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Geomorphic Evolution of a Holocene Beach-Ridge Complex, LeFevre Peninsula, South Australia[1]

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ABSTRACT

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Intensive drilling and radiocarbon dating are used to interpret the Holocene evolution of LeFevre Peninsula, located on the eastern shore of Gulf St. Vincent, South Australia. This beach-ridge complex is in a low to medium energy environment where longshore sediment drift is dominant. Sedimentation commenced at the end of the Postglacial Marine Transgression around 7,500 calendar yrs BP, indicating a similar sea level history to east Australian coastal barriers. A major sediment pulse between 7,500 and 5,500 yrs BP produced a rapid northward progradation of the regressive lithofacies. After 5,500 yrs a reduced rate of sediment supply and a change in coastline orientation contributed to spit recurvature and a flared beach-ridge pattern. The longshore spit progradation and shore parallel backbarrier facies of LeFevre Peninsula contrast with the shore-normal development of east Australian barriers which tend to block bedrock embayments and constrain backbarrier sedimentation.

ADDITIONAL INDEX WORDS: *Beach ridges, coastal geomorphology, coastal progradation, longshore transport, radiocarbon dating, sand barrier, South Australia, spits.*

INTRODUCTION

In Australia there have been numerous morphological studies of coastal sand barriers (including beach-ridge plains) over the past three decades, but it is only since 1970 that a more detailed understanding of barrier age structure and morphostratigraphy have been achieved by drilling and radiometric dating. Most of these studies have been carried out in the medium to high energy environments of eastern Australia, where barrier progradation has been shore-normal and longshore drift relatively insignificant (THOM *et al.*, 1981a,b).

In contrast, the present study of LeFevre Peninsula, South Australia (Figure 1), provides a unique opportunity for a study of the geomorphic development of a beach-ridge complex where longshore transport has been the dominant component in sediment accumulation. The site also provides a valuable opportunity to test the applicability of an intensive drilling and radiocarbon dating program in a low to medium energy environment, as opposed to previous studies in higher energy coastal environments where problems have been experienced with reworking of older deposits to give anomalously old radiocarbon dates.

This paper presents information obtained from six transects consisting of over forty boreholes and one hundred radiocarbon age determinations from an area of 18.7 square kilometres. The study is therefore probably the most intensive of its kind in the southern hemisphere.

ENVIRONMENTAL SETTING

LeFevre Peninsula is the northernmost sediment sink on the present metropolitan coast of Adelaide, South Australia (Figure 1). Prior to settlement on

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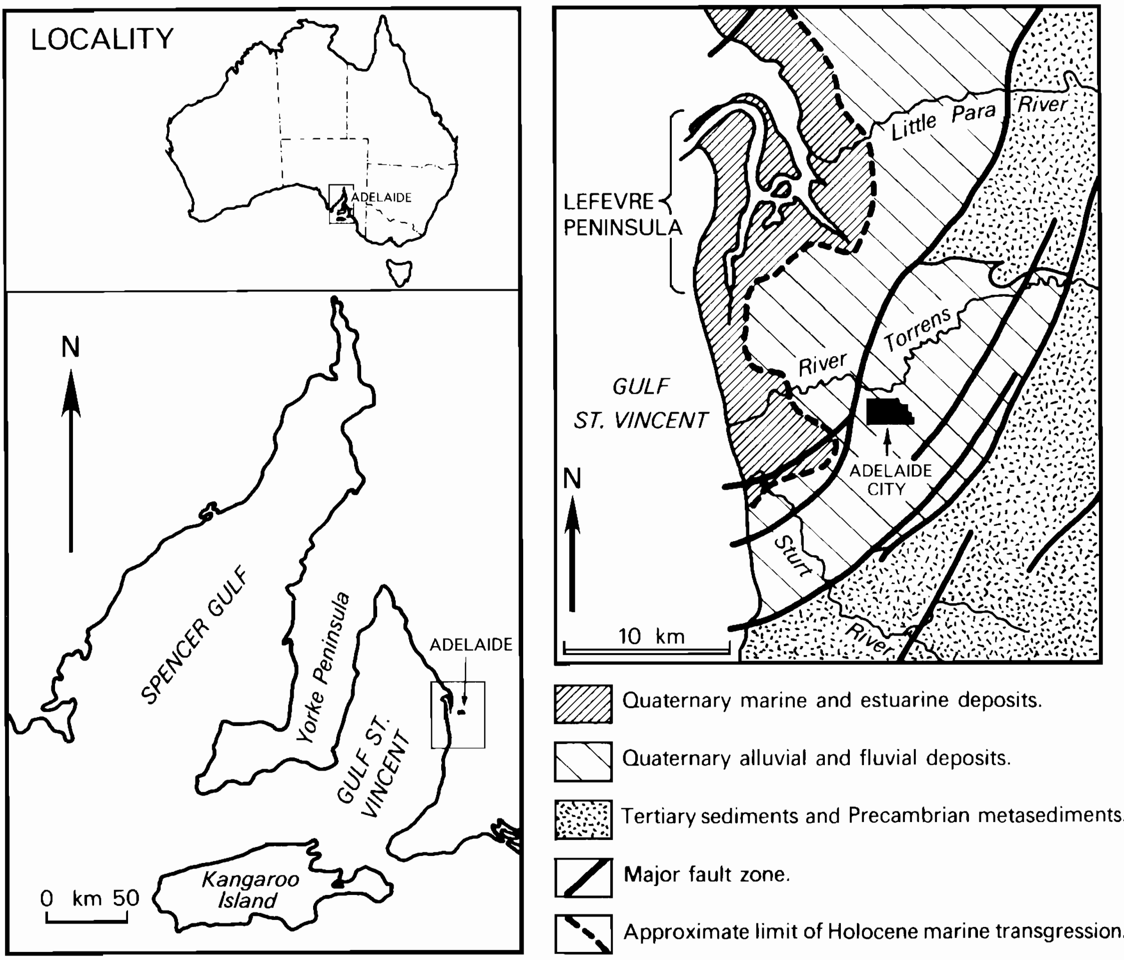

Figure 1. Location map and geological setting: LeFevre Peninsula, South Australia.

the peninsula clearly defined ridges and spits were visible which bifurcated and recurved to the east. At the southern end the ridges coalesced into a single frontal dune, while on the eastern side back-barrier marshes, mangrove swamps and supratidal deposits were associated with the estuary of the Port River (Figure 2). There has been extensive residential and industrial development on LeFevre Peninsula. The original northern shoreline was extended up to 1 kilometer by land reclamation to form Outer Harbor and the Port River now flows into Gulf St. Vincent through artificial breakwaters at the northern end of the peninsula (Figure 1). Subsequently, part of this area was developed as a marina and housing complex. Further reclamation on the northern and eastern sides of the peninsula has altered the position of the shoreline, obliterated much of the surface morphology of the beach-ridge complex, covered backbarrier and estuarine deposits, and removed the mangrove swamps. It is within this context that the present study took place.

The landform pattern of the Adelaide region has resulted from a series of arcuate northeast to southwest trending faults (see Figure 1), between which large blocks of mostly Precambrian rocks have been either uplifted or have subsided to form such features as the Mt. Lofty Ranges and Gulf St. Vincent (FENNER, 1930). LeFevre Peninsula forms part of the Adelaide coastline and is located on the eastern

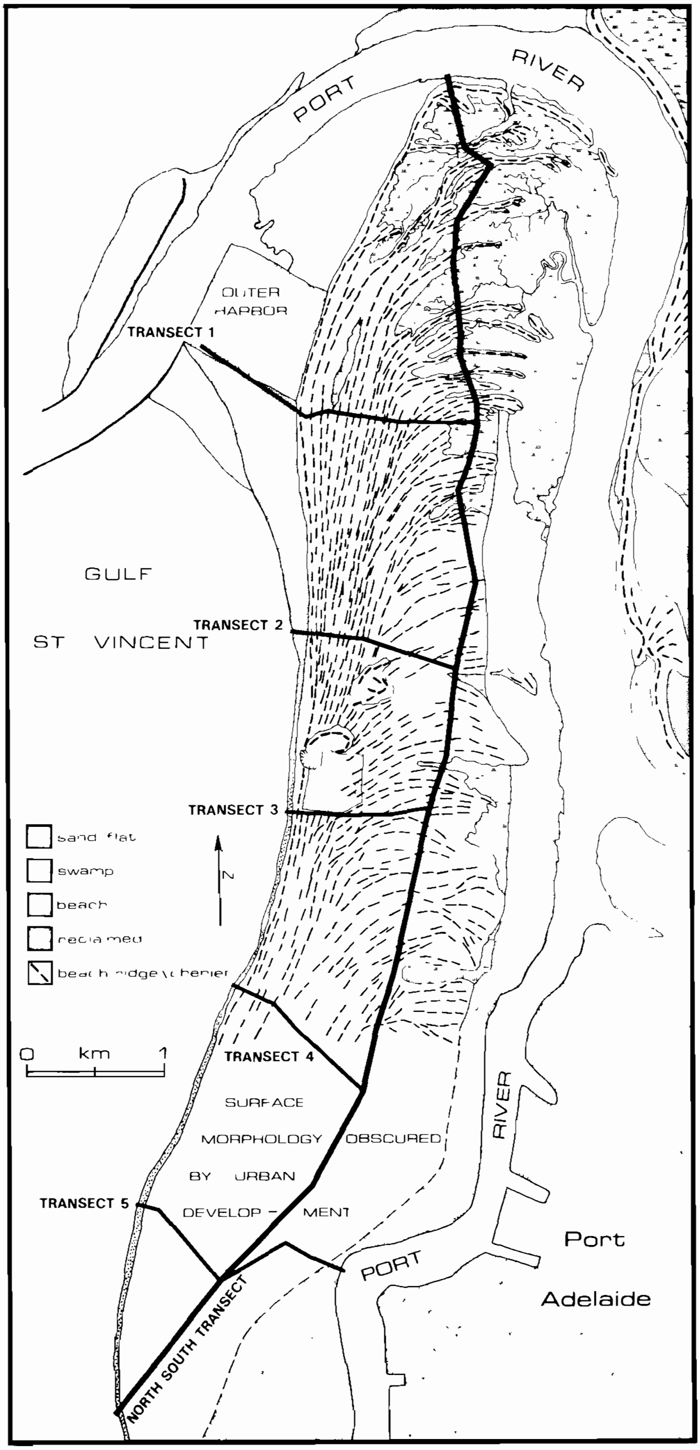

Figure 2. Geomorphology and transect location: LeFevre Peninsula.

margin of the flooded Gulf St. Vincent graben. The peninsula consists of marine and estuarine Quaternary sediments, beneath which lies a thick sequence of Tertiary strata over a Permian and Precambrian basement (DAILY *et al.*, 1976).

Gulf St. Vincent was periodically flooded by the fluctuating Quaternary sea. At the maximum of the Last Glaciation, about 18,000 years ago, sea level was well over one hundred meters below the present level, the Gulf was dry and the coastline was located well south of Kangaroo Island (VON DER BORCH, 1979). Subsequently, sea level rose rapidly, flooding Gulf St. Vincent and Spencer Gulf, to reach its present level about 7,500 calendar years ago. At that time the present position of LeFevre Peninsula was covered by about 8 meters of seawater with the shoreline located some kilometers to the east (Figure 1). The sediment reworked from the Gulf floor by the marine transgression accumulated along the present Adelaide coastline as a belt of subparallel linear dunes forming a sand barrier system, up to 12 meters high and 500 meters wide (WYNNE *et al.*, 1984). Apart from the major influx of reworked sandy sediment from the floor of the gulf, there have been only minor subsequent additions from local rivers and cliff erosion (HAILS *et al.*, 1982).

Estimates of current sediment movement along the Adelaide metropolitan coast vary from around 30,000 to 80,000 m^3 yr^{-1} including a large component of seagrass (20% to 50%: CULVER, 1970; WYNNE *et al.*, 1984). However, the amount of sediment now entering the system from the south is only in the order of 5,000 to 10,000 m^3 yr^{-1} (WYNNE *et al.*, 1984). The net movement of sand (*i.e.* between 30,000 and 80,000 m^3 yr^{-1}) in a northerly direction is in response to the predominant longshore drift component, which results from a south-westerly wave approach throughout most of the year (CULVER and WALKER, 1983). Although the periodicity of these waves is usually 2.5-4 seconds, most wave energy reaching the coast is provided by waves with periods of 5-6 seconds (WYNNE *et al.*, 1984).

Northward drift prevails, even in years with anomalous wind directions (such as 1956 when winds and waves from the north-west predominated) because of the effects on north-westerly waves of variable fetch and bathymetry (BYE, 1976). The result has been the northward accretion of LeFevre Peninsula, which has acted as the main sediment sink for this section of coast since the end of the last Postglacial Marine Transgression.

Large storm waves are comparatively rare on the Adelaide coast: wave heights of 0.5 m occur about half the time, but waves over 1.5 m occur only 6% of the time (WYNNE *et al.*, 1984). However, the occasional higher energy wave event approaching from the north-west is important in sediment reworking and accretion on LeFevre Peninsula, as these waves can move sediment out of the dominant northerly drift stream and into the recurved spits.

Astronomical tides in Gulf St. Vincent are semidiurnal with a tidal range of up to 2.5 m and are thought to cause significant tidal current movement (WYNNE *et al.*, 1984; BYE, 1976). However, storm surges can raise water levels up to 1.5 m above the normal astronomical tide level and may be an important factor in controlling the elevation of storm deposits. In addition, it has been claimed that there is evidence for relative sea level rise in the area over the last 100 years of between 2.4 mm yr^{-1} (CULVER, 1970) and 1.5 mm yr^{-1} (WYNNE *et al.*, 1984). This should be viewed in the context of reported subsidence of the local area (TALBOT, 1982; SAINSBURY, 1981) and in the broader context of Holocene sea level change for the region. BELPERIO *et al.* (1983) found no evidence to support the claims for higher mid-Holocene sea levels reported in the local literature and maintained that the lack of elevated strata argues against any such higher Holocene sea level. They also suggested that the slightly lower samphire facies reported from eastern Gulf St. Vincent shores may support the reports of subsidence in the area.

Settlement has now largely covered the Adelaide coastal plain and residential development, road construction and recreational facilities have virtually tied-up all the available dune sand in the Adelaide metropolitan beach system. As a result of the northerly longshore drift there is currently a management problem, with net loss on the southern beaches and a net gain on LeFevre Peninsula. Thus the series of beach ridges and recurved spits forming LeFevre Peninsula represent the pattern of accretion and provide evidence of the rate of accretion and the manner in which it took place during the mid- to late-Holocene.

In contrast to previous studies of the Adelaide coast which concentrated on current rates of sediment movement, the present investigation was concerned with very long term trends in sediment accumulation. The implications of these trends for coastal erosion management will be published elsewhere (HARVEY and BOWMAN, in prep.), as will details of the radiocarbon analyses and derivation of the age structure of the peninsula (BOWMAN, HARVEY and LEANEY, in prep.).

PREVIOUS STUDIES

The morphology and stratigraphy of Holocene strandline depositional sequences varies globally with contrasting relative sea level histories, superimposed on local depositional processes (CLARK *et al.*, 1978). THOM *et al.* (1978) provide a review of the major northern hemisphere studies of barrier deposits and conclude that there have been few detailed morphostratigraphic studies of Holocene sand barriers employing radiocarbon dating of incorporated shell or organic material. Of these the more important are from Holland where VAN STRAATEN (1965) dated coastal peats; from the US Gulf Coast where FISK (1959), LE BLANC and HODGSON (1959), SHEPARD (1960), BERNARD, LE BLANC and MAJOR (1962) and BERNARD and LE BLANC (1965) dated shell material; and from Mexico where CURRAY *et al.* (1969) dated both shell and peats to document the evolution of the extensive beach-ridge plain at Nayarit.

Detailed drilling and dating studies of barrier islands on the east and Gulf coasts of the USA include the early work of KRAFT (1971) and KRAFT, BIGGS and HALSEY (1973) and later studies by BELKNAP and KRAFT (1977), MOSLOW and HERON (1978), OTVOS (1978), KRAFT and JOHN (1979), MOSLOW and COLQUHOUN (1981) and RAMPINO and SANDERS (1981). More recently, a special volume of *Marine Geology* has been devoted to the theme of barrier island development (OERTEL and LEATHERMAN, 1985).

In south-eastern Australia detailed coastal barrier studies include those of SHEPHERD (1970), THOM (1974, 1984a, b), LY (1976), THOM, POLACH and BOWMAN (1978), BOWMAN (1979), ROY, THOM and WRIGHT (1980), THOM *et al.* (1981a, b), THOM, BOWMAN and ROY (1981), and THOMPSON and BOWMAN (1984). In northern Australia COOK and POLACH (1973), SMART (1976), CLARK, WASSON and WILLIAMS (1979), RHODES *et al.* (1980), RHODES (1982), FLOOD (1983) and CHAPPELL and GRINDROD (1984) have carried out similar work. JENNINGS and COVENTRY (1973), SHEPHERD (1981) and WOODS and SEARLE (1983) have provided Western Australian examples.

In South Australia a preliminary analysis of a Holocene beach-ridge sequence at Guichen Bay in the southeast was reported in THOM *et al.* (1981a), while in Spencer Gulf HAILS and GOSTIN (1978), GOSTIN, HAILS and POLACH (1981), BURNE (1982), BELPERIO, HAILS and GOSTIN (1983) and HAILS, BELPERIO and GOSTIN (1983) have used dating and drilling of coastal beach ridges as part of their Quaternary sea level and sedimentation investigations.

Of all the above Australian coastal studies those by Thom and his co-workers have used stratigraphic drilling and radiocarbon dating most extensively. However, for the size of the barrier complex, the present study has established by far the most detailed dating framework of any Australian investigation published to date.

METHODOLOGY

The pattern of sand ridges and recurved spits on LeFevre Peninsula and the distribution of surficial sedimentary units were mapped from 1949 monochrome and 1980 natural colour aerial photographs, supplemented by field observations (see Figure 2).

Subsurface information about the stratigraphy and age structure of the peninsula was obtained from 44 drillholes, located along a main north-south transect and five intersecting east-west transects (see Figure 2). This configuration of drillholes was chosen so as to economically yield the maximum amount of information about the three-dimensional age structure and stratigraphy of the peninsula, with the east-west transects providing cross-sections of the north-south trending sand ridges, and the main transect cutting across the recurved spits. However, the actual location of drill sites was usually determined by residential and industrial development, and at a few localities it was necessary to drill through several meters of fill to reach the underlying sediments.

Hydraulically driven thin-walled pushtubes were used to obtain undisturbed near-surface samples of some muddy backbarrier sediments, but otherwise a power auger drilling technique developed by THOM, POLACH and BOWMAN (1978) was employed for lithofacies identification (Figure 4). This incremental technique yielded uncontaminated but disturbed samples, most of which were field sieved to obtain whole shells, coarse shell hash or seagrass fibre/organics for radiocarbon dating.

Shell samples consisted of nearshore marine and estuarine species, dominated by *Katelysia*, *Cominella*, *Niotha*, *Batillaria*, *Amesodesma*, *Tellina* and *Spisula* (LUDBROOK, 1984). *Posidonia australis*, *Amphibolis antarctica*, *Heterozostera tasmanica* and *Halophila ovalis* were the seagrass species recognized (SHEPHERD and SPRIGG, 1976), but most seagrass material was heavily decayed and homogenized to a colloidal organic gel.

Radiocarbon analyses were carried out in the

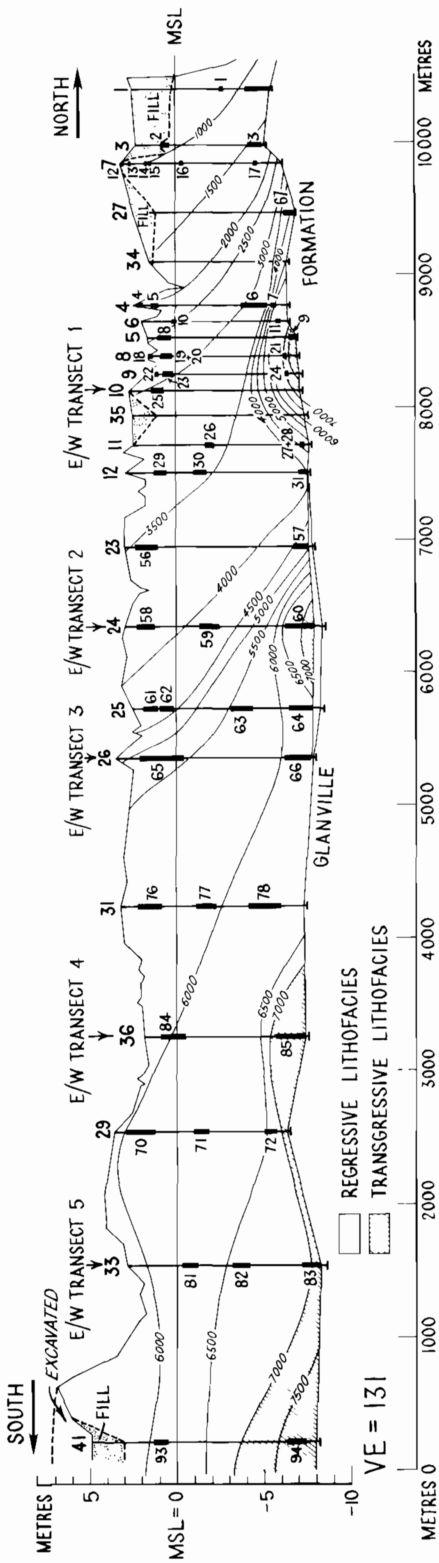

Figure 3. North-south cross-section: LeFevre Peninsula.

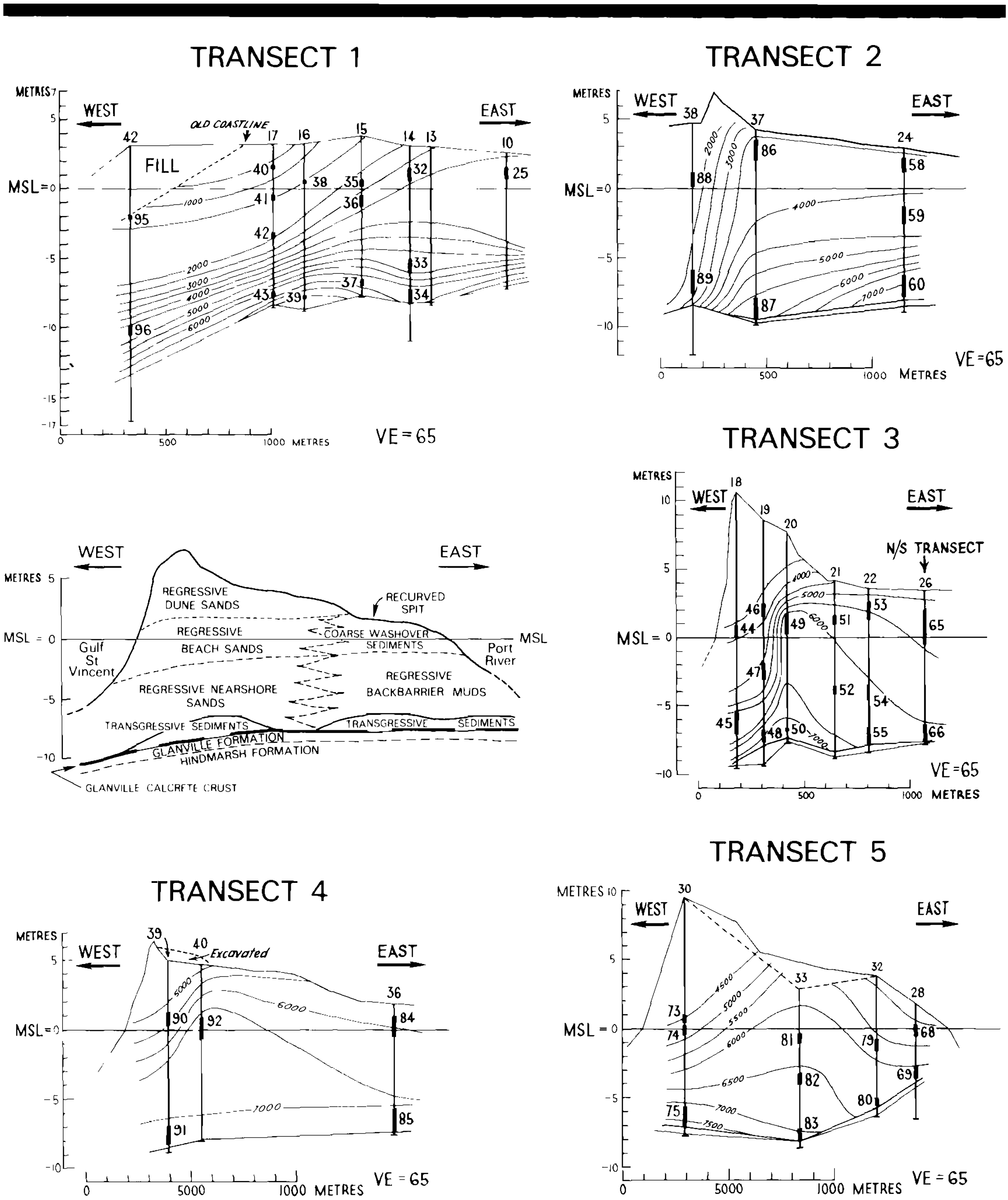

Figure 4. East-west cross-sections: LeFevre Peninsula.

CSIRO Division of Soils, Radiocarbon Laboratory, Adelaide. Shell samples were washed repeatedly in distilled water, crushed, and surface-etched with dilute hydrochloric acid (GILLESPIE, 1975). The residue was treated with an excess of HCl to evolve carbon dioxide for purification and conversion to benzene using standard procedures (POLACH, 1969, 1976). Seagrass material was repeatedly washed in distilled water and any adhering shell contamination was removed by hand, followed by a prolonged wash in dilute HCl. Some samples were also subject to an alkali pretreatment (BOWMAN, HARVEY and LEANEY, in prep.). The organic residue was burnt in a stream of oxygen and the resulting carbon dioxide was purified and converted to benzene as above. Where necessary because of small sample size, the CO_2 was diluted with ^{14}C-free commercial carbon dioxide.

Mass spectroscopic determinations of ^{13}C and ^{12}C abundances in the evolved CO_2 were used to derive the stable isotope ratios shown in Table 1 ($\delta^{13}C$). ^{14}C activities of the benzene samples were measured (after a three week storage to allow short-lived radioactive contaminants to decay) with a KONTRON MR300 liquid scintillation counter, using ANU Sucrose as the modern reference standard (POLACH, 1972; POLACH and KRUEGER, 1972).

Primary and $\delta^{13}C$ corrected millesimal depletion values were calculated using the standard formulae of POLACH (1969,1976) and will be reported elsewhere (BOWMAN, HARVEY and LEANEY, in prep.). The Libby ^{14}C half-life was used to derive conventional radiocarbon ages for the samples (POLACH, 1976; THOM *et al.*, 1981a) with one standard deviation error terms, as indicated in Table 1.

To enable calibration of these marine radiocarbon ages to calendar years it was necessary to compensate for the depletion of ^{14}C in the ocean relative to the land, by subtraction of an appropriate oceanic reservoir correction (ORC) (MANGERUD, 1972; BOWMAN and HARVEY, 1983). Although an average figure of 450±35 years has been proposed for the entire Australian coastline by GILLESPIE and POLACH (1979), a more reliably based and more appropriate value has been established for the southern Australian coast by BOWMAN (1985). Hence, 480±30 years was deducted from each *shell* radiocarbon age.

However, the correction was not applied to the seagrass dates as evidence exists that seagrass is unique amongst aquatic plants in its methods of carbon uptake, and hence not in ^{14}C equilibrium with the marine environment (MCROY and MCMILLAN, 1980; PARKER, 1964). Seagrass may derive carbon from atmospheric CO_2 dissolved in seawater, rather than from marine bicarbonate, and therefore could be in at least partial equilibrium with ^{14}C in the atmosphere. Although the $\delta^{13}C$ values for the seagrass samples in Table 1 are within the usual range for marine plants (POLACH, 1976, Figure 4), the values are generally lower than the $\delta^{13}C$ analyses of BELPERIO *et al.* (1984) for seagrass from Upper Spencer Gulf and do suggest a terrestrial influence.

Both the oceanic reservoir corrected shell ages and the uncorrected seagrass ages were calibrated to calendar years using the tables of KLEIN *et al.* (1982). This calibration was necessary to avoid using the non-linear radiocarbon time-scale when making calculations of rates of sediment accumulation (THOM *et al.* 1981a,b). However, as the KLEIN *et al.* calibration tables yield results in calendar years AD/BC (rather than years BP) and also use 95% confidence limits (rather than a single date), a more convenient expression of the calendar age was obtained by taking the arithmetic mean of the confidence limits and expressing this in years BP. An enlarged 2σ error term was derived by halving the 95% confidence interval. This procedure does not appear to negate the calibration principles inherent in the KLEIN *et al.* tables (M. Barbetti, pers. comm.). The resulting calendar ages and 2σ error terms are reported in Table 1. Further information about analytical procedures, ^{14}C results and dating problems encountered during the study are given in BOWMAN, HARVEY and LEANEY (in prep.).

Six cross-sections of LeFevre Peninsula were drawn using stratigraphic and morphological information obtained during the drilling and during a subsequent survey of the location and elevation of the boreholes. These cross-sections correspond to the five east-west drilling transects, plus the long intersecting north-south transect (see Figures 3 and 4).

With calendar ages plotted on the cross-sections, isochrons were then drawn at 500 year intervals to reveal the age structure of the peninsula. Apart from allowing for the statistical uncertainty associated with some dates, normal isoline conventions were followed in interpolating the isochrons. In only a few locations was extrapolation necessary. However, minor stratigraphic problems arose with the inclusion of a few of the seagrass dates from the northern end of the peninsula. These dates on colloidal organic material appear to have been slightly contaminated by modern carbon circulating in the groundwater. The exclusion of these anomalous seagrass dates has had no significant effect on the deduced age structure of the peninsula. Details of the problems encountered with the seagrass analyses are given in BOWMAN, HARVEY and LEANEY (in prep.).

Table 1. ^{14}C dates derived from the samples.

Sample Number	Material	$\delta^{13}C$ ‰	^{14}C Age BP$\pm 1\sigma$	CCA† BP$\pm 2\sigma$
1	shell	1.86	1080±70	620±90
2	shell	1.69	1230±90	740±150
3	seagrass	−11.84	1580±110	1530±190
4	shell	1.51	2410±80	1910±200
5	shell	1.61	2970±110	2560±210
6	shell	2.10	3330±90	3020±270
7	shell	1.28	4830±130	5010±410
8	shell	1.70	3010±80	2580±220
9	shell	1.09	7570±110	7890±460
10	seagrass	−12.06	2150±80	2140±220
11	seagrass	−12.24	2860±110	3030±270
12	shell	2.31	1260±80	760±150
13	shell	2.12	1250±80	750±150
14	shell	2.08	1550±80	970±210
15	shell	1.97	1670±80	1130±210
16	shell	1.43	1940±80	1370±180
17	seagrass	−11.81	1610±80	1540±190
18	shell	1.68	3150±80	2800±240
19	shell	0.98	3310±80	3010±260
20	seagrass	−14.1	2350±100	2430±300
21	shell	1.93	7030±90	7440±270
22	shell	1.12	2770±80	2410±300
23	shell	1.38	3190±80	2820±240
24	shell	1.65	6930±90	7370±240
25	shell	0.83	3640±100	3360±280
26	seagrass	−12.91	3090±90	3330±270
27	fine seagrass	−9.55	2920±80	3070±280
28	coarse seagrass	−11.82	2700±90	2810±240
29	shell	0.60	3280±90	2970±230
30	seagrass	−12.20	2820±80	2980±240
31	seagrass	−11.97	3310±100	3590±240
32	shell	2.14	3230±90	2950±230
33	shell	2.03	4690±80	4800±300
34	shell	1.82	5960±100	6190±300
35	shell	1.53	3070±80	2670±290
36	shell	2.08	2800±80	2420±300
37	shell	1.60	5960±90	6190±300
38	shell	2.05	1960±70	1450±150
39	shell	1.74	7090±90	7490±280
40	shell	1.49	1070±80	610±90
41	shell	1.57	1970±80	1460±150
42	shell	2.18	2270±100	1730±210
43	shell	1.83	5960±100	6190±300
44	shell	1.43	4090±90	3960±290
45	shell	1.44	5500±100	5820±220
46	shell	2.03	3900±80	3720±210
47	shell	1.99	4630±90	4670±300
48	shell	1.40	6540±100	6950±270
49	shell	0.76	5900±90	6120±270
50	shell	0.96	6710±100	7120±230
51	shell	0.71	5460±100	5700±190
52	shell	1.98	4850±90	5070±250
53	shell	1.17	5270±90	5560±250
54	shell	2.78	4760±150	4910±400
55	shell	1.39	6080±90	6360±280
56	shell	1.37	3820±90	3610±240
57	shell	1.90	4510±120	4550±290
58	shell	1.48	3850±80	3640±250

† Calibrated Calendar Age.

Table 1. continued

Sample Number	Material	$\delta^{13}C$ ‰	^{14}C Age BP±1σ	CCA† BP±2σ
59	shell	1.76	4170±90	4140±320
60	shell	1.40	6610±80	7050±210
61	shell	1.81	4240±90	4170±310
62	shell	1.44	4420±120	4430±310
63	shell	1.90	5200±90	5430±300
64	shell	1.56	5700±90	6020±290
65	shell	1.16	5120±80	5400±310
66	shell	0.56	5650±90	5960±320
67	shell	1.32	3880±80	3700±210
68	shell	0.28	4830±90	5030±280
69	shell	0.66	5990±90	6210±290
70	shell	0.95	5890±90	6120±270
71	shell	0.67	5780±90	6090±270
72	shell	1.02	6110±100	6380±280
73	shell	1.09	4460±80	4490±340
74	shell	1.56	4600±130	4680±400
75	shell	1.55	7030±100	7440±270
76	shell	1.02	5800±90	6100±270
77	shell	1.89	5560±100	5840±230
78	shell	0.72	5460±90	5700±190
79	shell	0.60	5280±100	5560±250
80	shell	0.94	5910±100	6170±310
81	shell	0.54	5810±100	6100±270
82	shell	0.81	6320±140	6760±380
83	shell	1.99	6520±100	6940±270
84	shell	2.00	5710±220	6000±380
85	shell	1.32	6770±100	7190±260
86	shell	1.82	3790±100	3590±240
87	shell	1.66	5420±90	5600±260
88	shell	1.63	2410±80	1910±200
89	shell	2.05	2600±80	2130±220
90	shell	1.28	5150±90	5410±300
91	shell	1.08	6970±120	7400±250
92	shell	1.24	6310±100	6700±310
93	shell	1.72	5660±90	5960±320
94	shell	1.69	7370±100	7720±380
95	seagrass	−11.89	1410±80	1340±180
96	shell	1.94	4640±90	4680±310

† Calibrated Calendar Age.

RESULTS

Morphology

Although post-war residential and industrial development have substantially altered and obscured the natural morphology of LeFevre Peninsula, field inspections aided by photo interpretation and the transect surveys have allowed the following morphological observations to be made.

The peninsula consists largely of a core of multiple north-south trending beachridges, which splay out from a narrow *stationary* barrier (THOM, POLACH and BOWMAN, 1978) at the southern end and which successively recurve towards the east (see Figure 2). However, whereas the ridges tend to recurve in groups along most of the length of the peninsula, they tend to bifurcate more distinctly north of transect 1 and recurve individually towards the east. They are also separated by more extensive intertidal mudflats in this area.

Although difficult to observe on the ground, it is clearly shown by the 1949 air photos that additional ridges have been successively added to the western side of the peninsula as it prograded northwards. The new ridges obliquely abut older ones. This is particularly evident north of transect 2, as is a general shift in the orientation of the ridges before they recurve.

Reclamation of the Outer Harbor port facility in the early 1900s and subsequent containment of the Port River have resulted in a substantial accumulation of sediment on the northwestern side of the peninsula and a major alteration to its shape (see Figure 2). Similar reclamation of intertidal swamps along the eastern side has smoothed the outline of the peninsula in this area but has not resulted in additional sediment accumulation.

The elevation of the peninsula generally decreases from west to east, as indicated in the cross-sections along transects 2 to 5, but this trend is not so evident from transect 1 northwards. There is also a general decrease in elevation along LeFevre Peninsula from south to north, although this is not very obvious from the north-south cross-section (see Figure 3), as it transects mainly the lower eastern side of the peninsula.

Lithofacies

Drilling of LeFevre Peninsula allowed six generalized lithofacies to be recognized: a basal limestone crust or clay ooze; transgressive sands and gravels; nearshore shell-rich sands; well-sorted beach and aeolian sands; backbarrier organic-rich muds; and coarse sandy and shelly washover deposits (see Figure 4).

The basal unit for the study is a thin, often hard, limestone crust within the Glanville Formation (HOWCHIN, 1888). It is thought to have resulted from subaerial exposure and superficial calcretization of shell-rich sediments during glacial low sea level times and has been dated as Late Pleistocene by BELPERIO *et al.* (1984) and KIMBER and MILNES (1984). Typically, it contains *Anadara trapezia*, *Pinctara carchariarum*, *Callucina lacteola* (Tate), *Euplica bidentata*, *Mactra eximia* and the large foraminifer *Marginopora vertebralis* (LUDBROOK, 1984).

The Glanville calcrete provided a convenient limit for drilling as it is relatively horizontal and was easily recognized in most drillholes at 7 to 10 meters below mean sea level. However, a slight rise was noted in the level of the Glanville towards the northern end of the peninsula (see Figure 3) and it was also found to drop away towards the west (see Figure 4), where it is exposed on the floor of Gulf St. Vincent (HAILS *et al.*, 1982).

In some drillholes on the peninsula the Glanville calcrete was not intersected. At these sites the top of the dark greenish-grey clay that usually directly underlies the thin Glanville crust was used to recognize the Pleistocene unconformity. Where drilling penetrated this soft clay, a stiff reddish-brown clay was encountered (see Figure 4), which typically was strongly mottled and gleyed and contained patches of pedogenic carbonate. In the Adelaide area the latter formation is known as the Hindmarsh Clay (FIRMAN, 1966).

The lowest Holocene unit in the sequence (see Figure 4) consists of coarse grey sand and shells, well-rounded gravels, and reworked fragments of the Glanville Formation. The occurrence of this lithofacies is discontinuous within the peninsula; it is usually thin (<2 meters thick), and has a sharply gradational contact with the units above. Shells are predominantly nearshore species such as *Katelysia*, *Niotha* and *Cominella*. The sand is predominantly coarse-grained, quite well-sorted, with gravels and reworked pieces of Glanville calcrete concentrated near the base of the unit. This unit is interpreted as a transgressive lithofacies, deposited in a nearshore/beach environment towards the end of the Postglacial Marine Transgression (THOM, POLACH and BOWMAN, 1978).

On the western side of the peninsula, immediately above the basal transgressive unit, occurs a thick wedge of grey, shell-rich sand that coarsens upwards (see Figure 4). The sand contains abundant seagrass remains, principally decayed rhizomes of *Posidonia australia*, as well as whole shells and detrital fragments of nearshore shell species such as *Katelysia*. This lithofacies is interpreted as a regressive nearshore deposit that formed as the peninsula prograded northwards. The age structure of the unit, as revealed by the pattern of radiocarbon dates discussed below, strongly supports this interpretation.

Immediately overlying the basal Holocene transgressive sands on the eastern side of the peninsula is a thick sequence of dark brown, organic-rich muddy sands, containing a high proportion of decayed seagrass debris and organic colloids. The non-organic fraction of this unit tends to fine upwards forming a clay-rich organic ooze, interbedded with discrete layers of compressed seagrass detritus. Shells obtained from this lithofacies are primarily of estuarine fauna (LUDBROOK, 1984), although there is also a nearshore marine component with *Amesodesma*, *Cominella*, *Batillaria* and Katelysia species being common. It is proposed that the unit formed in the lee of the peninsula as a backbarrier deposit similar to the relict form described by ROY, THOM and WRIGHT (1980) from eastern Australia. The lateral junction between this backbarrier unit and the regressive nearshore sands on the western side of the peninsula is variable in its location and nature. Drilling on the Peninsula south of transect 2 showed that in this area the regressive sands are sharply differentiated from the backbarrier muds, whereas towards Pelican Point the two lithofacies interfinger and intergrade much more extensively.

The uppermost lithofacies over most of the peninsula is composed of medium to fine, well-sorted, grey to buff coloured quartz sand (see Figure 4). Sorting of the sand improves and grain size decreases, in both an upwards and an eastwards direction. Although the sand is highly calcareous throughout, it was mostly from the lower part of this unit that sufficiently coarse pieces of shell were obtained to allow radiocarbon dating (see below). The unit extends upwards from below mean sea level and forms the extensive beach and dune ridges of the peninsula, including the high foredune ridges of the western side and the composite recurved ridges along the eastern side. It does not, however, extend into the individual recurved ridges found at the northern end of the peninsula (see below). The unit is interpreted as regressive beach sediments deposited in the onshore zone as the peninsula prograded northwards, which fine upwards into a capping of aeolian dune sand, and which pass laterally into tidal channel sediments.

Prior to reclamation for industrial use, much of the eastern margin of LeFevre Peninsula was low in elevation and the backbarrier estuarine lithofacies discussed above outcropped at the surface as intertidal mangrove swamp and samphire marsh deposits. However, a distinctively different lithofacies forms the discrete recurved spits that locally overlie the backbarrier estuarine muds at the northern end of the peninsula. Trenches excavated across recurved spits near Pelican Point exposed poorly sorted coarse sands rich in whole shells, large shell pieces and coarse seagrass detritus. The unit is strongly bedded and displays typical washover sedimentary characteristics (THOM, 1984a). Details of the stratigraphy and sedimentary characteristics of the spits will be presented in BOWMAN and HARVEY (in prep.).

Stratigraphic Pattern and Age Structure

The three-dimensional age structure and the generalized stratigraphy of LeFevre Peninsula are depicted on the cross-sections in Figures 3 and 4. The excellent congruence of the isochron patterns on the north-south and east-west cross-sections probably results from the minimal reworking of sediment and shell in the relatively low energy environment of the Gulf. A major trend is also evident in the isochrons, with the deposit becoming consistently younger from south to north. The main north-south transect (see Figure 3) illustrates this trend very clearly, with the isochrons ranging from >7,000 years at the southern end of the peninsula to <1,000 years at the northern end.

The general northwards development of LeFevre Peninsula can also be traced through the successive east-west cross-sections (see Figure 4). At the southern end of the peninsula older sediments dominate, but these become less significant further northwards as the deposit becomes; (1) progressively younger, (2) encompasses a greater age range, and (3) displays a more gradational isochron pattern.

Two age discontinuities are apparent in Figure 3. Both are associated with the thin basal transgressive deposits discussed above. Ages for shell obtained from these deposits exceed 7000 calendar years (Sample numbers 9, 21, 24; Table 1). Similar ages were obtained from the transgressive unit where it was sampled in drillholes on the east-west transects and it is apparent from the isochrons (see Figure 4) that the unit is more contiguous on the western side of the peninsula than along the line of the main north-south transect.

DISCUSSION

Results of this study indicate that the postglacial transgressive sea had reached the area by 7500 calendar years BP and that initial sediment deposition incorporated some reworked Pleistocene calcrete. The timing of initial deposition is in agreement with nearby evidence of the landward extent of marine deposition at the end of the postglacial transgression (BELPERIO, HAILS and GOSTIN, 1983) and is of a similar age to comparable deposits in southeastern Australia (THOM *et al.*, 1981a; THOM and ROY, 1985).

The transgressive deposits within LeFevre Peninsula are disconformable with the overlying regressive lithofacies except at the southern end where sediment influx was continuous. The distribution of the lobes of transgressive material has been influenced by the morphology of the thin calcrete substrate. They contain some reworked basal material near the contact with the Glanville.

The major sediment accumulation is associated with a regressive lithofacies which consists of shell-rich sand and seagrass remains. This lithofacies does not contain *in situ* seagrass banks as occur in northern Spencer Gulf (BELPERIO *et al.*, 1984) where a lower energy environment permits progressive sediment build up within the seagrass banks so that subsequently they may reach mean sea level. In present day Gulf St. Vincent a number of seagrass banks occur with submarine "blowout" features, such as described by SHEPHERD and SPRIGG (1976). However, most of the seagrass in Gulf St. Vincent is in meadows rather than in massive banks and contains very little sediment above the underlying calcrete substrate (A.P. Belperio pers. comm.). Holocene sedimentation has incorporated substantial amounts of reworked seagrass within the regressive lithofacies, but subsequent decay of the seagrass component and possible contamination by modern radiocarbon have made it less satisfactory than shell for dating purposes.

At the southern end of the peninsula the formation of the high sand ridges relates to the rapid influx of sediment after 7,000 yrs BP, causing substantial northward progradation. After 5,500 yrs BP a reduced rate of sediment supply, together with the movement of sediment into an embayment, were largely responsible for the subsequent spit recurvature and flared ridge pattern on the northern part of the peninsula. The recurvature may also be related to the changed orientation of the coastline increasing the influence of northwesterly waves.

As the peninsula prograded northwards the backbarrier lithofacies accumulated in the lee of the barrier with deposition commencing under open bay conditions but becoming progressively more estuarine and muddy as marine processes became less effective. This contrasts with U.S. studies where backbarrier deposition is by overwash deposits and flood-tide delta accumulation (BOOTHROYD, FRIEDRICH and MCGINN, 1985) or by tidal delta accumulation interspersed with deposition of silt and biogenic material by estuarine processes (HOWARD and FRY, 1985). However, marsh sedimentation does occur behind some east coast U.S. barriers (KRAFT, BIGGS and HALSEY, 1973).

The northward progradation of LeFevre Peninsula progressively diverted the mouth of the Port River until it reached its present position. This contrasts with east coast Australian studies where barrier development has blocked embayments and restricted the area of backbarrier deposition (ROY, 1984).

The sediment data are represented spatially (Figure 5) to show the pattern of sediment age at mean sea level. This diagram demonstrates clearly the major influx of sediment between 7000 and 5,500 yrs BP and the subsequent decrease in sediment supply and recurvature to the northeast. The contrast between the series of low ridges in the north and the single barrier further south is related to these changes in sedimentation.

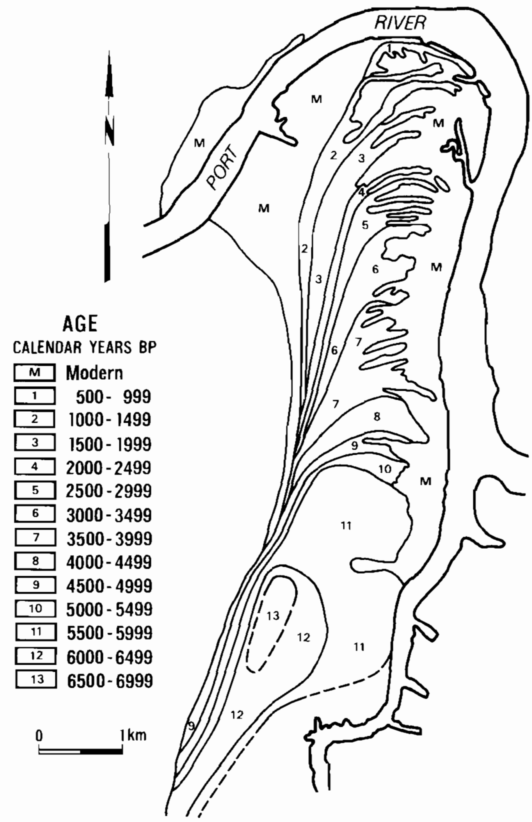

Figure 5. Sediment age distribution at mean sea level: LeFevre Peninsula.

The changing proportion (by east-west cross-sectional area) of sediment age in a northerly direction is illustrated in Figure 6. For transects 4 and 5 the bulk of sediment is clustered around 7000 to 5000 years, whereas in transect 2 (further north) the peak is at 4000 to 3500 years. The northernmost transect shows a bimodal distribution with peaks at 2000 to 1500 years and 3500 to 3000 years. The diagram confirms the progressive north-

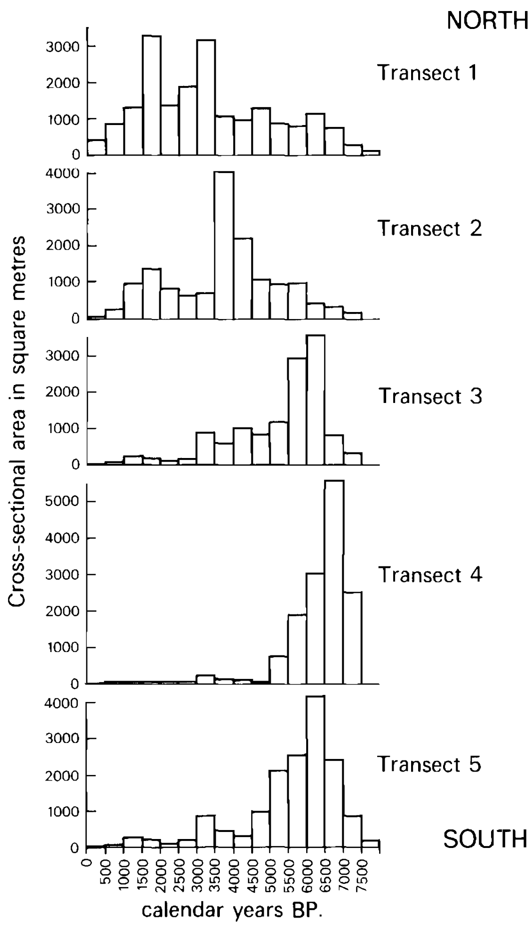

Figure 6. Sediment age distribution in east-west transects.

ward decreasing age of sediment deposition and highlights the massive sediment influx between 7000 and 5500 years resulting from the Postglacial Marine Transgression. The sediment peaks occurring between 4000 and 3000 years in transects 1, 2 and to a much lesser extent in transect 5 suggest the possible occurrence of a sediment influx around that time. This is discussed in more detail in HARVEY and BOWMAN (in prep.).

Results from this study are in agreement with the sea level history for southeastern Australia, although no dated material from LeFevre Peninsula provides an unambiguous sea level indicator. All dates fall below the lower boundary of the revised sea level envelope for eastern Australia (THOM and ROY, 1985), except for dates from stormwash deposits. Dated mangrove deposits (E. Burton pers. comm.) on the Adelaide coast south of the peninsula indicate a sea level similar to present around 7000 years ago. However, dated samphire deposits inland from the peninsula indicate a slightly higher sea level (about 0.5 m) than present around 6500 years ago (BELPERIO, HAILS, and GOSTIN, 1983). This may indicate a very localized area of subsidence.

The study also provides a contrast with most other Australian barrier studies in the mode of barrier formation. As shown by THOM (1984a, b) and THOM and ROY (1985) the southeast Australian barriers tend to be characterized by; (1) high wave energy and reworking of sand to depths of 60 m, (2) bedrock headlands and offshore promontories tend to block alongshore sediment transport, and (3) steep continental shelf with water depths up to 40 m encountered at the mouths of some embayments.

None of these characteristics apply to the LeFevre Peninsula which experiences lower energy conditons, is located within an extensive shallow gulf rather than on a steep continental shelf, and is subject to predominantly longshore sediment transport.

THOM (1984b) draws comparisons between Holocene barrier sedimentation in southeast Australia, North America and Europe. He notes the lack of evidence in southeast Australia for barrier-spit and tidal-inlet migration compared with the northern hemisphere, and also observes that Australian barriers tend to be thicker, more equant (in cross-section) sand accumulations than their sheet-like overseas counterparts. Although LeFevre Peninsula is similar to other Australian barriers in its cross-sectional shape, it also has much in common with northern hemisphere barrier-spits formed by tidal-inlet migration. However, in the case of LeFevre Peninsula, tidal inlet migration is associated with longshore barrier progradation, rather than barrier breaching, extensive washover deposits and sediment reworking, as is common on the higher energy east coast of the United States.

Whereas LeFevre Peninsula has developed under lower energy conditions than are found along either the southeastern coast of Australia or the U.S. east coast, the barriers flanking the Murray Mouth provide a South Australian contrast displaying washover features and flood tide delta accumulations typical of high energy conditions (BOURMAN and HARVEY, 1983).

CONCLUSION

The study is unique in its age structure resolution and has demonstrated the viability of an intensive drilling and radiocarbon dating investigation in a relatively low energy marine environment, allowing the reconstruction of long term trends in coastal sedimentation. The consistency of the age structure of the peninsula is attributed to the low incidence of reworked detrital shell.

The evolution of LeFevre Peninsula has been determined by the interaction of changing rates of sediment supply during the mid to late Holocene with the extension of the peninsula into an embayment of variable bathymetry and consequent changes in wind, wave and tide regimes.

The age structure shows a northward progradation of the peninsula over the last 7,000 years resulting from the dominant northward longshore drift of sediment. Both the morphology and the stratigraphy of the peninsula reflect this northward progradation.

Results of the study apparently support sea level histories determined for stable areas of southern and southeastern Australia. Transgressive sediments were first deposited in the area around 7500 calendar years BP. The major pulse of sediment following the last Postglacial Marine Transgression is similar to that which occurred in many localities in eastern Australia. It is likely that subsequent smaller sediment pulses also occurred.

Major contrasts are evident between the patterns of longshore barrier progradation and back-barrier sedimentation on LeFevre Peninsula and those documented in southeastern Australia. Longshore spit progradation has constrained backbarrier sediments in the case of LeFevre Peninsula, whereas most east coast studies document shore-normal sand accumulation blocking bedrock embayments.

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