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Quantifying rates of coastal progradation from sediment volume using GPR and OSL: the Holocene fill of Guichen Bay, south-east South Australia

C. S. BRISTOW* and K. PUCILLO†
*School of Earth Sciences, Birkbeck College, University of London, Malet Street, London WC1E 7HX, UK (E-mail: c.bristow@ucl.ac.uk)
†School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2500, Australia

ABSTRACT

Guichen Bay on the south-east coast of South Australia faces west towards the prevailing westerly winds of the Southern Ocean. The bay is backed by a 4 km wide Holocene beach-ridge plain with more than 100 beach ridges. The morphology of the Guichen Bay strandplain complex shows changes in the width, length, height and orientation of beach ridges. A combination of geomorphological interpretation, shallow geophysics and existing geochronology is used to interpret the Holocene fill of Guichen Bay. Six sets of beach ridges are identified from the interpretation of orthorectified aerial photographs. The ridge sets are distinguished on the basis of beach-ridge orientation and continuity. A 2·25 km ground-penetrating radar (GPR) profile across the beach ridges reveals the sedimentary structures and stratigraphic units. The beach ridges visible in the surface topography are a succession of stabilized foredunes that overlie progradational foreshore and upper shoreface sediments. The beach progrades show multiple truncation surfaces interpreted as storm events. The GPR profile shows that there are many more erosion surfaces in the subsurface than beach ridges on the surface. The width and dip of preserved beach progrades imaged by GPR shows that the shoreface has steepened from around 2·9° to around 7·5°. The changes in beach slope are attributed to increasing wave energy associated with beach progradation into deeper water as Guichen Bay was infilled. At the same time, the thickness of the preserved beach progrades increases slightly as the beach prograded into deeper water. Using the surface area of the ridge sets measured from the orthophotography, and the average thickness of upper shoreface, foreshore and coastal dune sands interpreted from the GPR profile, the volume of Holocene sediments within three of the six sets of beach-ridge accretion has been calculated. Combining optically stimulated luminescence (OSL) ages and volume calculations, rates of sediment accumulation for Ridge Sets 3, 4 and 5 have been estimated. Linear rates of beach-ridge progradation appear to decrease in the mid-Holocene. However, the rates of sediment accumulation calculated from beach volumes have remained remarkably consistent through the mid- to late Holocene. This suggests that sediment supply to the beach has been constant and that the decrease in the rate of progradation is due to increasing accommodation space as the beach progrades into deeper water. Changes in beach-ridge morphology and orientation reflect environmental factors such as changes in wave climate and wind regime.

Keywords Beach ridge, foredune, GPR, prograde, sediment accumulation rate

INTRODUCTION

The south-east coast of South Australia is a swash-aligned, wave-dominated coast, with a microtidal regime. Offshore lies a relatively narrow continental shelf with para-autochthonous cool-water carbonate production. The hinterland is composed of Tertiary limestones which extend beneath Guichen Bay. They are overlain by some of the world's best examples of Quaternary beach ridges formed during sea-level highstands (Huntley *et al.*, 1993, 1994). The preservation of highstand ridges is aided by a gently rising hinterland and an almost complete absence of surface drainage across a Tertiary limestone, karst, topography (Sprigg, 1979).

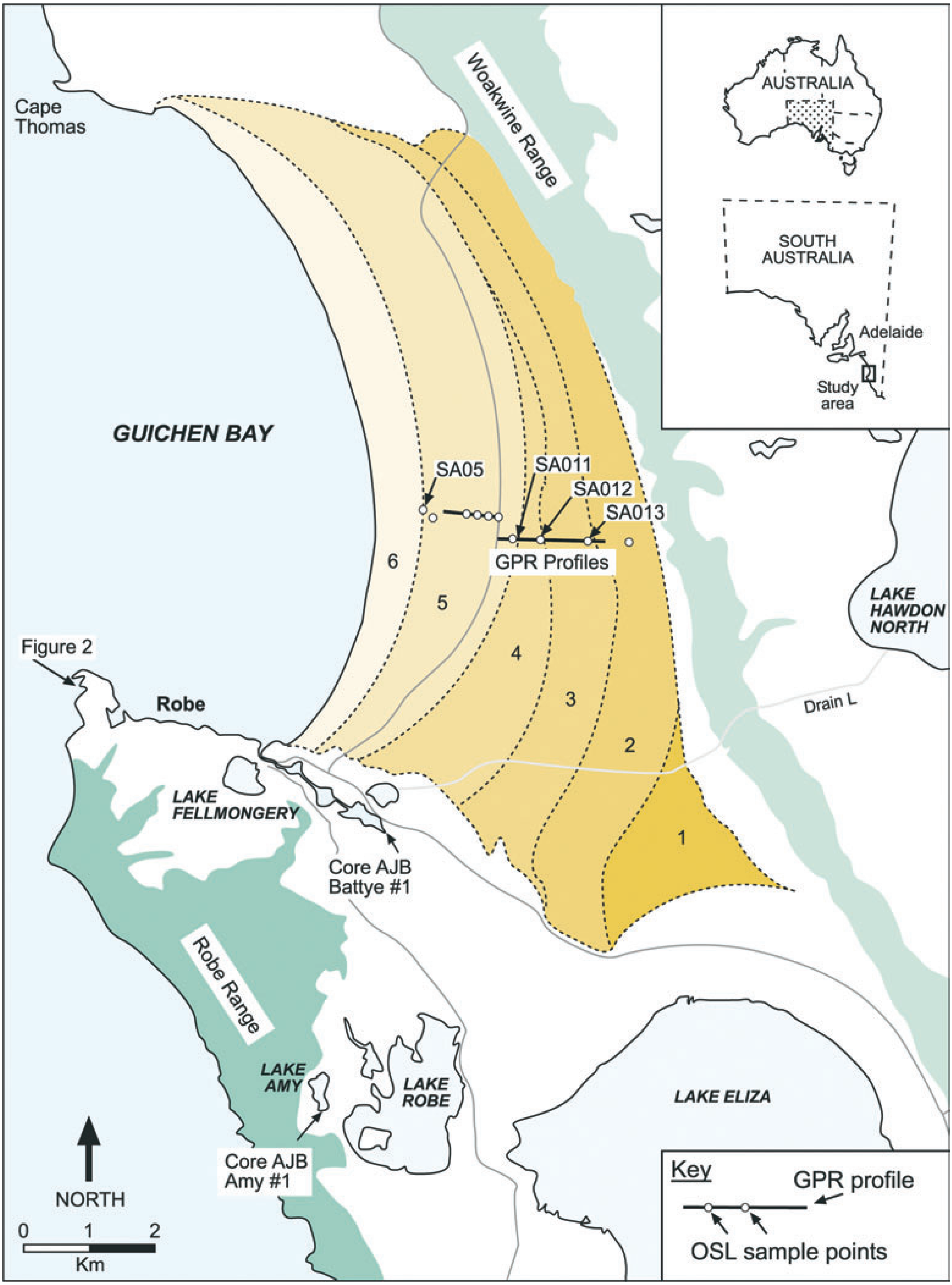
This paper describes the Holocene stratigraphy of Guichen Bay in south-eastern South Australia, which has an outstanding sequence of beach ridges preserved on a 4 km wide beach-ridge plain (Fig. 1). These ridges provide an inventory of Holocene shoreline evolution and the progradational infill of Guichen Bay. There are more than 100 beach ridges preserved. The term 'beach ridge' is defined by Otvos (2000, p. 84) as 'relict, semiparallel, multiple ridges, either of wave (berm) ridge or wind (multiple backshore foredune) origin'. The study of relict strandplains and their stratigraphic context reveal high-resolution records for reconstructing the evolution of a coast (Steers, 1946; Zenkovitch, 1967). Formation conditions of beach-ridge plains include low tidal range, a tectonically stable shoreline and quasi-stable sea levels with a local surplus of sediment (Mason *et al.*, 1997). Strandplains represent a high-resolution record of coastal geomorphology and accretion history from which it may be possible to infer past changes in sea level (Lewis & Balchin, 1940; Van Heteren *et al.*, 2000), or determine the chronology of high-magnitude storm events (Nott & Hayne, 2001), storminess (Fairbridge & Hillaire-Marcel 1977; Mason & Jordan, 1993), or changes in sediment supply (Goodfriend & Stanley 1999).

Almost all studies of beach-ridge evolution use projections from transects or linear rates of progradation. However, rates of progradation calculated from linear profiles across a coastal plain fail to take account of changes in shoreline geometry or changes in sediment thickness within a prograding beach-ridge sequence where water depth should be expected to influence rates of accretion. For example, a beach prograding offshore will be building out into progressively deeper water, and as water depth increases then there will be an associated increase in accommodation space. If sediment supply is constant then the linear rate of progradation will decrease even though the volume of sediment accumulation remains constant. In this paper, a method for establishing the volumes of sediment accumulation within a prograding beach-ridge sequence is tested. Orthorectified aerial photographs are used to analyse the geomorphological evolution of the beach ridges. In addition, ground-penetrating radar (GPR) has been used to investigate the internal structure and subsurface stratigraphy of the beach ridges at Guichen Bay. Integrating the subsurface profiles and planform evolution with age determinations from previous studies by Murray-Wallace *et al.* (2002), a holistic interpretation of the Holocene fill of Guichen Bay is obtained. The influence of changes in sea level, sediment supply and wave climate are considered as forcing factors on Holocene shoreline development.

LONG BEACH, GUICHEN BAY

Long Beach in Guichen Bay has a zeta beach form enclosed by headlands at Robe in the south and Cape Thomas in the north. The Bonney Shelf offshore from Robe is around 70 km wide with the shelf edge at a depth of around 180 m. The shelf narrows towards the south and increases in width towards the north where it passes into the contiguous Lacepede Shelf. Offshore sediments are described in James *et al.* (1992), and the shelf sediments include a mixture of carbonates and terrigenous clastics. The carbonates include reworked coralline algae, bryozoa, bivalves and foraminifera, while the clastic quartz is ultimately derived from the Murray River. The river mouth is located 200 km north of Robe.

Fig. 1. Location map for Guichen Bay on the south-eastern coast of South Australia. The bay forms a re-entrant between the Robe Range and Woakwine Range Pleistocene aeolianite ridges which were formed during sea-level highstands (green). On the Holocene strandplain (yellow), six ridge sets are identified within this study based upon the orientation, continuity and truncation of beach ridges interpreted from orthorectified aerial photographs shown in Fig. 3. The location of GPR profiles for this study and OSL sample points from Murray-Wallace *et al.* (2002) are also shown.


AUSTRALIA
SOUTH AUSTRALIA
Adelaide
Study area
Cape Thomas
Woakwine Range
GUICHEN BAY
SA05
SA011
SA012
SA013
GPR Profiles
6
5
4
3
2
1
Figure 2
Robe
LAKE FELLMONGERY
Core AJB Battye #1
LAKE HAWDON NORTH
Drain L
Robe Range
LAKE AMY
LAKE ROBE
LAKE ELIZA
Core AJB Amy #1
NORTH
0 1 2
Km
Key
GPR profile
OSL sample points

WAVE AND TIDE REGIME

Guichen Bay is microtidal, with a tidal range around 0·4 m during neap tides reaching a maximum of 1·1 m during spring tides with an average spring tidal range of 0·7 m. The tides are semidiurnal but unequal with one high–low tide cycle much smaller than the other. The south-eastern coast of South Australia is dominated by south-westerly waves from the Southern Ocean where the prevailing westerly winds, blowing over a very long fetch, generate high-energy south-westerly swell. The wave climate is dominated by long-period (12–16 sec) south-westerly swell. Significant swell height exceeds 4 m for 6% of the time and exceeds 2 m for 68% of the time (Short and Hesp 1980), with a modal deep-water wave height $H = 3$ m, $T = 12$ sec (Short & Hesp, 1982). The shelf is swept by swell waves. Wavelengths of 200 m have been reported with sediment movement down to depths of 140 m (James *et al.* 1992). The dominant incident swell arrives essentially normal to the shore because of refraction within Guichen Bay, while the southern side of the bay is sheltered by the headland at Robe.

SEA-LEVEL CHANGE

Sea-level changes in parts of South Australia have been reviewed recently by Belperio *et al.* (2002). They conclude that South Australia experienced rapid sea-level rise to 6400 years BP because of global de-glaciation, followed by regionally variable isostatic emergence. Marine flooding of the embayment between the Robe Range and Woakwine Range is reported by Cann *et al.* (1999) to have occurred around 7900 years BP on the basis of a peat at a depth of 1·55–1·61 m in Lake Amy dated at 7870 ± 170 cal yr BP. This peat is believed to be associated with a raised water table and the development of swamplands within the embayment. Soon after, seawater flooded the area as evidenced by intertidal sediments with *Katelysia rhytiphora*, dated 7530 ± 170 cal yr BP, recovered from a depth of 2·65 m in a core AJB Battye no. 1 on the southern edge of Guichen Bay (Cann *et al.*, 1999). They also suggest that beach progradation at Guichen Bay had closed the northern end of the embayment by 4000 years BP. Murray-Wallace *et al.* (1996) calculate an average uplift rate of 0·05 m ka^{-1} to 0·070 m ka^{-1} for the coastal plain near Robe. This would have resulted in around 0·35–0·5 m of uplift because of the peak of the post-glacial marine transgression caused by regional neotectonism, and epiorogenic uplift of the Corong coastal plain with a superimposed effect of hydroisostacy post-7 ka. It can therefore be assumed that the Holocene fill of Guichen Bay should be set within a framework of rapid transgression peaking around 7000 to 6400 years BP followed by slow regression.

SEDIMENT SUPPLY

The hinterland of Guichen Bay is dominated by the Woakwine range, a 300 km long, elongate ridge of fossilized coastal dunes which is a compound feature including five units, Woakwine I to Woakwine V (Schwebel, 1984). Woakwine I which is the youngest of the aeolian units within the range has been variously dated at 125 ± 20 and 100 ± 30 ka (Schwebel, 1984), 118 ± 4 and 132 ± 9 ka (Huntley *et al.*, 1994), between 70·9 ± 4·8 and 151 ± 13 ka (Murray-Wallace *et al.*, 1999), and 120 ± 8·7 and 175 ± 11 ka (Banerjee *et al.*, 2003). The Woakwine Range formed during the last interglacial maximum (oxygen isotope substage 5e) over a relict shoreline formed during oxygen isotope substage 7 (Murray-Wallace *et al.*, 1999). This ridge of dunes overlying transgressive shoreface sediments has a cap of calcrete and is completely stabilized and vegetated. The ridge does not provide a source of sediment today and there is no other terrigenous sediment source within the bay. Almost all the sediment that has accreted within Guichen Bay is derived offshore.

The sediments of the Bonney Shelf offshore from Guichen Bay have been described by James *et al.* (1992). They have been mapped as quartzose bryozoan–bivalve sands (James *et al.* 1992). The sands are typically fine grained with an average composition of 20% quartz, 40% reworked relict carbonate, 15% bivalves, 15% bryozoans, 5% benthic foraminiferans and 5% other. The quartz sand is derived from the Murray River which is described by James *et al.* (1992) as a 'failed delta' because it is currently contributing negligible amounts of sediment to the shelf. The Murray River has a very low gradient and flows into Lake Alexandrina, an enclosed portion of the river estuary. The little sediment that does reach the ocean is plastered along the Coorong barrier shoreline and not transported offshore. However, during sea-level lowstands, the Murray River flowed across the north-western side of the

Lacepede shelf in a submarine channel now buried beneath recent sediments. The submarine channel connected into the Murray submarine canyon system which transported most of the fluvial sediment into deepwater. Although most sediment was probably funnelled into deepwater, some sand was blown from the channel to form extensive aeolian sand sheets (James *et al.* 1992). Easterly, onshore aeolian sediment transport would have been enhanced by a northward shift of the 'roaring forties' low pressure system and strong westerly winds. The quartz sands on the Lacepede Shelf are a relict feature spread across the shelf during sea-level lowstands. Extensive, relict Pleistocene lowstand beach ridges have been mapped on the Lacepede Shelf by Sprigg (1979). The high percentage of relict carbonate on the shelf also points to extensive reworking, and James *et al.* (1992) describe the shelf as a palimpsest.

The headland at Robe is composed of aeolian dune sands with a calcrete cap. Schwebel (1983) recognized three constructional episodes for the Robe Range. Robe 1 refers to modern active dunes, with older Robe 2 and Robe 3 correlated with oxygen isotope substages 5a and 5c, respectively. Dating of the dune sands by Huntley *et al.* (1994) gives an age of 116 ± 6 ka corresponding with oxygen isotope substage 5c. More recently, Banerjee *et al.* (2003) indicate ages of 61 ± 3·6 ka for Robe 2 and 116 ± 6 ka for Robe 3; they confirm the correlation of Robe 3 with the last interglacial highstand *sensu lato* (oxygen isotope substage 5c) but indicate that Robe 2 is a local deposit not associated with a high sea-stand. The Robe Range is presently undergoing intensive erosion by marine abrasion processes (Fig. 2) as indicated by the sea cliffs and a series of offshore stacks extending south along the coast. This erosion of the coastal aeolinite cliffs and their submarine equivalents is a probable source for some of the sediment that forms the Holocene fill of Guichen Bay.

Further evidence for the sediment supply can be derived from ^{14}C dating of beach-ridge sediments (Murray-Wallace *et al.*, 2002). Radiocarbon dates for bioclastic sands beneath the older ridges give early Holocene ages (7240 ± 220 to 8110 ± 210 cal BP; Murray-Wallace *et al.*, 2002). Radiocarbon dates for coarse bioclastic sands beneath younger ridges give ages of 2290 ± 180a to 180 ± 180a cal BP, indicating a recent sediment source. Amino acid racemization ages of detrital carbonate sands on the relict foredunes and the modern beach give a late Pleistocene age (Murray-Wallace *et al.*, 2002) from which it can be assumed that the carbonate sand has three age populations. Large skeletal carbonates are either formed and moved onshore during the transgressive flooding and highstand or approximately syndepositional, while fine material includes a component of reworked older carbonates derived from the late Pleistocene Robe Range which surrounds the entrance to the bay. Thus, the sediments accumulating within Guichen Bay are derived from carbonate sediments formed during

Fig. 2. Marine erosion of Pleistocene aeolinites at Robe. The dune sands have been dated as 116 ± 6 ka corresponding to oxygen isotope substage 5c (Huntley *et al.*, 1994) and are capped by a calcrete. Sediment eroded from the cliffs and their submarine extension probably forms a source for some of the Holocene sediments in Guichen Bay.

the early Holocene transgression, lowstand quartz sands blown across the shelf, an admixture of modern carbonates, principally bryozoa and bivalves, and erosion of previous highstand sediments which form the headland at Robe.

BEACH-RIDGE EVOLUTION

Orthorectified colour aerial photographs have been used to map beach ridges at Guichen Bay (Fig. 1). On the aerial photograph, it was difficult to recognize the ridges themselves and the intervening swales have been mapped instead. The swales have been picked for mapping because the dark vegetation of the swales shows up better on the aerial photograph. In addition, the dune ridges are sometimes discontinuous and broken by blowouts or merged together making discrimination difficult. Furthermore, by defining the swales with lines using a GIS, it is possible to define the ridges as polygons which is more useful for later analysis of beach-ridge areas and volumes. Analysing the pattern of beach ridges revealed six sets of beach-ridge accumulation.

Ridge Set 1

The initial accretionary beach ridges (Ridge Set 1) are restricted to the south-east corner of the embayment. Beach ridges in this area have a low elevation and in plan are convex to the west. The area of Ridge Set 1 is 3 320 710 m^2 (Table 1). These ridges are not included in the GPR profile and were not sampled by Murray-Wallace *et al.* (2002). However, from their location in the south-east corner of the embayment, and their relationship with the other beach ridges, it is apparent that the Ridge Set 1 beach ridges are the earliest beach ridges in the Guichen Bay strandplain. Their convex to the west morphology may indicate that they were part of a cuspate foreland which developed while Guichen Bay was still connected to Rivoli Bay 40 km to the south.

Ridge Set 2

Ridge Set 2 beach ridges extend north along the eastern margin of Guichen Bay adjacent to the foot of the Woakwine Range. These ridges are distinguished by the discontinuous nature of the ridges, curved crestlines and angular discordance between ridges (Figs 1 and 3). During September 2003, when the GPR and topographic surveys were undertaken, this area was partly flooded. The flooding prevented completion of the GPR survey but indicates that the area is low lying. The topographic profile of Thom *et al.* (1981) indicates elevations of the dune crests *ca* 2 m and the interdune swales *ca* 1·5 m. The area of Ridge Set 2 is 10 337 840 m^2 (Table 1).

The Ridge Set 2 beach ridges are at a lower elevation than the other beach ridges. At the time of the survey, the interdune swales were flooded while the swales between younger dune ridges were dry. Thus both the dune ridges and interdune swales of the oldest ridges are at a lower elevation than the younger ridges. The variable geometry of the Ridge Set 2 ridges is attributed to bathymetric controls on wave refraction and diffraction within Guichen Bay at the time that the ridges were formed. At this time, Guichen Bay was at the northern end of a seaway between the Robe Range and the Woakwine Range that connected Guichen Bay in the north with Rivoli Bay in the south during the early to mid-Holocene sea-level highstand. It is possible that tidal currents in and out of the seaway affected sedimentation at the southern end of Guichen Bay until the embayment was blocked off by beach-ridge accretion.

Ridge Set 3

The end of the second ridge set and the start of the third ridge set is picked where the beach ridges form a much more continuous sweep around the bay (Fig. 1). Ridge Set 3 beach ridges have a subdued topography with foredune beach-ridge crests reaching elevations between 5 and 6 m with a peak of 6·5 m. The lowest elevation of an interdune swale is 4·7 m. The area of Ridge Set 3 is 8 307 308 m^2 (Table 1).

Ridge Set 3 beach ridges have low relief but are higher than Ridge Set 2 ridges and interdune swales. The increased continuity of beach-ridge crests indicates that the bathymetric controls on wave refraction within the bay had decreased as the bay was infilled.

Ridge Set 4

Ridge Set 4 is marked by a change in beach-ridge orientation and a wedge-shaped accumulation, widest in the south, narrowing and pinching out towards the north. In addition, Ridge Set 4 includes the highest beach ridges on the Holocene coastal plain at Guichen Bay. One distinct

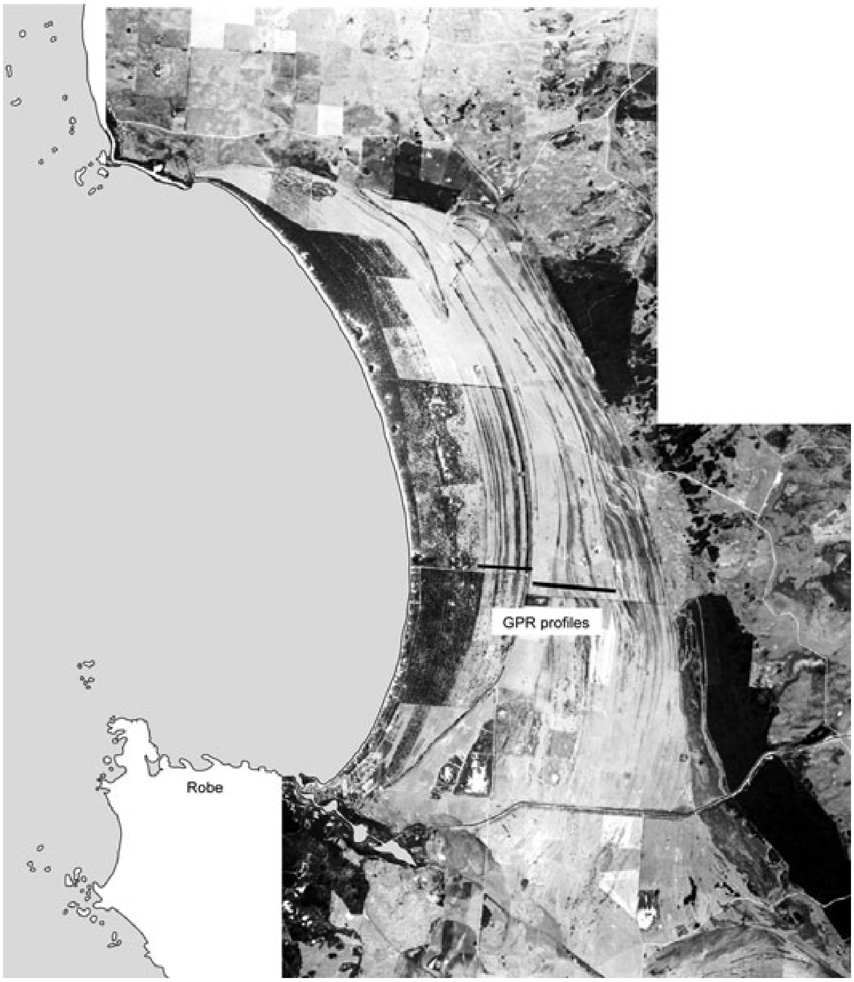


Fig. 3. Orthorectified aerial photographs of Guichen Bay showing the beach ridges and darker interdune swales. Changes in the orientation of beach ridges and their continuity and truncations are used to map ridge sets shown in Fig. 1. Ridge Set 1, early, convex to the west beach ridges that may have formed part of a cuspate foreland between Guichen Bay in the north and Rivoli Bay in the south. Ridge Set 2 extends along the eastern edge of Guichen Bay at the foot of the Woakwine Range, the beach ridges are discontinuous with many truncations attributed to local bathymetric influence on wave orientation. Ridge Set 3 beach ridges are more continuous with fewer truncations between ridges, there is a notable increase in the width of the set towards the southern end of the strandplain. Ridge Set 4 is widest in the south and beach ridges appear to be truncated by Ridge Set 5. Ridge set 5 beach ridges show continuous crestlines in a smooth curve around the bay with the area of maximum accretion shifted north to the centre of the bay. Ridge Set 5 beach ridges are higher and more continuous than the earlier Ridge Sets 2, 3 and 4. Ridge Set 6, beach-ridge progradation continues but beach ridges are less well defined due to an increase in vegetation cover.

ridge is higher than all the other dune ridges in this area, reaching an elevation of 12·2 m on the surveyed transect. Ridge Set 4 has an area of 5 067 407 m^2 (Table 1). It is speculated that the increase in beach-plain width in the south followed the closure of the connection to Rivoli Bay in the south.

Ridge Set 5

Ridge Set 5 beach ridges are characterized by well-defined, swash-aligned beach ridges that are continuous along strike. Ridge Set 5 appears to truncate ridges of Ridge Set 4. The beach ridges of Ridge Set 5 reach a maximum width in the middle of the bay. West of the road, Ridge Set 5 dune crests reach elevations of between 7·5 and 8 m, while the interdune swales have minimum elevations between 4·6 and 4·9 m. The beach ridges are notably higher than the ridges of Ridge Sets 2, 3 and 4, while the swales are at a similar elevation to those of Ridge Set 3, but higher than the swales of Ridge Set 2. The area of Ridge Set 5 is 16 054 638 m^2.

Table 1. Area of each ridge set in Guichen Bay, derived from interpretation of orthorectified aerial photographs draped over a digital terrain model

Ridge Set	Area (m^2)
1	3 320 710
2	10 337 840
3	8 307 308
4	5 067 407
5	16 054 638
6	5 855 026

Ridge Set 6

The sixth and youngest set of dune ridges is marked by a change in vegetation from grazed pasture to thick scrub and bush. The morphology of the beach ridges may be similar to those of Ridge Set 5, but it is not possible to distinguish the ridges and swales adequately from the aerial photograph. However, it is noticeable that the maximum width of Ridge Set 6 is in the northern half of the bay. The area of Ridge Set 6 is 5 855 026 m^2 (Table 1).

The analysis of the beach-ridge pattern shows an evolution of planform with the ridges becoming less curved and more continuous over time. There is also a northward shift in progradation with initial progradation in the south of the embayment shifting to a broader zone of progradation with an increase in the width of the beach ridges in the north and centre of the Guichen Bay beach-ridge plain. This change is most apparent between Ridge Sets 4 and 5; Ridge Set 4 is widest in the south and wedges out towards the north, Ridge Set 5 is widest in the centre of the bay and appears to truncate Ridge Set 4 ridges. The reorientation of the beach ridges must indicate a change in the contemporary shoreline. Here, it is suggested that the shoreline change is due to a change in wave climate, either because of a change in wave approach or a change in wavelength. The northward shift in deposition from the southern end of the bay in Ridge Sets 1 to 4, to the centre of the bay in Ridge Set 5 and the northern half of the bay in Ridge Set 6 could be due to a change in wave approach with wave approach swinging around from north of west to the south of west. The decrease in the curvature of the beach ridges can be explained by a decrease in wave refraction. A decrease in wave refraction could result from either an increase in water depth or an increase in wavelength. Given the regional regressive sea-level trend, an increase in water depth offshore and within the entrance to Guichen bay is unlikely. Therefore, the most likely explanation is an increase in wavelength. Hence it is suggested that the change in beach-ridge orientation and decrease in curvature is best explained by a change in wave climate with wave approach shifting towards the south accompanied by an increase in wave length. Waves with longer wavelength are refracted less as they enter shallow water and as a result the swash-aligned shoreline has a decreased radius of curvature.

SURFACE TOPOGRAPHY

A topographic profile across the beach ridges at Guichen Bay has been measured and levelled in to South Australia Government Benchmarks and reduced to Australian Height Datum (AHD). The beach ridges at Guichen Bay show a progressive increase in elevation from Ridge Set 2 through to Ridge Set 4 with the highest ridge in Ridge Set 4 which reaches an elevation of 12·2 m. An increase in foredune elevation is best explained by a decrease in the rate of progradation because low rates of beach progradation allow more time for dry sand to be blown from the beach into foredune ridges (Psuty, 1992), allowing more time for the construction of bigger and higher foredune ridges. The corollary is that high rates of progradation reduce the time available for foredune construction, resulting in an increased number of lower foredune ridges.

GPR PROFILES

Following trial investigations using 100, 200 and 50 MHz antennae, a 2250 m GPR profile across the beach ridges was collected using a Sensors and Software Pulse EKKO 100 (Sensors and Software Inc., Mississauga, Canada), with 100 MHz antennae and a 1000 V transmitter. The profiles were collected in step mode with antennae spaced 1 m apart, perpendicular to the direction of travel (parallel broadside configuration) and measurements every 0·5 m. Topographic measurements were made every 5 m and at breaks in slope along the profile using a Leica total station (Leica Geosystems AG, Heerbrugg, Switzerland). The elevations are measured relative to Government of South Australia Survey Marks 6823/481 and 6823/1321 for topographic correction. The velocity was determined using common mid point (CMP) surveys as 0·12 m ns^{-1} for the dry sands above the water table and a velocity of 0·06 m ns^{-1} was used for the saturated sands beneath the water table. These velocities have been used in the GPR interpretation with the depth scale changing above and beneath the water table. Given velocities of 0·06 and 0·12 m ns^{-1}, the resolution of the GPR should be around 0·15 m beneath the water table and 0·3 m above it, assuming resolution at one quarter of a wavelength (Reynolds, 1997). Data quality is very good with good resolution of the beach and beach-ridge sediments. The GPR profiles have been migrated using 2D F–K migration to restore dipping reflections to their true vertical position.

The GPR profile covers the central section of the 4 km wide beach-ridge plain at Guichen Bay. The limits of the profile were constrained at the seaward end by thick bush and disturbance caused by quarrying. There is also a break in the profile at 804 m where the profile crosses the road from Robe to Kingston. The profile stops at the fence on the west side of the road and restarts at the fence on the eastern side of the road. There is a small offset at this point because of access restrictions. At the landward end, the profile was limited by floodwaters standing in the swales between the beach ridges.

The GPR profile contains dipping reflections that are interpreted as reflections from sedimentary structures within the beach ridges and within the underlying beach deposits. In addition, the water table is imaged as a high-amplitude, continuous, locally horizontal reflection. The profiles show good resolution of sedimentary structures both above and below the water table. It is not possible to present the full 2250 m GPR profile in this paper, but three sections – from 0 to 100 m (Fig. 4), 1000 to 1150 m (Fig. 5) and 1950 to 2080 m (Fig. 6) – have been selected to show the main features revealed by the GPR survey. Interpretation of the GPR profiles includes both radar facies analysis and radar stratigraphic interpretation. On the GPR profiles, three radar facies associations are identified.

Radar Facies 1 – water table

The water table is widely imaged in dune sands (Harari, 1996; Bristow & Bailey, 2000; Bristow *et al.*, 2000; Botha *et al.*, 2003) as a continuous, almost horizontal, high-amplitude reflection that cuts across dipping reflections from sedimentary structures. Across most of the area, the water table is identified at an elevation of 5 m, although the water table elevation decreases towards the coast, falling to 3·5 m at the western end of the GPR profile (Figs 4–6). The water table reflection is seen to intercept the surface in interdune swales which is consistent with field observations of surface flooding of the interdune swales when the survey was made in August 2003. The GPR survey was conducted after heavy winter rainfall when the water table was relatively high, although rushes and swamp vegetation in the swales show that they are prone to flooding.

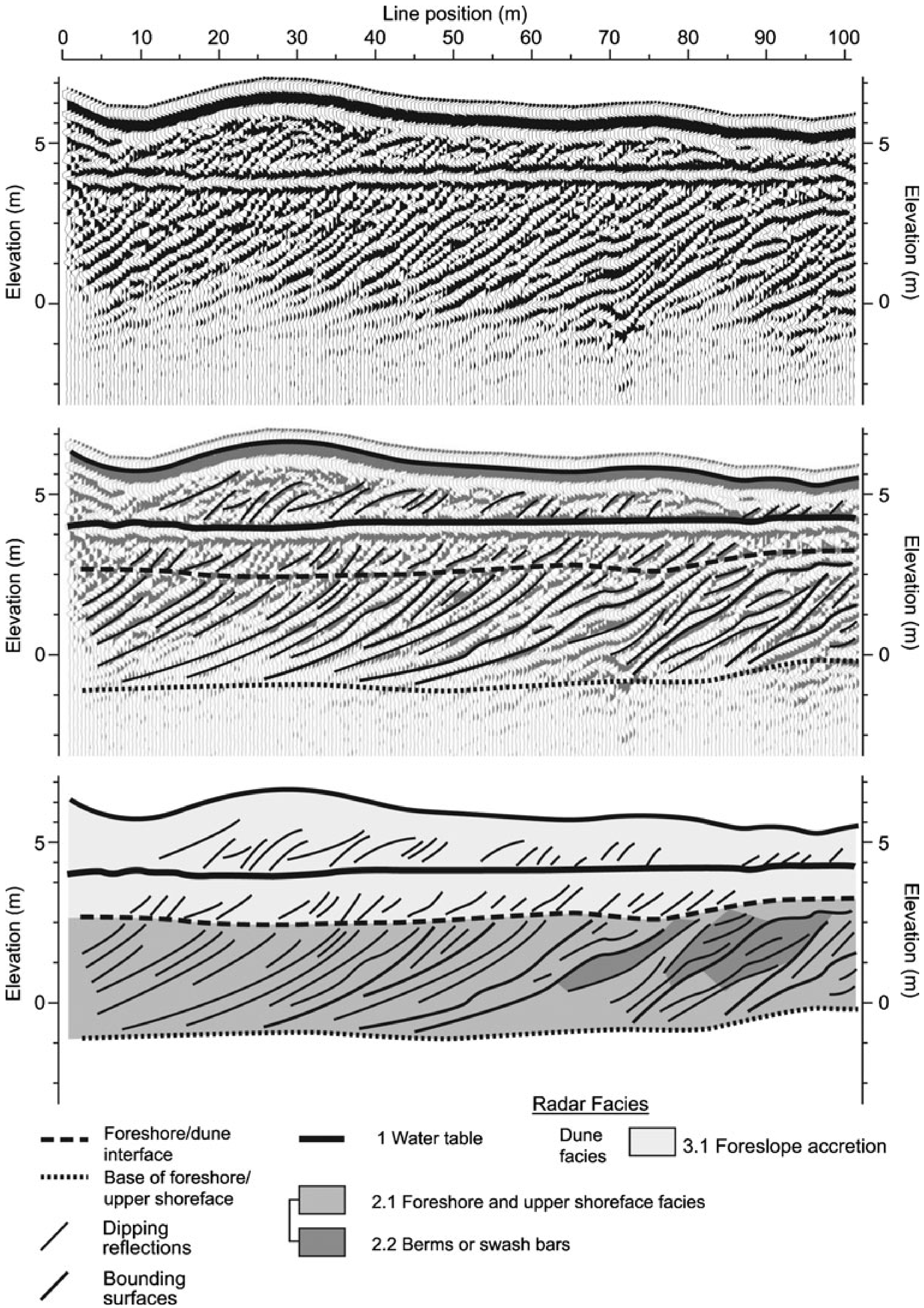
Radar Facies Association 2 – beach facies

Radar Facies 2·1 – beach surfaces

Inclined tangential reflections, that dip towards the sea and can be traced down-dip for tens of metres, dominate the lower part of the GPR profiles (Figs 4–6). The inclined reflections are not only sub-parallel but can also truncate other reflections and may be onlapped or downlapped by other dipping reflections. The inclined tangential reflections are usually found beneath the water table but sometimes extend above it. The down-dip termination of the inclined reflections is usually a downlap termination. However, in some places, the basal reflection is missing because of attenuation.

The inclined tangential reflections are interpreted as beach surfaces. The majority of the inclined tangential reflections are beach progrades which include the foreshore and upper shoreface. Where they truncate underlying reflections, the surfaces are erosional and are interpreted as storm erosion surfaces. By analogy with recent sediments from other areas, the truncation surfaces are attributed to upper shoreface and foreshore erosion by storm waves (Neal *et al.*, 2002). The down-dip termination of the inclined reflections is interpreted as a break in slope at the base of the upper shoreface. The base of the upper shoreface has been picked as the base of the beach deposits and used to calculate the thickness of the Holocene beach deposits. Attenuation at the base of the beach reflections may be due to a transition to a muddy substrate on the lower shoreface. The presence of mud beneath the beach deposits is indicated on a sketch cross-section in Sprigg (1979).

The dip of the inclined reflections at the landward end of the GPR profile (Fig. 6) is around 2·85°. At the seaward end of the GPR profile, the inclined reflections dip towards the sea at around 7·5° (Fig. 4), and the dip of the beach progrades is more than twice as steep as that at the landward end. This change in beach slope may indicate a transition from a dissipative to a reflective beach.


Line position (m)
0 10 20 30 40 50 60 70 80 90 100
Elevation (m)
Radar Facies
Foreshore/dune interface
Base of foreshore/ upper shoreface
Dipping reflections
Bounding surfaces
1 Water table
2.1 Foreshore and upper shoreface facies
2.2 Berms or swash bars
Dune facies
3.1 Foreslope accretion

This may be attributed to an increase in wave energy as the beach progrades out into Guichen Bay.

Radar Facies 2·2 – Berms
Between the inclined tangential reflections there are lower-angle, inclined reflections that onlap the inclined tangential reflections, e.g. at an elevation of 1 m between 80 and 95 m (Fig. 4). The onlap terminations mark constructional ridge sets of beach accretion through the welding of berms onto the beach. The GPR profiles of a beach-ridge plain at Aldeburgh (Neal *et al.*, 2002) show similar prograding berm-ridge units.

Radar Facies Association 3 – dune facies

Radar Facies 3·1 – dune foreslope accretion
Low-angle, inclined, seaward-dipping, discontinuous reflections are commonly found at the top of the GPR profiles either just above or just beneath the water table reflection. These are interpreted as dune foreslope accretion where sand blown from the beach is trapped by vegetation growing on the foredune causing the dune to prograde seawards (Carter & Wilson, 1990; Bristow *et al.*, 2000).

Radar Facies 3·2 – vegetated foredune
Hummocky discontinuous reflections that are mostly convex-up with some concave-up reflections are usually found close to the top of the profiles above or just below the water table. Although hummocky discontinuous radar facies have been identified in GPR profiles from a number of different environments (Jol & Bristow 2003), comparison with GPR profiles across other coastal dunes (Bristow *et al.*, 2000) suggests that this radar facies is interpreted as vegetated foredunes. The hummocky discontinuous reflections represent hummocky topography formed around sand-trapping vegetation (Bristow *et al.*, 2000).

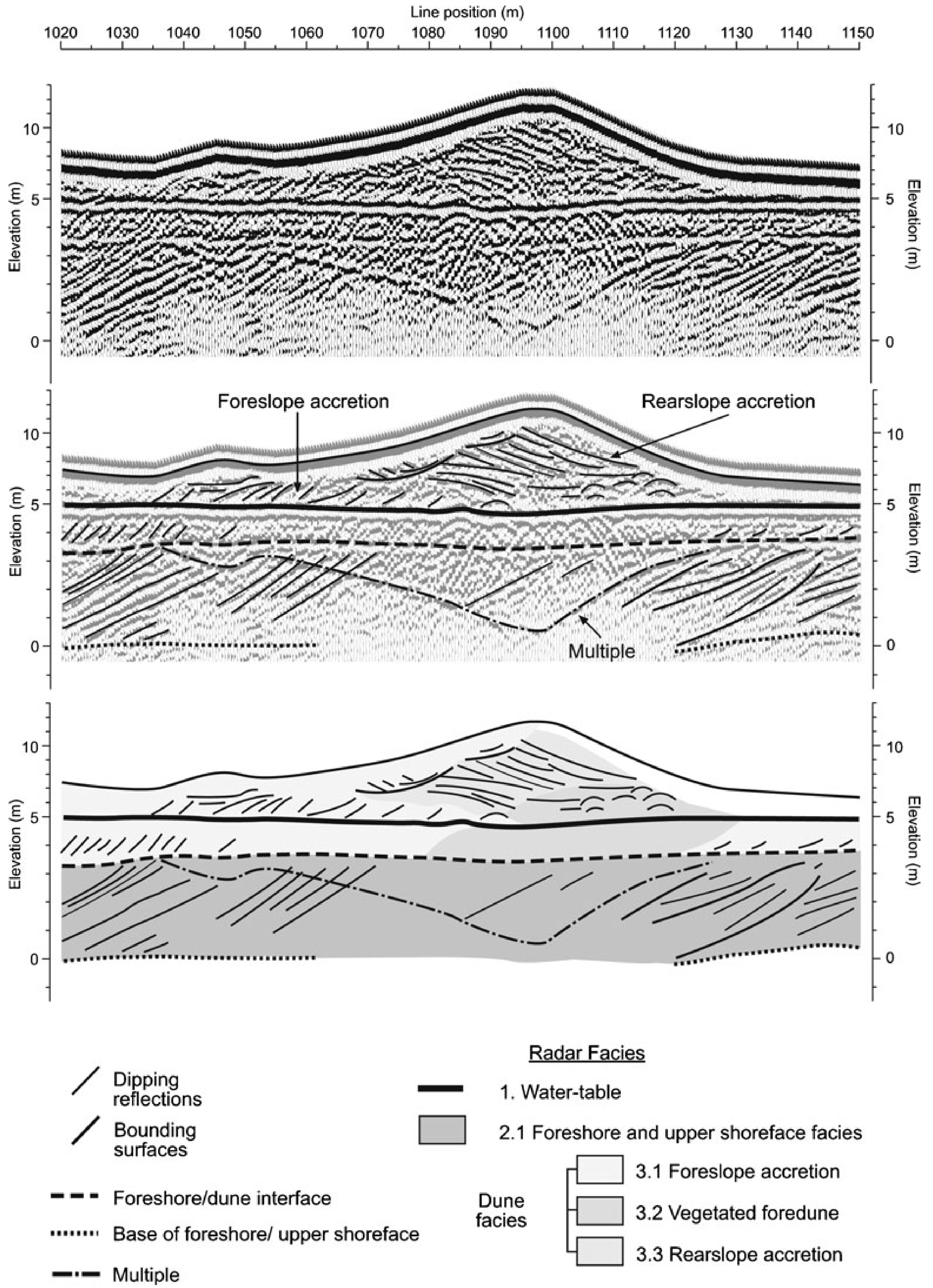
Radar Facies 3·3 – dune rearslope accretion
The biggest dune ridge, which reaches an elevation of 12·2 m (Fig. 5), contains landward dipping reflections where sand has been blown over the dune crest and accumulated on the landward side of the dune. These reflections show that the dune has migrated inland. This dune has a long and continuous crestline with no conspicuous blowouts indicating limited landward migration. A break in slope on the windward side of the dune and a change in radar facies from hummocky discontinuous to rearslope accretion (Fig. 5) are interpreted to indicate that the dune has migrated inland by around 35 m. Given that this dune is larger than all the other foredune ridges, it presumably took longer to accumulate and it probably marks a temporary hiatus in the shoreline progradation. It is notable that the highest dune ridge occurs in Ridge Set 4 where there is a marked change in beach-ridge orientation, which records a change in shoreline orientation.

SEDIMENT THICKNESS

The thickness of Holocene sediments within the beach ridges in Guichen Bay has been calculated as the difference in elevation between the base of the upper shoreface sands and the surface of the beach-ridge topography. The surface elevation of the beach ridges was measured in the field using a total station and levelled into South Australian benchmarks. The elevation of the base of the upper shoreface sands has been determined from topographically corrected GPR profiles. The base of the upper shoreface is picked at the down-dip termination of inclined upper-shoreface reflections (Radar Facies 2·1) which usually downlap low-angle reflections interpreted as finer-grained sediments on the floor of Guichen Bay.

The elevation of the base of the upper shoreface sand descends from an elevation of 1 m at the eastern, landward end of the GPR profile to an elevation of −1 m at the western, seaward end of the GPR profile. This change in elevation parallels the dip of the top of the underlying Tertiary limestones (Fig. 7) and is interpreted as the floor of Guichen Bay. A cross-section of Guichen Bay in Sprigg (1979) indicates that the section

Fig. 4. GPR profile from 0 to 100 m at the seaward end of the surveyed section shows inclined tangential reflections in the lower part of the profile with many truncated reflections. These are interpreted as upper shoreface and foreshore sediments with erosional truncation during storm events followed by beach progradation and berm accretion (Radar Facies Association 2). The foreshore and upper shoreface deposits extend to −1 m AHD. The water table is a strong horizontal reflection at 3 m elevation. Above the water table the reflections are more discontinuous and hummocky reflections are from vegetated foredunes (Radar Facies Association 3). The dune to beach facies change occurs at an elevation of 2 m. Note the change in depth scale above and beneath the water table.



Line position (m)
1020
1030
1040
1050
1060
1070
1080
1090
1100
1110
1120
1130
1140
1150
Elevation (m)
10
5
0
Foreslope accretion
Rearslope accretion
Multiple
Dipping reflections
Bounding surfaces
Foreshore/dune interface
Base of foreshore/ upper shoreface
Multiple
Radar Facies
1. Water-table
2.1 Foreshore and upper shoreface facies
Dune facies
3.1 Foreslope accretion
3.2 Vegetated foredune
3.3 Rearslope accretion

between the top of the Tertiary limestones and the base of the Holocene beach-ridge sediments includes estuarine muds which would explain the attenuation of the GPR reflections at the base of the upper shoreface sands. The cross-sectional area of the Holocene, upper-shoreface, foreshore and beach-ridge sediments has been used to calculate an average thickness for three of the sets of beach-ridge accretion, Ridge Sets 3, 4 and 5 (Fig. 8).

BEACH-RIDGE CHRONOLOGY

The ages of the beach ridges in Guichen Bay have been determined by Murray-Wallace *et al.* (2002) using optically stimulated luminescence (OSL). Their results show that the beach ridges were formed between 5400 ± 230 yr and the present day. Some of the samples dated by Murray-Wallace *et al.* (2002) map onto or close to the boundaries of the ridge sets defined in this study. Their sample SA013 is close to the boundary between Ridge Sets 2 and 3 (Fig. 1), while their sample SA012 falls almost exactly on the boundary between Ridge Sets 3 and 4, and their sample SA011 is close to the boundary between Ridge Sets 4 and 5 (Fig. 1). Sample SA005 is almost on the boundary between Ridge Sets 5 and 6 (Fig. 1). The OSL sample ages from Murray-Wallace *et al.* (2002) indicate that Ridge Set 3 accreted between 5400 ± 230 and 5300 ± 230 BP. The apparent duration, 100 years, is less than the error range of each sample (Table 2). Samples SA012 and SA011 which include Ridge Set 4 have ages of 5300 ± 230 and 4400 ± 220 yr indicating that Ridge Set 4 accreted over a period of around 900 years (Table 2). Ridge Set 5 is bracketed by samples SA011 and SA005 with ages of 4400 ± 220 and 1800 ± 80 yr, respectively, indicating deposition over a period of 2600 years (Table 2).

RATES OF PROGRADATION

Using the OSL ages of Murray-Wallace *et al.* (2002) and the widths of the ridge sets defined in this study, it is possible to calculate rates of progradation (Table 2). The results suggest that Ridge Set 3 beach ridges prograded at 7·8 Myr^{-1}, while Ridge Set 4 beach ridges prograded at 0·43 Myr^{-1} and Ridge Set 5 beach ridges prograded at 0·54 Myr^{-1}. There is an order of magnitude difference between the rate of progradation for Ridge Set 3 (7·8 Myr^{-1}), and those for Ridge Sets 4 and 5 (0·43 and 0·54 Myr^{-1}). Given the errors associated with the OSL age determination, there is some uncertainty over the rates derived above because the age difference between samples SA012 and SA013 is less than the error attached to each sample. However, taking the outer limit of the calculated OSL ages for SA012 and SA013 still gives rates of progradation for Ridge Set 3 four times that calculated for Ridge Sets 4 and 5.

SEDIMENT ACCUMULATION

The base of the upper shoreface has been determined at downlapping reflection terminations on the GPR profile. The depth beneath the surface and the elevation of the subsurface topography, have both been used to calculate the cross-sectional area of Ridge Sets 3, 4 and 5 (Fig. 8). For Ridge Set 5, the base of the upper shoreface has been projected seawards beyond the limit of the GPR profile, and the surface elevation data are partly based upon the topographic profile of Thom *et al.* (1981). The cross-sectional area of each ridge set has been divided by the horizontal width along the profile to give an average thickness for each ridge set. This average thickness has been multiplied by the area of each ridge set calculated from the interpretation of orthophotography to produce an estimate of the sediment volumes within each ridge set (Table 2). Ridge Set 3 has a volume of 41 556 698 m^3, Ridge Set 4 has a volume of 45 435 131 m^3, and Ridge Set 5 has a volume of 106 529 961 m^3. There are some uncertainties within these estimates because of the accuracy of the depth determinations on the GPR profiles, and potential lateral variations in thickness along the beach ridges. Despite these potential errors, realistic estimates of the volumes of sediment within each ridge set are obtained.

Fig. 5. GPR profile from 1020 to 1150 m crosses the highest foredune ridge. Within the foredune ridge reflections indicate rearslope accretion and on the seaward side of the foredune ridge seaward-dipping reflections are interpreted as dune foreslope accretion deposits. The water table is a strong horizontal reflection at 5 m. Beneath the water table, the dune topography is mirrored by a multiple which locally obscures primary reflections from foreshore and upper shoreface deposits which can be seen at either end of the profile. The contact between foreshore and dune deposits is picked at elevations between 3·5 and 4 m.

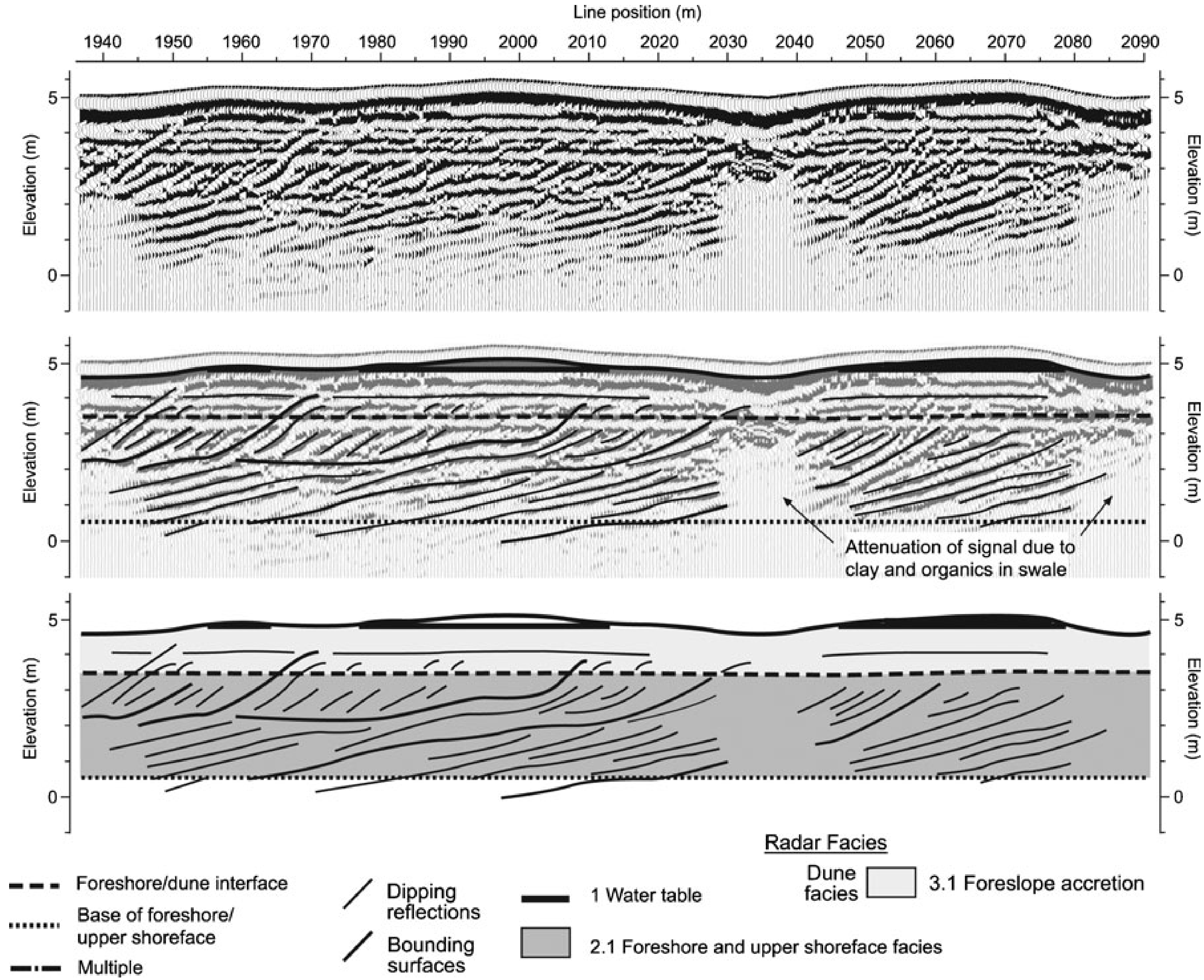


Fig. 6. GPR profile between 1930 and 2090 m shows typical reflection character from the inland end of the profile. The water table at an elevation just below 5 m is very close to the surface, the ground wave is expanded in the interdune swales where the water table is at the surface. The contact between dune and beach sediments is picked at an elevation around 3·5 m and the reflections from beach progrades extend down to an elevation of 0 m AHD. The beach progrades have a lower angle of dip than the progrades closer to the coast in Fig. 4.

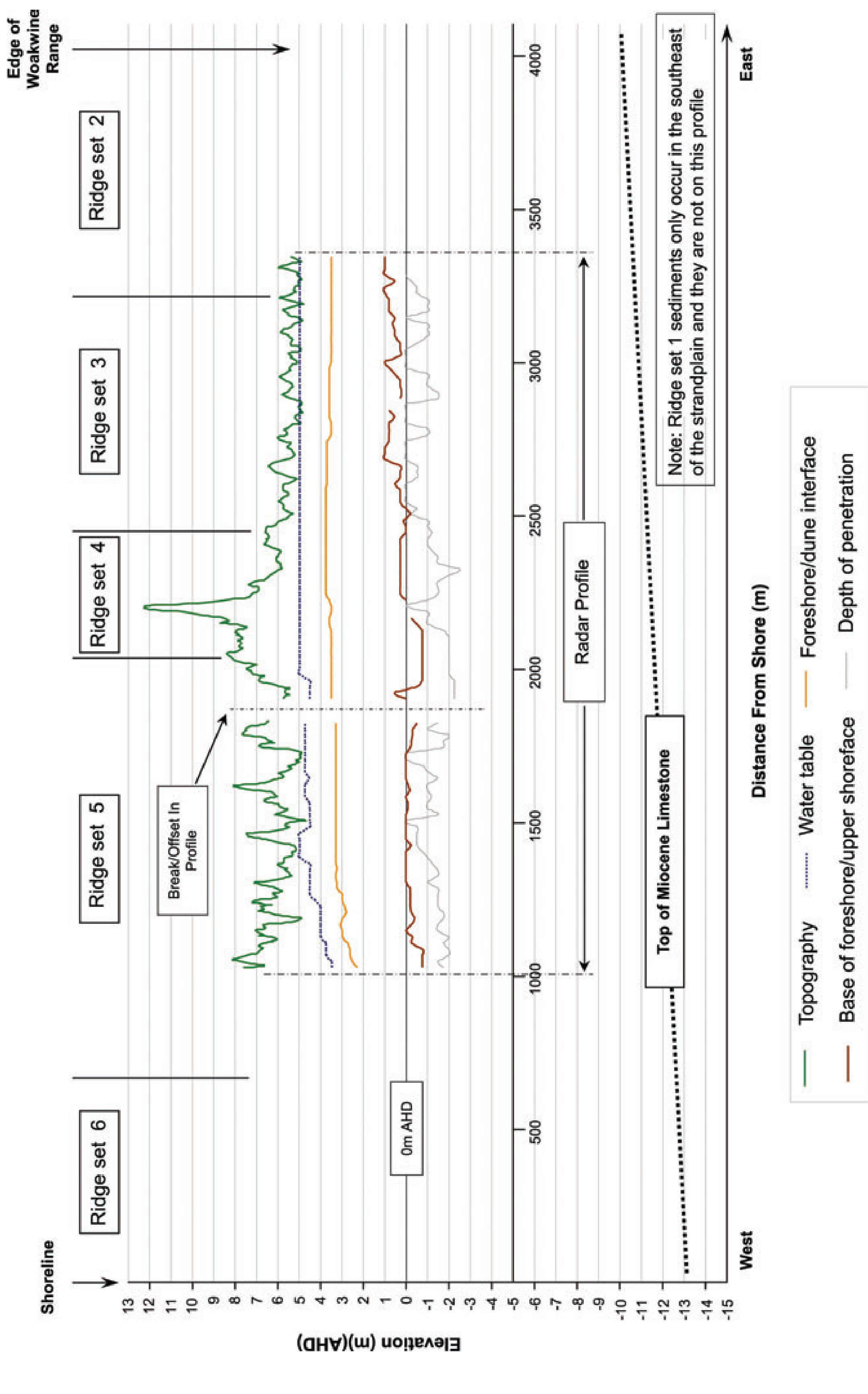


Fig. 7. Elevation profile measured across the beach ridges and depth picks of salient features on the GPR profile including the water table, the base of the upper shoreface and the top of the underlying Miocene limestones.

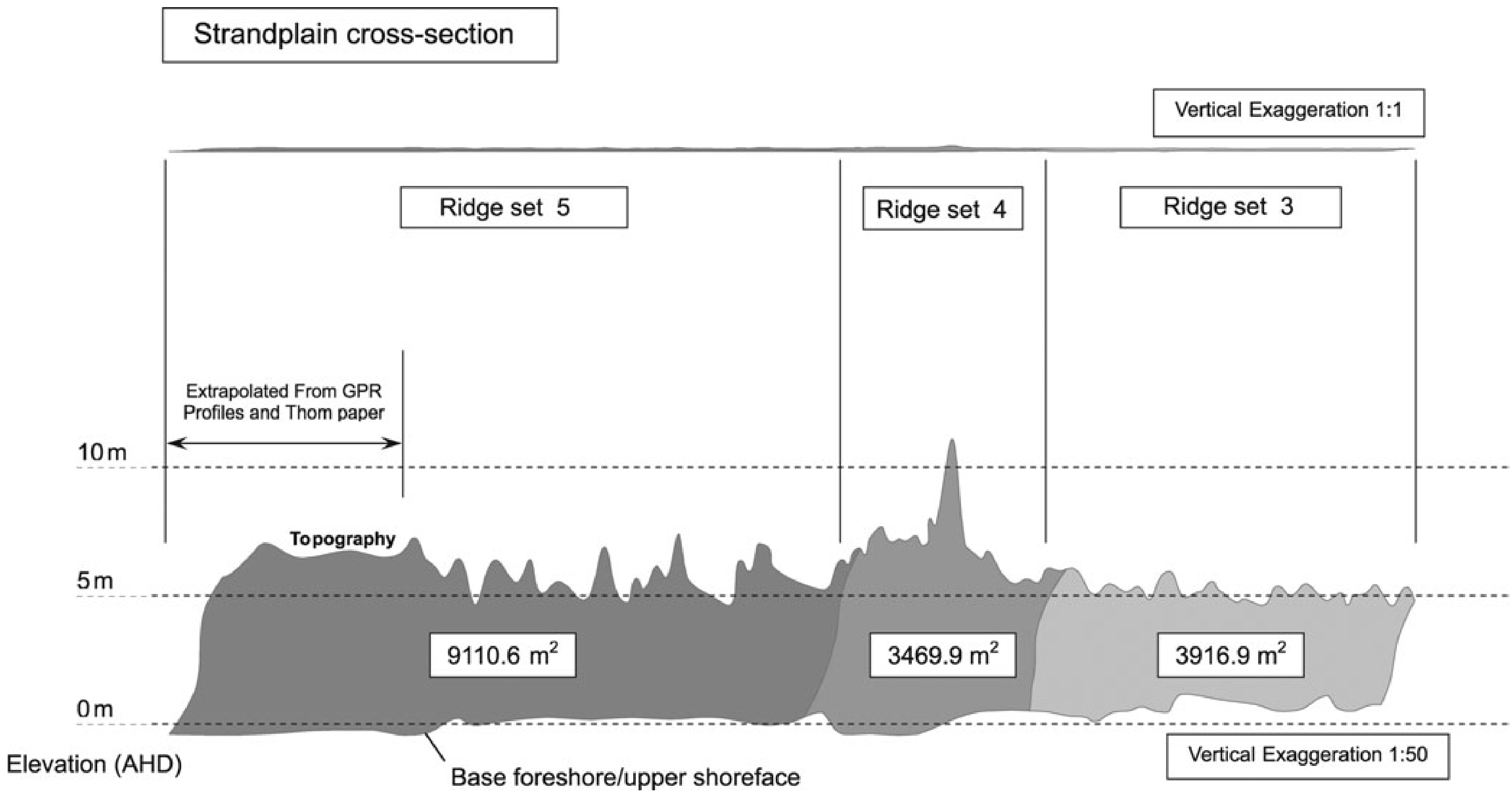


Fig. 8. Cross-sectional area of Ridge Sets 3, 4 and 5, based on the difference in elevation of the base of the upper shoreface reflections picked from the GPR profiles and the beach-ridge topography. The lower panel shows a vertical exaggeration of 1:50. An average sediment thickness for each ridge set was calculated from the cross-sectional area and this was used to compute sediment volumes in Table 2.

Table 2. Beach-ridge chronology, rates of progradation, and rates of sediment accumulation.

	Ridge Set 3	Ridge Set 4	Ridge Set 5
Age from	5400 ± 230	5300 ± 230	4400 ± 220
Age to	5300 ± 230	4400 ± 220	1800 ± 80
Duration (years)	100	900	2600
Width (m)	783	387	1565
Progradation (m $year^{-1}$)	7·8	0·43	0·6
Area (m^2)	8 307 308	5 067 407	16 054 638
Thickness (m)	5	9	6·6
Volume (m^3)	41 556 698	45 435 131	106 529 961
Accumulation (m^3 $year^{-1}$)	41 556	50 483	40 973

Thickness estimates from the GPR profile and topography.
The chronology has been derived from luminescence ages in Murray-Wallace *et al.* (2002).

Having calculated the volumes of sediment within Ridge Sets 3 and 4, rates of sediment accumulation are estimated using the OSL ages of Murray-Wallace *et al.* (2002). Ridge Set 3 has a volume of 41 556 698 m^3 accumulated over a period of around 100 years (5400 ± 230–5300 ± 230 yr), giving a sediment accumulation rate of 41 556 m^3 $year^{-1}$. Ridge Set 4 has a volume of 45 435 131 m^3 accumulated over a period of 900 years (5300 ± 230–4400 ± 220 yr), giving an accumulation rate of 50 483 m^3 $year^{-1}$. Ridge Set 5 has a volume of 106 529 961 m^3, which accumulated over a period of 2600 years (4400 ± 220–1800 ± 80 yr), giving a sediment accumulation rate of 40 973 m^3 $year^{-1}$ (Table 2). These sediment accumulation rates of 41 556 m^3 $year^{-1}$, 50 483 m^3 $year^{-1}$, and 40 973 m^3 $year^{-1}$, measured over periods ranging from 100 to 2600 years rare remarkably similar and suggest that sediment supply to the beach ridges has been consistent through the mid- to late Holocene.

DISCUSSION

During the Holocene, Guichen Bay has been infilled by prograding upper shoreface and foreshore sands capped by aeolian foredune beach ridges. The topographic expression of beach ridges at Guichen Bay is due to the preservation of vegetated foredune ridges overlying prograding beach deposits. The beach ridges are divided into six sets based upon their morphology, continuity and orientation. Ridge Set 1 is restricted to the south-eastern corner of the embayment where the beach ridges are convex to the west. Ridge Set 2 ridges show many truncation surfaces attributed to bathymetric effects within Guichen Bay. Ridge Set 3 beach ridges have greater continuity. Ridge Set 4 is widest in the south and pinches out towards the north. This probably followed the closure of the southern seaway connecting Guichen Bay to Rivoli Bay. Ridge sets 3 and 4 have been dated by Murray-Wallace *et al.* (2002) at between 5400 ± 230 yr (sample SA013) and 4400 ± 220 yr (sample SA011) indicating that the northern entrance to the seaway was closed slightly earlier than the 4000 years of Cann *et al.* (1999). Beach ridges in Ridge Sets 5 and 6 show a progressive decrease in radius of curvature, and a change in orientation, accompanied by a northward increase in ridge set width with the locus of deposition shifted from the southern end of the embayment towards the north. It has been suggested that changes in beach-ridge orientation document shifts in wind direction (Curray *et al.*, 1969; Mason *et al.*, 1997) which control the nearshore wave climate. At Guichen Bay, changes in beach-ridge orientation are attributed to changes in wave approach which is conditioned by inshore bathymetry and the direction of swell approaching from offshore. In this case, the large-scale shift in beach-ridge orientation in Ridge Sets 4, 5 and 6 may be attributed to a change in swell direction, whereas small-scale changes in beach-ridge orientation within Ridge Sets 2 and 3 are due to local changes in bathymetry.

Latitudinal shifts in palaeowind direction are widely invoked to explain changes in aeolian geomorphology in Australia (Sprigg, 1979; Nanson *et al.*, 1995). However, the spread of overlapping ages within desert dune sands makes it difficult to determine when changes occurred. The discrete, and dateable, discontinuities preserved within beach-ridge sequences, provide an opportunity to test models of latitudinal shift in palaeowind. The change in beach-ridge orientation within Guichen Bay suggest that a shift from a more westerly swell to the present south-westerly swell may have occurred gradually but with a significant shift between Ridge Sets 4 and 5. Based on the age determinations of Murray-Wallace *et al.* (2002), this would have occurred around 4400 ± 220 yr ago. The decrease in the radius of curvature of the beach ridges is attributed to a decrease in wave refraction in Guichen Bay that is probably caused by an increase in the wave length of the approaching west and south-westerly swell.

Studies of sea-level change in South Australia show that sea level has fallen during the mid- to late Holocene by 0·07 m k yr^{-1} (Murray-Wallace *et al.*, 1996). This would have resulted in a fall in relative sea level of 0·35 m as Guichen Bay was infilled over the past 5000 years. It has been suggested that the contact between the beach and dune facies can be used as a proxy for sea level, and that optical dating of the basal dune sands can be used to date changes in sea level (Knight *et al.*, 1998; Van Heteren *et al.*, 2000), although changes in wave run-up because of storm actvity should also be considered (Knight *et al.*, 1998). The elevation of the beach–dune contact picked from a change in radar facies (Fig. 7), is consistent between 3·5 and 4 m for most of the GPR profile. However, there is an apparent decrease in the elevation towards the shoreline at the western end of the profile (Fig. 7).

The beach ridges which form the visible topographic features on the coastal plain at Guichen Bay are vegetated foredunes. The foredune elevation increases from Ridge set 2 through Ridge Set 3 to a maximum in Ridge Set 4. The increase in foredune elevation is best explained by a decrease in the rate of coastal progradation which allows more time for dry sand to be blown from the beach to the foredunes. This is confirmed by the OSL ages of Murray-Wallace *et al.* (2002), who noted a dramatic decrease in the rate of beach progradation in the mid-Holocene at Guichen Bay which they attributed to a decrease in the rate of sediment supply. The present results show that while there was a decrease in the rate of progradation, the rate of sediment accumulation has remained remarkably consistent through the Holocene varying between 40 000 and 50 000 m^3 $year^{-1}$. It is suggested that the decrease in the rate of progradation is due to an increase in accommodation space as the beach prograded into deeper water. The reduction in the rate of progradation also resulted in increased time for foredune construction and therefore bigger foredunes. The combination of an increase in accommodation space and an increase in the foredune elevation resulted in increased sediment thickness and therefore a decrease in the rate of progradation.

The GPR profile shows many inclined, seaward-dipping reflections, extending down to depths of −1 m AHD – these are interpreted as beach progrades. The progrades show multiple truncation surfaces interpreted as storm events within upper shoreface and foreshore sediments. Above the progrades are discontinuous dipping reflections, interpreted as foredune deposits. The storm erosion surfaces identified within the upper-shoreface sediments on the GPR profiles do not always extend up into the foredune deposits. The surface topography of the foredune beach ridges is not directly linked to the subsurface truncation surfaces and does not show the stratigraphic complexity of the beach progradation/truncation.

The thickness of the upper-shoreface beach sediments increased over time as the beach prograded out into Guichen Bay. It is also noticeable that the dip of the beach progrades also increased. These observations are probably linked, and can be explained by an increase in water depth, and an increase in wave energy as the beach prograded into deeper water in the middle of the bay. This increase in accommodation space accompanied by a shift in wind and wave approach is a more likely explanation for the apparent change in the rate of beach progradation observed by Murray-Wallace *et al.* (2002).

Using sediment thickness data from the GPR profile, and the surface area of ridge sets of beach-ridge accretion, sediment volumes were calculated. Using existing OSL ages for beach ridges, rates of sediment accumulation have been calculated, which appear to be quite consistent. Thus, although the rate of progradation decreased during the mid-Holocene, this was not because of changes in the rate of sediment supply. Rather, the decrease in the rate of progradation determined by Murray-Wallace *et al.* (2002) is best explained by an increase in sediment thickness as the upper shoreface prograded into deeper water in Guichen Bay. There may also be a positive feedback because as the water depth increases and the rate of progradation decreases, there is more time for dune construction and higher foredunes are formed. While this can explain the increase in the elevation of dune ridges from Ridge Sets 2 to 4 and 5, it does not explain the changes in the orientation of the beach ridges which requires an additional change in wind direction. It is probable that the beach-ridge orientation is swash aligned and that the change in the orientation of the beach ridges and the shift in the width of the beach-ridge sets both record a change in the direction of wave approach. Wave approach up to Ridge Set 4 was from the north of west, swinging around to the west during Ridge Set 5 and then to the south of west during Ridge Set 6. In addition to the change in beach-ridge orientation, there is a decrease in the radius of curvature of the beach ridges indicating a decrease in wave refraction which is attributed to an increase in wave length. Thus the beach ridges at Guichen Bay record an increase in wavelength on the coast of south-east South Australia during the mid- to late Holocene. This increase in wavelength and change in wave approach is presumably related to westerly circulation patterns offshore.

CONCLUSIONS

During the Holocene, Guichen Bay has been infilled by prograding upper shoreface and foreshore sands capped by exceptionally well-developed aeolian foredune beach ridges which record the evolving shape of the bay and its beach. The beach ridges are divided into six ridge sets based upon their morphology, continuity and orientation. The foredune elevation increases from Ridge set 2 through Ridge set 3 to a maximum in Ridge set 4. The increase in foredune elevation is best explained by a decrease in the rate of coastal progradation which allows more time for dry sand to be blown from the beach to the foredunes. Conversely, when the rate of progradation increases the height of the foredune ridges decreases. In this case, the rate of progradation appears to be controlled by accommodation space.

The beach ridge orientation is swash aligned and therefore contains a record of wave approach and palaeowind direction. Changes in the orientation of the beach ridges, and the width of the beach ridge sets, record a change in the direction of wave approach which swung from the north of west, through west, to slightly south of west in the middle to late Holocene.

A 2·5 km GPR profile across the strandplain shows many inclined, seaward-dipping reflections, extending down to depths of −1 m AHD, and these are interpreted as beach progrades. The height of the beach progrades and the dip of the beach progrades both increased as the beach prograded into the bay, most likely in response to increasing water depth and increasing wave energy.

Rates of sediment accumulation calculated using sediment thickness data from the GPR profile, and calculations of beach-ridge areas from aerial photography, show that while progradation rates have changed, the rates of sediment accumulation have remained consistent through the Holocene varying between 40 000 and 50 000 m^3 $year^{-1}$. This contradicts the findings of an earlier study which used linear rates of progradation to suggest a decrease in sediment supply during the mid-Holocene. Rather, the decrease in the rate of progradation is due to an increase in accommodation space as the beach prograded into deeper water.

Changes in the rate of progradation calculated from a linear profile across the beach ridges do not take account of changes in ridge set width along strike, changes in sediment thickness and sediment volume. Calculating the rates of sediment accumulation from volumetric data is more reliable than linear projections for the interpretation of beach-ridge progradation because they can take account of changes in bathymetry, alongshore variations in progradation and shoreline morphology.

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