following the Last Glacial Maximum sea-level rose rapidly to near its present level, reaching that position approximately 7000 yr ago (Belperio, 1995). Any Last Glacial Maximum desert type dunes that extended across the continental shelf were swept up by the advancing sea and incorporated with marine shell hash to provide sediment for development of the modern coastal barrier system of Sir Richard and Younghusband Peninsulas (from 7000 yr ago) and the extensive sand flats inland from the barrier. The modern barrier sands near the Murray Estuary are more quartz rich than those to the southeast (Sprigg, 1959a), perhaps reflecting the reworking of the former desert dunes near the estuary. The construction of Sir Richard Peninsula completed the elbow of the main Goolwa channel (Fig. 6). Extensive evidence of Aboriginal occupation in the form of shell middens (Fig. 7), comprised dominantly of the Goolwa cockle, *Donax deltoides* occurs within

Fig. 8. Photograph of a back-barrier Mid Holocene tree stump (*Allocasuarina*) with attached Holocene shells recovered from the open ocean coastline of Sir Richard Peninsula.

this Holocene coastal dune system and radiocarbon ages on shells from these middens consistently fall within the range of 3500 to 200 yr (Bourman and Murray-Wallace, 1991).

In recent times the barriers of Sir Richard Peninsula and Younghusband Peninsula appear to be migrating landwards, concordant with the inferred rate of relative sea-level rise. Evidence of landward migration is indicated by the sporadic exposure on the modern beach (Bourman and Murray-Wallace, 1991) of:

1. Back-barrier lagoonal sediments containing rodent skeletons, shells and tree stumps.
2. Exposure of interdunal protosols on the modern beach face and coastal erosion of Aboriginal middens.

Table 3

Radiocarbon dates. The conventional radiocarbon ages were calibrated using the University of Washington Quaternary Isotope. Laboratory calibration program (Stuiver and Reimer, 1993). The calibration includes a correction for the marine reservoir effect of delta $r = -5 \pm 35$, equivalent to -450 ± 35 yr for marine and estuarine surface water environments previously determined by Gillespie and Polach (1979). The uncertainties are at the 2 sigma level (i.e. 95% confidence level)

Sample	Species	Laboratory no.	Location: 1:50,000 map reference	Conventional radiocarbon ages	Calibrated radiocarbon ages
H.Is 19A	*Allocasuarina*	Wk-4786	Goolwa 6626-I 3047/60640	4,110 ± 60 yr BP	4,630 ± 210 cal yr BP
H.Is 19B	Gastropod	Wk-4787	Goolwa 6626-I 3047/60640	4,880 ± 150 yr BP	5,190 ± 380 cal yr BP
Younghusband 1	*Donax* (*Plebidonax*) *deltoides*	Wk-5824	Narrung 6726-IV 3235/60540	2,900 ± 60 yr BP	2,620 ± 160 cal yr BP
H.Is 1	*Tellina* (*Eurytellina*) *albinella*	Wk-4784	Goolwa 6626-I 3074/60657	5,980 ± 80 yr BP	6,410 ± 190 cal yr BP
H.Is 18	*Polinices conicus*	Wk-4785	Goolwa 6626-I 3037/60663	3,540 ± 60 yr BP	3,420 ± 160 cal yr BP

3. Folding and elevation of back-barrier lagoonal sediments to heights of up to 10 m APSL by differential loading of muds by advancing dunes. As the landward migration of the barriers continues, sand from the barrier is blown into the back-barrier lagoon, clogging the channels.

Evidence of the landward encroachment of the Holocene barriers is provided by the sporadic exposure of back-barrier lagoonal sediments on the ocean beach. Shells included in the back barrier sediments have been dated at approximately 8000 yr BP (Bourman and Murray-Wallace, 1991). A fossil tree stump (*Allocasuarina*) (Fig. 8), also located on the open ocean beach of Sir Richard Peninsula, has been dated at 4110 ± 60 yr BP (Wk-4786) and the attached shells, in which the tree had grown, at 4880 ± 150 yr BP (Wk-4787) (Table 3). Aboriginal middens (2000 to 3000 yr old) originally on sand dunes have been exposed at the shoreline by erosion and have been incorporated into the beach sediments (Bourman and Murray-Wallace, 1991). Erosion on Sir Richard Peninsula appears to have been most severe at the neck of land at the proximal end of the barrier, immediately upstream of the Goolwa barrage, which forms a barrier between the ocean and the freshwater storage. River erosion at the outer and downstream end of the meander may contribute to the narrowing of the barrier at this location, but this region also appears to be the focus of greater wave attack. The non-parallelism of transverse dunes and the coastline and the closer proximity of older secondary dunes to the shoreline at the proximal end of the peninsula suggest that the coastline may have been slightly reoriented during the Late Holocene (Bourman and Murray-Wallace, 1991). Late Holocene aeolian sediments of the area appear to comprise brown coloured soil and sand dune materials. Thermoluminescence dating has established that they are approximately 3–4000 yr old (TL age 3.9 ± 0.8 ka, W2257, Table 1) and they carry much evidence of Aboriginal occupation.

The landward migration of the barriers continues; sand from the barrier is blown into the back-barrier lagoon, clogging channels and differentially loading the plastic lagoonal muds (Fig. 9a). In some locations differential loading by the migrating sand dunes (Fig. 9b) has resulted in the deformation of fossiliferous

Fig. 9. (a) Photograph of soft sediment deformation structures at Tea Tree Crossing, Coorong Lagoon. (b) Transgressive coastal dunes migrating over back barrier sediments.

Holocene, back-barrier lagoon sediments (Brown, 1965). The back-barrier muds at the Tea Tree Crossing of the Coorong Lagoon have been squeezed, folded and differentially uplifted to levels up to 10 m above their original position and resemble intrafolial folds. This appears to have occurred within a relatively short time period. Mud folds have a fairly widespread distribution along the Coorong Lagoon; the writers have observed them at Tea Tree Crossing in the south, to Cattle Point in the north. While loading of soft sediments is sufficient to explain their characteristics, seismic events may have also contributed to their deformation and elevation. Care must be taken in interpreting these deposits especially if only small exposures are available as their current position does not reflect their original in situ setting.

7. Mid-Holocene sand flat

An extensive sand flat occupies the southern halves of Hindmarsh and Mundoo Islands as well as sporadically bordering the margins of Lakes Alexandrina and Albert (Fig. 1). The sand flat is typically mantled with a thin veneer of black/grey smectitic clay, probably related to terrestrial sediments delivered to an enlarged lake system. The sand flat surface occurs at elevations up to 2 m above present sea-level and intertidal shells recovered from 60 cm below the surfaces have been radiocarbon dated at 5980 ± 80 yr BP (Table 3). The sand flat appears to be related to a well established Holocene transgressive peak between 6500 and 5000 yr BP, and which appears to have stabilised by about 3500 yr BP as indicated by dated shells near present sea-level on the southern shore of Hindmarsh Island (3540 ± 60 yr BP WK-4785). These changes, together with a trend towards drier conditions, are also reflected in the character of foraminifera recovered from Holocene sediments (Cann et al., 2000). Indicators of this post-transgressive, regressive phase around the margins of the lakes include abandoned cliff lines, infilled embayments and Holocene sediments (Taylor and Poole, 1931; de Mooy, 1959a,b; von der Borch and Altmann, 1979; Gloster, 1998) and regressive lakeshore/dune ridges on the former lakeshore margins. The sand flat is a recent analogue of a last interglacial sand flat that occurs on the mainland to the west of Hindmarsh Island.

8. Contemporary processes and landform change

8.1. Historical coastal changes

There is ample evidence of both historical and longer term coastal erosion along the Encounter Bay shoreline of the Murray Lakes estuary. Some 90% of the world's sandy shorelines are currently undergoing erosion (Bird, 1985), and the sandy shoreline of Encounter Bay is no exception. Reasons suggested for the accelerated erosion on these sandy shorelines have included: diminution in sediment input from rivers and offshore sources, reduced sand supply from eroding cliffs and stabilised seaward moving dunes, impacts of breakwaters and sea walls both by starving beaches and/or changing the incidence of wave attack, loss of sand from beaches by landward drifting of dunes, deliberate and unintentional removal of sand from beaches, increased wave attack due to dredging, erosion of shoals or loss of sea grass meadows, increased wave attack due to a relative rise in sea-level, increased frequency and severity of storms, reduction in volume of beach material due to weathering of beach materials and increased erosion related to elevated water tables (Bird, 1985). These factors have been considered in assessing erosion of the shorelines in the study area.

Historical coastal changes are demonstrated by the erosion of European structures such as beach shelters and former surveyed roads, the locations of which now occur in the subtidal zone. For example, the locations of some coastal roadways in the Goolwa area, surveyed approximately 150 yr ago to within 150 links (30.2 m) of high water are now submerged. Furthermore, at Goolwa Beach, a beach shelter originally built on the upper part of the beach was removed after it became permanently inundated (Bourman, 1979). Eyewitness accounts document dramatic coastal erosion at Middleton, where the coastline has eroded some 200 m from 1900 to the present (Bourman, 1974, 1979). Hodge (1932) wrote:

> "Up to about 20 years ago Middleton was noted for its wonderful beach. At low tide it was probably nearly a quarter of a mile (400 m) wide

Fig. 10. Photograph of coastline at Middleton, which has been affected by erosion over the past 90 yr. Originally a sandy coastline with a backing sand dune system, it now comprises a cliffed coastline cut into alluvial sediments. Over the past 20 yr erosion has been minimal and from time to time small sand dunes accumulate at the base of the cliffs and become partly vegetated, suggesting that a new equilibrium condition may be developing.

> from sandhill to sea, and so firm that vehicles could be driven for miles along its reaches in an easterly direction. But the sea encroached quite suddenly and there is now comparatively but little beach and ordinary high tides practically reach the sand hills".

Photographs taken of the beach in the late 19th century confirm that it was of extensive width. Today there are no sand dunes backing the beach and the sea now sporadically erodes a line of low alluvial cliffs at high tide (Fig. 10). The oral history of the area suggests that the coastline has been eroded by as much as 400 m since 1897 (Bourman, 1974), but this extent of erosion is not wholly supported by independent evidence. Nevertheless, comparison of aerial photographs taken in 1949 and 1972 clearly indicate that erosion of terrestrial alluvial deposits have formed a cliff line up to 10 m high and that there was a coastal retreat of many metres in the 23 yr period.

The oldest accurate map of the area was prepared in the 1860s when surveys were made to within 150 links (30.2 m) of high water level. Measurements from fixed points in September 1974, 106 yr after the first survey revealed that the cliff line had eroded by as much as 45 m, equivalent to a rate of 0.4 m yr^{-1}. Landowners in the affected area provide evidence of the truncation of fence lines at a rate of 0.3 m yr^{-1} over the period 1944–1974, erosion of the same order of magnitude as that determined by resurveying. Even greater erosion has occurred to the west of the resurveyed line. Comparison of the original map with aerial photos suggests that near the mouth of Middleton Creek some 200 m of erosion has occurred, an average rate of 1.9 m yr^{-1} for the 106 yr period.

Glacio-eustatic rises in sea-level, increased storminess, diminished sand supplies and human interference have all been cited as possible causes of erosion on sandy beaches (Thom, 1974; Bird, 1985). There are no records of major coastal works in the area and the onset of erosion preceded the completion of the weir system in the River Murray. Furthermore, the removal of beach material has been of minor importance, so that the coastal recession at Middleton does not seem to be related to human interference. Similarly, there is no evidence for a sudden decrease in sand supply either from offshore or alongshore. Increased storminess and a slight rise in relative sea-level may have contributed to the erosion, but the spatial distribution of erosion focussing along the Middleton shore does not appear to relate to these general causes of erosion. Coastal erosion has occurred in similar alluvial sediments at Tunkalilla Beach 20 km to the west, within the Mount Lofty Range Province, but the amount of erosion is 10 times less (Bourman, 1979). Thus, the main cause of the erosion appears to be localised, and may be related to tectonic subsidence as there was a series of earth tremors which affected the area around the turn of the century and coincided with the onset of the erosion phase. Initially erosion was very rapid as the geomorphological threshold was crossed, but progressively erosion slowed down. Over the past 20 yr erosion has been minimal and from time to time small sand dunes accumulate at the base of the cliffs and become partly vegetated suggesting that a new equilibrium condition may be developing. However, renewed subsidence could herald a new phase of accelerated coastal erosion.

Middleton Beach lies within the Murray Basin Province, which, based on the elevation of the last interglacial shoreline, is subsiding relative to both the Mount Lofty Ranges and the Mount Gambier area. A postulated series of faults follows the eastern flank of the Mount Lofty Ranges and passes through the Middleton-Port Elliot region. Gravity contours also indicate a fault-like structure at depth (Morony, 1971). Thus, the cause of the extensive erosion at Middleton is possibly related to tectonic subsidence as marked erosion has been noted to the east of the inferred fault but not the west.

Erosion of the alluvial Middleton cliffs has been accomplished largely by storms, during which the lower cliffs of the eastern end of the beach, some 2–4 m high are often overtopped by waves. The area backing the beach was originally farm land but it is now a housing development. A buffer zone of about 45 m has been left between the cliff top and the housing development, which seems reasonable in light of the present reduced erosion of the cliff line.

8.2. Impacts of river regulation

The River Murray Estuary has been heavily modified by progressive river regulation (Thoms and Walker, 1992, 1993; Bourman and Barnett, 1995). Since barrage construction there have been 20–30 periods of no flow when the barrages have been closed for 100 or more consecutive days. Consequently, there has been a reduction in the water flow available for flushing of the river mouth. With construction of the barrages, reduction in river flow by 75% and contraction in the tidal prism by 90%, the former mobile flood tidal deltaic sediments (Fig. 11) have become fixed with vegetation (some 70 different species), forming a permanent island, Bird Island, now 1 km in diameter and with a maximum height of 5 m (Fig. 12) (Bourman and Harvey, 1983). Much of the island stands above the level of the highest recorded flood of 1956. The growth and consolidation of the flood tidal delta (Bird Island) landward of the Murray Mouth has been the most significant geomorphological impact of river regulation. The mouth blocked in 1981, for the first time in recorded history, necessitating artificial clearance (Bourman and Harvey, 1983). The continuing growth of Bird Island and sedimentation in the surrounding channels has the potential to result in more frequent and permanent blockages of the Murray Mouth with consequences for the ecological health of the region. Permanent storage of coastal deposits in the stabilised flood tidal delta may lead to increased coastal erosion as the coastline is deprived of some of its protective sediments. It has been estimated that the mouth may be substantially cleared by a flow of 20,000 ML day^{-1} for one month or more (Harvey, 1996).

As well as the construction of the barrages impacting on sedimentation at the mouth, the detailed operation of the barrages is important. Notably the decision not to operate the Mundoo Barrage, which is the closest to the mouth, has had deleterious consequences. The Mundoo Barrage predominantly

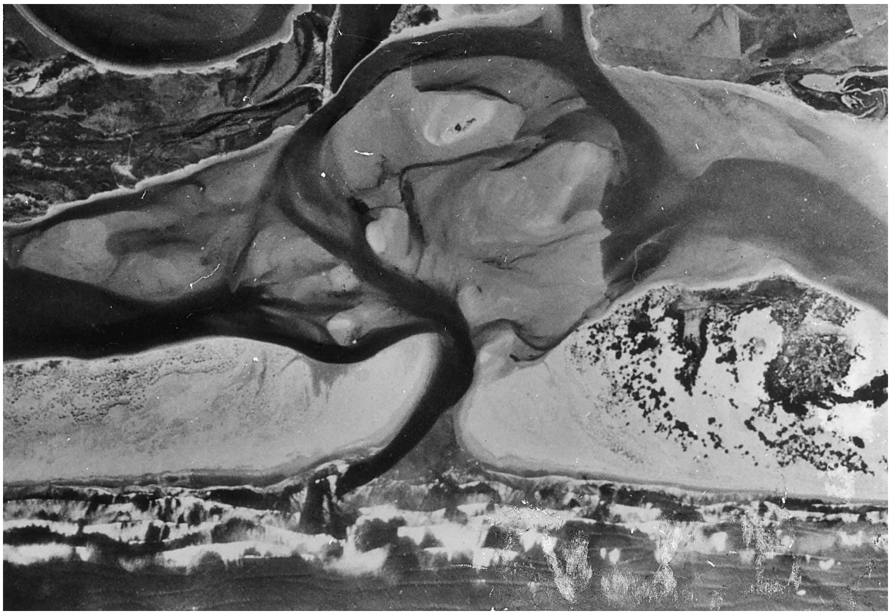

Fig. 11. Aerial photograph of the Murray Mouth showing flood tidal sedimentation in 1945, five years after barrage construction. Source: Mapland, South Australia.

consists of causeways with only a small number of discharge gates that are extremely cumbersome to operate. It is impossible to respond to rapid changes in conditions induced by wind so that this barrage is seldom used. Previously the Holmes Creek–Mundoo Channel accommodated >10% of the original total flow of the River Murray (McIntosh, 1949; Lawrie, 1939) and was the most direct route to the sea. The total flow through the system has been reduced to 25% of its previous flow, with the amount being discharged through the Mundoo Barrage being negligible. These factors have accelerated sedimentation in the channels both upstream and downstream of the barrage and have hastened the vegetation and stabilisation of the flood tidal deltaic sediments.

The barrages have dramatically reduced tidal influences in the estuary. According to Johnston (1917) the area of the estuary affected by tides was 97.3 km^2 with the tidal prism estimated at 16,900 ML. More recently, Walker (1990) calculated the spring tidal prism at 20,000 ML. Johnston (1917) noted that the tidal flux was equivalent to the average flow of river water through the mouth, so that tidal flushing could maintain the mouth during long periods of no river flow. Not surprisingly, the reduction in the tidal prism by 90% has had a dramatic impact on the size of the river mouth, which has decreased progressively in its dimensions from the time of the earliest surveys to today. Not only does the size of the mouth vary, but also its position also changes. Since the time of its reopening, following closure in 1981, the location of the mouth has migrated some 1.6 km to the west, extending the distal end of Younghusband Peninsula to protect the oceanic side of Bird Island from waves and surges entering the lagoon through the Murray Mouth. Consequently, Bird Island is sheltered by both Mundoo barrage and Younghusband Peninsula, favouring the accumulation and stabilisation of even more sediments.

In addition to river and tidal flows, storm surges also maintain the mouth. During the mouth closure of 1981 a new channel was cut by a storm surge but the channel rapidly silted up as quieter meteorological conditions returned. The importance of storm surges in maintaining the mouth was demonstrated by Chappell (1991), who reported only 28 storms capable of moving sand at the mouth during the seven months prior to mouth closure, in comparison with an average of 44 storms for similar periods during his 1940–1990 study. Periods when the mouth threatens to close have

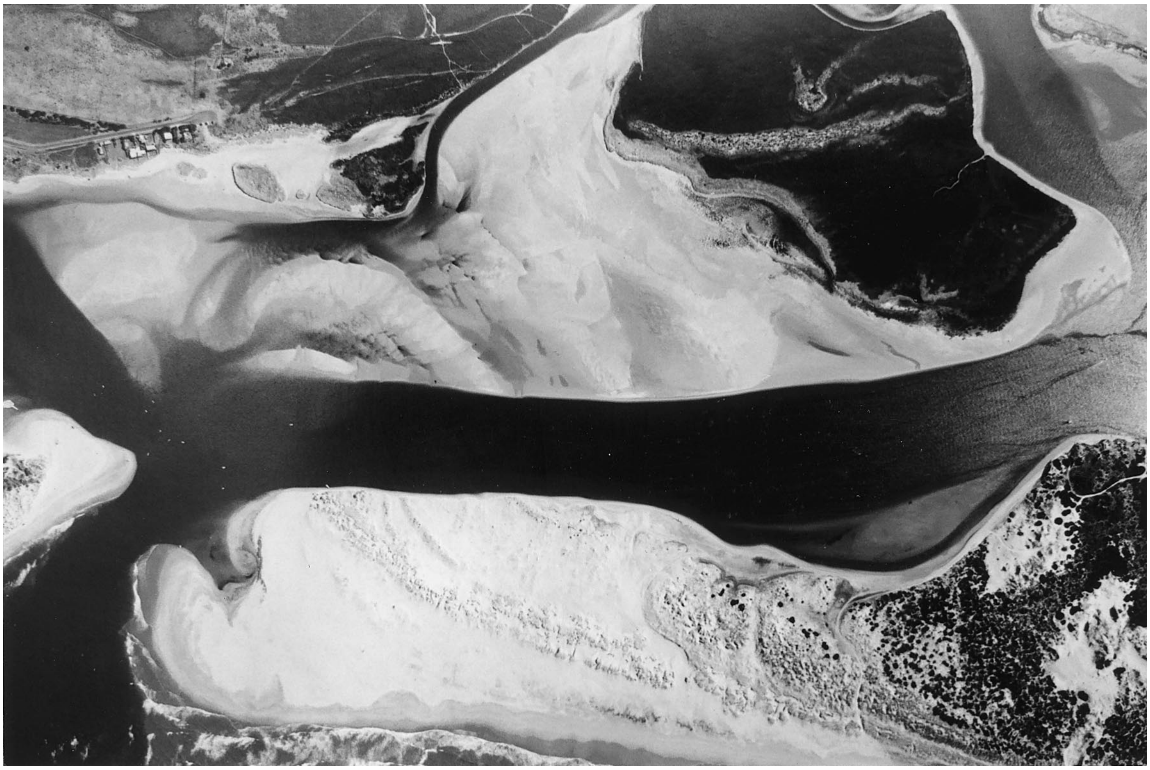

Fig. 12. Aerial photograph of the Murray Mouth area taken in the 1990s indicating the build up of the flood tidal sediments and their stabilisation by vegetation. Note the change in the position of the Murray Mouth compared with Fig. 11. Source: Mapland, South Australia.

been associated with decreasing tidal amplitudes downstream of the barrages (Harvey, 1996).

Accelerated human-induced coastal changes at the mouth of the River Murray include the rapid accumulation and consolidation of flood tidal deltaic sediments (Bird Island) and the rapid formation and vegetation of sand dunes (Fig. 13). These changes are documented at an annual to decadal rate and they produce landforms and sediments that facilitate the recognition and explanation of older features in the landscape that developed at century to millennium rates. For example, former flood tidal deltas, analogues of the recently formed Bird Island, can be recognised well beyond the historical range of fluctuation in the position of the Murray Mouth. Moreover, during the 1.6 km migration of the Murray Mouth from the time of its artificial re-opening in 1981 after closure, sand swept into the back-barrier lagoon by flood tides formed exposed shoals that were deflated to develop dunes that formed and were vegetated within a 12 month period. Apparently anomalous dunes occur on the landward side of the back-barrier lagoon on the south coast of Hindmarsh Island over a 3 km zone. These Holocene dunes have no present sandy beach source. Thermoluminescence dating reveals that they developed after the major barrier systems of Sir Richard and Younghusband Peninsula, and they almost certainly formed during migrations of the Murray Mouth when the opening was much larger than at present. Furthermore, the distribution of Aboriginal middens on Sir Richard Peninsula supports this interpretation. The middens only occur on the proximal half of the Peninsula, suggesting that former mouth migrations destroyed any middens that were present, with the current distal half of Sir Richard Peninsula reforming as the mouth migrated back to the southeast (Bourman and Murray-Wallace, 1991). Many of the middens date at 2000 to 3000 yr BP (Bourman and Murray-Wallace, 1991), the extremes of Holocene migration of the Murray

Fig. 13. Bird Island and the Murray Mouth during the closure of the mouth in 1981. The island is now vegetated by some 70 different plant species, and has a highest point of 5 m, well above the level of the highest recorded flood in the area. Source: Mapland, South Australia.

Mouth are marked by former flood tidal sediments, and the dunes on the landward side of the back barrier lagoon also occur between these extremes. Thus, the geomorphological development of the southern shore of Hindmarsh Island over the past 3000 yr is reflected in modern, accelerated changes, which first gave the clues to such an interpretation.

8.3. *Effects of artificially raised lake levels*

Following construction of the barrage system, the impounded freshwater lakes were held at a level 0.75 m higher than the natural level (McIntosh, 1949). This artificially elevated level has had several geomorphological impacts. In sheltered areas, prograding shorelines have developed, assisted by the prolific growth of freshwater reeds and rushes. In exposed localities, especially where the Holocene sand flat with its clay rich horizon overlying unconsolidated sand occurs, accelerated shoreline erosion is prevalent. This effect has increased the rate of sedimentation in the lakes and there has also been a change in the character of the sediments deposited. Raised water table levels associated with the elevated lake level has increased salinity in depressions and blocked drainage channels.

A significant geomorphological impact of river and lake level regulation is the accelerated shoreline erosion in exposed localities at rates of up to 12 m yr^{-1}, with an average of 1 m yr^{-1} (McCord, 1979; Coulter, 1992). On exposed coasts shoreline erosion is especially marked on areas where clays overlie sand. Wherever this happens, the rate of shoreline erosion does not appear to be slowing down as might be expected with movement towards a new equilibrium condition. There appears to be little to do but to protect the shoreline from erosion by physical means and mask by fencing off stock and planting reeds and rushes. Recent shoreline erosion has accelerated sedimentation and deterioration in water quality. An estimated 595,000 tonnes of salt are deposited in the lakes every year with the costs of land and production losses since barrage construction being \$4.2 million (1992 \$) (Coulter, 1992). Lakeshore erosion occurred prior to barrage construction, especially under flood and storm conditions such as in 1956 when there were wind-generated lake setups, which create multiple swash levels. Noye (1973) and Noye and Walsh (1976) observed a wind-generated lake setup of 600 mm over two hours in the Coorong Lagoon. Few advantages would be achieved by now dropping the artificially elevated lake levels as the eroding shorelines have steep drop offs of up to 1 m, so the shoreline would probably continue to erode in vulnerable geological sites. Under pre-barrage conditions wind-generated lake setup and waves caused lakeshore erosion, but these erosional events were more sporadic than at present.

On the sheltered coasts where there is no wind generated lake setup the shorelines have actively prograded where the colonisation of freshwater reeds and rushes have trapped sediments. Vegetated digitate deltas have formed where small streams enter the lakes and sandy spits have also formed on the sheltered sides of the lakes (Gloster, 1998).

8.4. Changes in lake sedimentation

The amount of quartzose clastic sediment reaching the coast may have been greater in the past. Sprigg (1952) attributed higher quartzose contents in beach sediments near the Murray Mouth to former terrestrial sediment inputs from the river. Certainly, the construction of dams and weirs higher up the river system has cut off the supply of coarser sediments to the coast (Thoms and Walker, 1992, 1993), but it is doubtful if there were vast supplies of coarse sediment to the coast from the river during the Holocene. The character of the Holocene sediments does not suggest this, and Johnston (1917) reported mainly fine, clay-sized materials carried in suspension as the stream load prior to the completion of the regulatory structures along the river. The quartzose sediments near the estuary could have been derived from the Last Glacial Maximum quartzose dunes that prevailed in the area and probably on the continental shelf prior to the post-glacial marine transgression.

Barnett (1993, 1994, 1995) noted an acceleration in the sedimentation rate in Lake Alexandrina over the past 100 yr and attributed it partly to accelerated lakeshore erosion. The long term rate of sedimentation (millennium scale) was established at 0.5 mm yr^{-1} whereas the shorter term (decadal) rate was 1.7 mm yr^{-1}. The accelerated sedimentation rate has been accompanied by minor increases in organic carbon, total phosphorous and copper. Furthermore, there has been a change in the character of the sediments upstream of the barrages with a change from bioclastic sands to muds at a rate of 4.5 mm yr^{-1} over past 50 yr.

8.5. Migrations of the Murray Mouth

The position of the Murray Mouth is constantly changing and very rapid migrations of the mouth of the River Murray have been noted (Figs. 14 and 15). The position of the Murray Mouth is extremely dynamic, migrating over 1.6 km since 1837 when the first survey of the mouth was undertaken. Movements of 14 m in 12 h have been observed. Even greater migrations of up to 6 km over the past 3000 yr are suggested by the ages and distributions of Aboriginal middens on Sir Richard Peninsula BP (Bourman and Murray-Wallace, 1991). The migration of the mouth has geomorphological implications in that flood tidal deltaic sediments are placed in a shadow from wave action, become stabilised and vegetated. Furthermore, as the mouth migrates the focus of wave attack through the mouth changes and erosion occurs on the landward side of the lagoon, with the eroded sediments being deposited in the shadow area, where dunes may form. Waves entering through the Murray Mouth have occasionally been noted to reflect from the south shore of Hindmarsh Island and to erode the landward side of the coastal barrier. Harvey (1996) calculated erosion of the distal end of Sir Richard Peninsula at an average rate of 80 m a year since 1981, causing an estimated loss of 45 ha of vegetated dunes and about 3×10^6 m^3 of sediment.

8.6. Storm-generated ephemeral transverse sand ridges

Current aeolian processes are important. Storm-generated ephemeral transverse sand ridges (Fig. 16), with a wavelength of 20 m and an amplitude of 30 cm, have been observed along Sir Richard

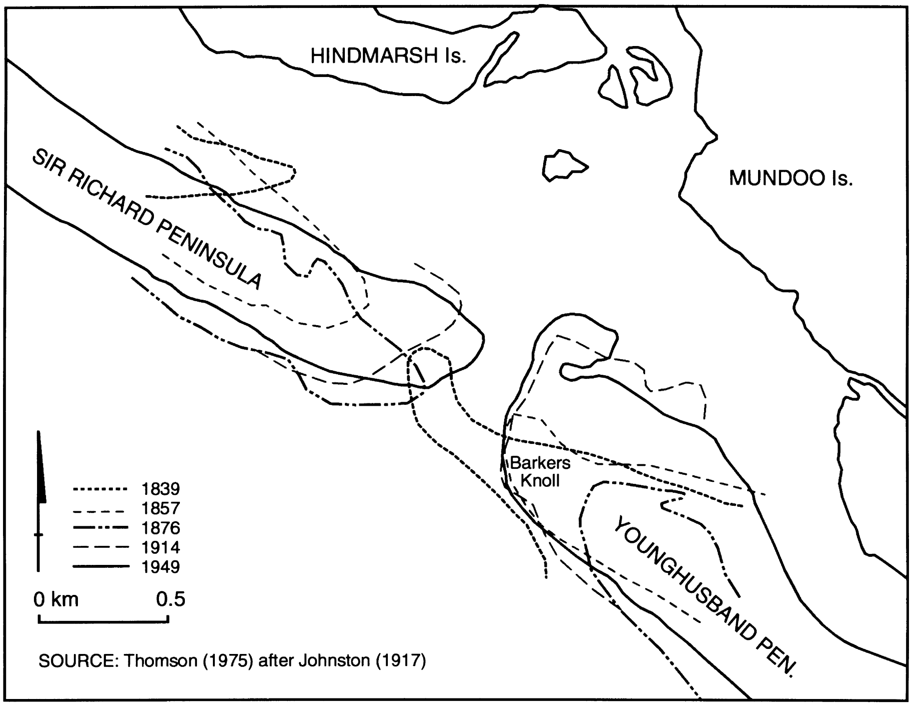

Fig. 14. Map showing migrations of the Murray Mouth between 1839 and 1949. Source: Thomson, 1975.

Peninsula, when, during wind speeds of 45 km hr^{-1}, 5000 m^3 of beach sediments were in transit along the 10 km long sand spit (Bourman, 1986). Although it would be extremely fortuitous for these ephemeral features to be preserved in the geological record, this possibility should not be dismissed.

Under conditions of high winds transverse to the shoreline, shells have been observed to have blown to elevations of 50 m, and may even be transported across the barrier system from the open ocean beach to the back-barrier lagoon. Accelerated sedimentation of the Goolwa and Coorong Channels by aeolian coastal sands has also occurred, and in some locations along Younghusband Peninsula, aeolian sands are currently spilling into the waters of the Coorong (Bourman and Barnett, 1995), altering the character of the sedimentary deposits. Johnston (1917) attributed the shallow Goolwa Channel downstream from Reedy Island to sand dune encroachment from Sir Richard Peninsula. This process was hastened by European impacts on the modern beach/dune system due to introduction of rabbits, grazing of introduced stock, use of Off-Road-Recreational-Vehicles (ORRV's). Records of early explorers, however, suggest that some of the dunes of Younghusband Peninsula were mobile prior to European impact (Bourman, 1974). These were either natural or enhanced by Aboriginal occupancy. In some localities there are Aboriginal shell middens some around 3000 yr old (2900 ± 60 BP, Wk 5824) that are associated with extensive rhizoliths indicating that some areas of bare drifting sand were formerly quite densely vegetated, and some middens have been covered by dunes and are only now being exhumed.

Although there are still considerable areas of drifting sand on the barriers, since barrage construction was completed in 1940, the activities of stock and rabbits have been restricted and revegetation of drift areas was undertaken, so that the dunes are more stable now than they were some 50 yr ago. Nevertheless, other influences such as the growing use of ORRV's have many impacts on dune and beach stability (Gilbertson, 1981). They flatten beaches, remove sand from them and render them more susceptible to erosion. They destroy vegetation in dunes and along the toes of foredunes during high

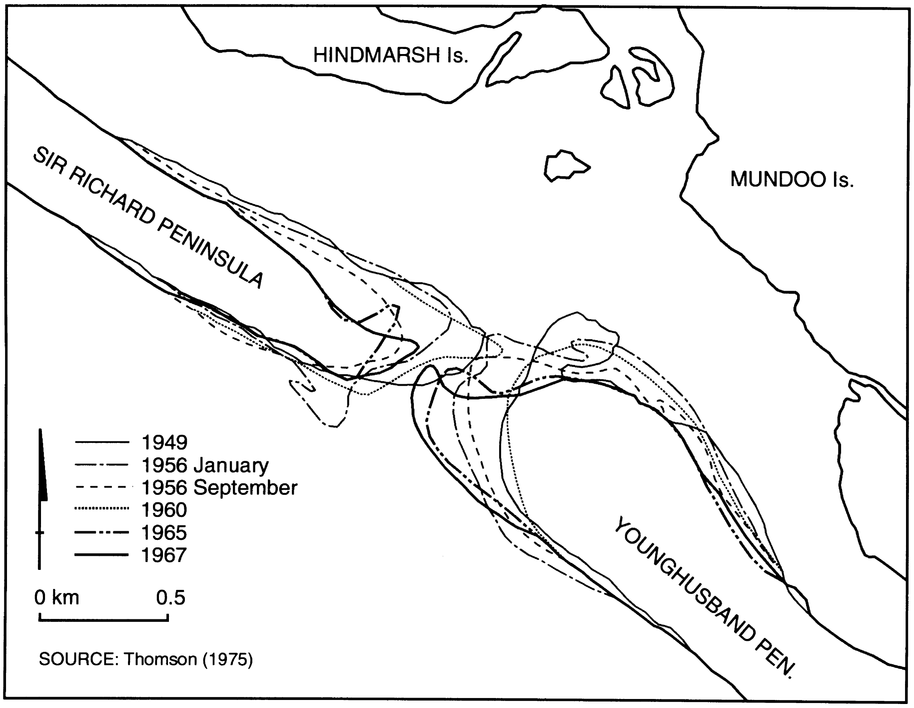

Fig. 15. Map showing migrations of the Murray Mouth between 1949 and 1967. Source: Thomson, 1975.

tide travel, accelerating sand drift. Paton (pers. comm., 1998) also suggests that they break the salt crust on sandy beaches, which renders them more susceptible to deflation.

9. Summary

Despite being sited in one of the most stable land masses in the world the estuary of the River Murray displays some dramatic examples of rapid coastal change during the Quaternary. The most rapid changes have occurred where Europeans have impacted either directly or indirectly on the landscape. These accelerated changes have been useful in that they have led to the rapid development of landforms which has facilitated the recognition and interpretation of features formed earlier in the Quaternary.

Within the region of the River Murray Estuary there is a classic record of Quaternary sea-level fluctuations and the last interglacial shoreline, the age of which has been verified by amino acid racemisation dating techniques, is traceable over almost 400 km. By close attention to critical sea-level indicators preserved in the last interglacial deposits this shoreline presents clear evidence of ongoing tectonism in the Late Quaternary, at maximum rates of $0.14\ \mathrm{mm\ yr^{-1}}$. Rapid coastal erosion along the Middleton and Goolwa coasts, initiated around the year 1900, may well be related to this tectonism as the area was affected by several large earthquakes about this time.

The modern coastal barriers of Sir Richard and Younghusband Peninsulas formed quite rapidly, in the last 7000 yr, which is probably a comparable time for formation of the last interglacial barrier. There is clear evidence of the landward migration of the barriers during the Holocene, as back-barrier lagoonal materials are sporadically exposed on the ocean beach, and differential loading of the soft back barrier sediments by the advancing barrier dunes has caused soft sediment deformation including vertical displacement.

Evidence of the migration of the Murray Mouth over distances of some 6 km in the past 3000 yr is based on the ages and distributions of Aboriginal

Fig. 16. Photograph of ephemeral storm-generated transverse ridges, with a wavelength of 20 m and an amplitude of 30 cm, on Sir Richard Peninsula.

middens on the barriers, as well as on the identification of fossil flood tidal deltas at the migration extremities and on the occurrence and distribution of coastal dunes on the landward side of the back-barrier lagoon. These dunes formed during the migration of the mouth. Similar identifiable features have formed in the past 168 yr of European records, partly accelerated by human impacts. In particular, a flood tidal delta has formed and become stabilised by vegetation (Bird Island) in the past 40 yr, since the barrage system across the lower part of the River Murray Estuary was completed in 1940. Some smaller vegetated shoals have already been fused onto the southern shore of Hindmarsh Island, and the prognosis is that the same will occur with Bird Island.

Other human impacts related to river regulation include both accelerated erosion and sedimentation in favourable sections of the former estuary that is now largely two major freshwater lakes with artificially elevated water levels. River regulation has also impacted on the rates of lake sedimentation and altered the character of the sediments. There has been an increase in sedimentation and the deposition of finer grained material. Climate and global sea-level variations throughout the Pleistocene and the Holocene have resulted in the formation of dunes of differing compositions and characters.

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reproduced with permission of the Department of Environment, Heritage and Aboriginal Affairs, Resource Information Division, MAPLAND, 300 Richmond Road, Netley, South Australia 5037, Telephone 61 + 8-8226-4946.

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