Holocene depositional history of three coastal sand ridge plains, southeastern Australia

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ABSTRACT

Holocene coastal sand ridge plains, also known as prograded barriers or strandplains, occur on many coastlines around the world. During the 20th century and into the 21st century, these coastal landforms have been investigated in order to understand the timing and mode of their emplacement, and their potential as paleoenvironmental records. Radiocarbon dating of coastal sand ridge plains in southeastern Australia has made a significant contribution to our knowledge of the Holocene deposition of these environments. This study examines three coastal sand ridge plains in southeastern Australia: Moruya (Bengello Beach), Wonboyn and Callala Beach. The Holocene depositional history of these sites was investigated using optically stimulated luminescence (OSL) dating of aeolian sands from individual ridges to construct a chronology of progradation. Ground penetrating radar (GPR) was used to image subsurface structures, and airborne Light Detection and Ranging (LiDAR) data provided a detailed picture of the morphology of each site. LiDAR data also enabled the determination of precise ridge heights and the calculation of aeolian sediment volumes. OSL dating at each site demonstrated that progradation proceeded at linear rates from ~7500 years ago to present. The OSL chronology of progradation at Moruya was a significant revision to the previously accepted pattern implied by radiocarbon dating. The age of progradation commencement around ~7500 years ago at each site corresponds closely with cessation of the post-glacial marine transgression on this coastline. Rates of progradation at Moruya and Wonboyn were ~0.3 m/yr, while Callala Beach prograded at ~0.1 m/yr. The Moruya embayment had the highest average aeolian sediment accumulation rate of the three sites at ~3600 m³/yr, Wonboyn had a slightly lower value of ~1760 m³/yr and Callala Beach had the lowest average sediment delivery at ~650 m³/yr. GPR data collected in shore normal transects across each site demonstrated that each barrier has built seawards in increments with a series of preserved storm beachfaces separated by accumulated material. The process of ridge building indicated by the GPR imaged reflectors appears similar to the process of incipient ridge development observed at Moruya in beach profiling over the past ~40 years; where ridge building occurs during post-storm recovery of the beachface. Each site is dominated by a modern foredune which is substantially higher than all other landward ridges. At Moruya,
GPR across this foredune reveals a series of landward dipping reflectors indicating the landward cascading of aeolian sediments not observed on any other ridges. These foredunes appear to represent an unprecedented degree of dune development on these barriers. This reconstruction of Holocene deposition at Moruya, Wonboyn and Callala Beach may inform future management of sandy coastlines as it quantifies the volumes of sediment involved in coastal progradation in southeastern Australia.
ACKNOWLEDGEMENTS

There are many people who need to be thanked, who have helped, guided and shaped my research direction and purpose. Firstly, Professor Colin Woodroffe, who has been a fantastic PhD supervisor. I have greatly appreciated the freedom to follow my burgeoning interests in this area of coastal geomorphology, and yet Colin has been able to both direct the course of my work, and perhaps reign in my ideas and focus me on where the key questions lie. Colin has been knowledgeable and has provided invaluable comments and constructive criticism in relation to the writing I have done in recent months. While no paragraph has escaped some form of modification, Colin’s suggested changes have always been improvements and this thesis is better for such feedback.

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As my PhD has entailed geochronology and geophysics alongside my natural forte of spatial analysis I have many people to thank for their practical help, advice and direction in bringing together this thesis. My thanks go also to Dr. Zenobia Jacobs for her direction and overseeing of my OSL laboratory work and data analysis. The OSL laboratory assistance of Dr. Terry Lachlan and Yasaman Jafari has been of great benefit to my OSL dating work and I wish to extend my grateful thanks to them. I am also grateful to Mads Toft from Mala Geoscience Australia for his professional assistance and advice with GPR data collection and processing. The advice and technical assistance of Brent Peterson has been of great help in all aspects of fieldwork during my candidature. Edward Oliver and Chris Owers also assisted in the field.

I am also grateful to my wife Elizabeth Oliver for her constant support during my candidature. Elizabeth has always provided a listening ear during my PhD and has been encouraging of my interests and keen to see my work developing.
DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any tertiary institution and, to the best of my knowledge, contains no material previously published by or written by any other person, except where due reference is made in the text of this thesis.

Thomas Oliver
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Sandy coastlines are common around the world and comprise a range of landforms constructed by dynamic processes. Coastal ‘barriers’ are one such feature of coastal systems and are accumulations of sediment above present sea-level formed by waves, tides and wind (Roy 1994) forming an intermediate zone between the ocean and the hinterland. The first use of the term ‘barrier’ by Gilbert (1885) was in relation to shore-parallel ridges on lake shores, and the term was not applied to coastal settings until Johnson (1919) adopted the term to describe sandy coastal deposits. Coastal barriers often cut off the mouths of embayments, and may be attached to bedrock structures, as is common in southeastern Australia, or unattached, as found in the barrier islands of southeastern and eastern United States (Woodroffe 2003).

Many types of barriers were recognised by Johnson (1919), including spits, salients and tombolos, cuspate forelands and detached forms which create coastal lagoons, swamps, inlets and barrier estuaries. The most widely accepted classification for an Australian setting is based on morphological character and long-term shoreline movement described by Roy et al. (1994). Roy et al. (1994) identify three broad categories which reflect sea-level changes: stillstand, transgressive and regressive, under which a series of morphologies further subdivide the various forms (Figure 1.1) such as transgressive dune barrier, prograded barrier or strandplain, stationary barrier and receded barrier.

The focus of this thesis will be on the depositional history of three ‘prograded barriers’ (according to the Roy et al. (1994) classification) also known as ‘strandplains’ or ‘beach ridge plains’ in southeastern Australia. The general morphology and stratigraphy of a prograded barrier (Figure 1.1) shows a series of shore parallel ridges which have built seawards on the exposed side of lagoon or estuary emplaced over transgressive sand deposits. The overall barrier is ‘filling in’ a geologically inherited embayment and a river or coastal inlet is often present proximal to one of the bedrock margins (Figure 1.1). Such a morphology is typical of prograded barriers of southeastern Australia (Roy & Thom 1981). Prograded barriers preserve historical shoreline position and orientation and are used as indicators of coastal processes in the past (Tamura 2012).
The first reconstructions of prograded barrier morphology, chronology and stratigraphy were based on drilling and radiocarbon dating of sites such as Nayarit, Mexico (Curray et al. 1969), Galveston Island, southeast Texas (Bernard & Le Blanc 1965) and Kiawah Island in South Carolina (Moslow & Heron 1981). These studies established the seaward accumulation of sand over the late Holocene as well as demonstrating the complexity of coastal evolution which involved the deposition of other units such as lagoonal or estuarine mud prior to barrier growth.

A coastal compartment and sediment budget approach to understanding prograded barrier morphology was proposed by Davies (1974) where a surplus of sand supplied to a compartment or ‘store’ resulted in coastal progradation. North American authors have used a sediment budget approach in understanding the formation of prograded barriers, attributing shoreline succession to zones of confluence in littoral drift patterns (Stapor 1971a, 1973, 1974, 1975; Stapor et al. 1991; Stapor & May 1983). Others have combined the notion of a sediment budget with measures of accommodation space due to sea-level changes in order to understand coastal barrier morphology (Curray 1964; Cowell et al. 2003a,b; Stive et al. 2009).

**Figure 1.1:** a) Stillstand barrier types according to Roy et al. (1994) and b) a generalised morphology and c) stratigraphy of a prograded barrier deposit.
In southeastern Australia, stratigraphic reconstruction and radiocarbon dating of prograded barrier deposits has been completed for a number of sites and a cohesive picture of late Holocene depositional history was established (Roy et al. 1994; Thom et al. 1981a). Such work has been instrumental in understanding the Holocene deposition of the southeastern Australian coastline where barrier growth has proceeded at various rates following Holocene sea level reaching at or close to its present height. These compartment-scale investigations of prograded barrier deposits in southeastern Australia have resulted in the modelling of Holocene coastal deposition on this coastline (Daley 2012; Kinsela 2014; Cowell et al. 2003b). Other models of coastal change have also been applied at shorter timescales to understand coastal behaviour on the decadal to interdecadal time scale relevant to coastal managers (Cowell et al. 1999b; Deng et al. 2014). Such models attempt to quantify the critical factors for barrier development such as substrate gradient, wave and tide energy, sediment supply and accommodation space.

Another approach to understanding coastal deposition and prograded barrier development has been to consider sediment supply interactions between beach and dunes (Psuty 1992). Such an approach has involved the quantification of sediment budgets for various components of the barrier system in an attempt to understand the interaction of these components and how this in turn may control barrier morphology (Anthony 1995; Bauer & Davidson-Arnott 2002; Garrido et al. 2013; Saye et al. 2005).

With the development of optical dating techniques, prograded barrier deposits around the world have been subject to chronological investigations using this dating method (Guedes et al. 2011; Murray-Wallace et al. 2002; Reimann et al. 2011). In addition, ground penetrating radar (GPR) has been used to investigate coastal barrier stratigraphy (Bristow & Pucillo 2006; Dillenburg et al. 2011; Gontz 2014), and Light Detection and Ranging (LiDAR) has been used to describe barrier morphology (Timmons et al. 2010). Such new technologies offer the potential to reinvigorate the study of coastal barriers and provide further opportunity to continue to unravel the unique coastal morphodynamic and environmental records these coastal landforms contain (Tamura 2012).
This research investigates the Holocene deposition of three prograded barrier systems on the NSW south coast; Moruya (Bengello Beach), Wonboyn and Callala Beach, using optically stimulated luminescence (OSL) dating, GPR and LiDAR elevation data.

This thesis is arranged such that Chapter 1 reviews the literature concerning prograded barrier deposits, with special attention given to the work of Australian researchers from the 1950’s to the 1970’s. Chapter 2 presents the methodology used in this study describing the three main techniques OSL, GPR and LiDAR. Chapters 3, 4 and 5 relate to Moruya (Bengello Beach), Wonboyn and Callala Beach respectively and present the results relating to each of these sites. In Chapter 6 a discussion contrasts these sites in order to better understand the local and regional controls on Holocene barrier deposition. Comparisons are also drawn with other studies of Holocene barrier development and future work is outlined. Chapter 7 presents the primary conclusions of this study.

**NSW south coast setting**

The NSW south coast is broadly defined as the region from Sydney down to Cape Howe on the border with Victoria which fringes the Tasman Sea (Figure 1.2). The geology of this region may be divided into two distinct basins; the Sydney Basin which extends south to Batemans Bay and the Lachlan Fold Belt from Batemans Bay to beyond Cape Howe. The Sydney Basin is a Permian Triassic sandstone sequence with structures traverse to the coastline and resulting in low to moderate coastal relief (Roy & Thom 1981). The Lachlan Fold Belt is composed of Palaeozoic metamorphic and igneous rocks with structures parallel to the coast and forming a high relief coastline (Roy & Thom 1981). Tertiary basalts also feature along this coastline e.g. near Narooma. This regional geology of the south coast of NSW has formed a coastline where Holocene sediments infill generally small bedrock controlled embayments and have formed mainland beaches, barrier estuaries and drowned river valleys. Rivers of the NSW south coast are small in comparison with the northern coast of NSW and Queensland with the Shoalhaven River having the highest discharge of the major river systems and catchments depicted in Figure 1.2. Their contribution to the sediments infilling bedrock embayments is considered to be minimal (Roy et al. 1980) and far outweighed by the supply of ‘marine sands’ from the inner continental shelf inherited from Quaternary landform processes acting at different sea levels.
Figure 1.2: Map of the NSW coast south of Sydney showing major towns, rivers and catchments and the location of the three barriers investigated in this study.
The general nature and distribution of sediments on the continental shelf as well as the distribution of nearshore wave energy is summarised in Figure 6 of Roy and Thom (1981) and the coastline south of Sydney is depicted as having a greater proportion of nearshore wave energy, rocky barriers impeding sediment movement and mud and fine sand provinces compared to the north coast. With the general approach of waves to the south coast of NSW from the S to E (Mortlock & Goodwin 2015) this whole coastline has a tendency for northward littoral drift patterns (Roy et al. 1980). However, littoral drift processes are more restricted south of Sydney than further north due to the more embayed nature of the coastline impeding sediment movement on the inner shelf. Some individual embayments display a strong drift aligned character, for example Tathra beach where the Bega River joins the Tasman Sea, which has a distinct zeta form shape at the present time. However, in general the shoreline orientation and curvature of beaches and barriers of the south coast of NSW are more strongly influenced by wave refraction into embayments rather than strong down-drift movement of sediment. The refraction of waves into bedrock embayments has a tendency distribute sediment in such a way that the wave orthogonals are perpendicular to the shoreline (Figure 1.3) (Davies 1958b). This process is imprinted in the morphology prograded barriers investigated by this study.

![Figure 1.3: A) sediment movement when the coast is not aligned with dominant wave approach and B) a coastline configured to the dominant wave approach. Modified after Davies (1958b).](image)

The tidal range on the NSW coast south of Sydney is micro tidal with water levels oscillating 1-2 metres in a mixed semi-diurnal pattern. Wind patterns along this coastline have a strong seasonality with onshore winds from the NE in summer and offshore W to SW winds in winter (Figure 1.4). While the dominant wave approach is from the SE, strong summer NE fetches often produce small short period swells which
interact with longer period S ground swells. ‘East Coast Lows’ are intense low pressure systems which linger over the NSW coast can occur throughout the year and often produce damaging waves, winds and rainfall.

**Figure 1.4:** Summer and winter wind roses for Bega at 3 pm. Wind direction and strength is depicted by the brown coloured bars and their distance out from the centre of the rose indicates the percentage occurrence in 10% intervals. The larger inner circle for the winter rose indicates a greater percentage of calm.

### Holocene sea-level change in NSW

Holocene sea-levels around the Australian margins have been subject to considerable debate (see Lewis et al. (2013) for fuller discussion). Sloss et al. (2007) indicate that NSW has experienced a 0.5 -1.5 m highstand beginning from around 7700 cal yrs BP and continuing until around 2000 cal years BP after which there was a sea-level fall to current mean sea-level (Figure 1.5). Other authors have suggested that there has been an oscillating late Holocene sea-level curve e.g. Baker and Haworth (2000). This oscillating pattern interpreted from the elevation of intertidal species may be a product of these species adjusting to variable coastal exposure from wave climate or estuarine geomorphic changes.
In the context of Holocene barrier progradation, it should be noted that sea-level fall is not essential in order to achieve progradation, although falling sea-level would generally promote this, due to the shallowing of the offshore profile which in turn promotes onshore movement of sand as the shoreface adjusts to mean wave climate conditions. Although Billy et al. (2015) demonstrates that shoreline progradation has occurred with a slowly rising sea-level. Kinsela et al. (2016) used three sea-level scenarios in modelling Holocene progradation at Tuncurry and in each case a relative sea-level fall could not explain the observed volumes of sediment prograded over the Holocene; rather an ‘overfit’ shelf was the primary driver of progradation.

*Figure 1.5: Proposed Holocene sea-level curve for NSW after Sloss et al. (2007).*
CHAPTER 1: COASTAL SAND RIDGE DEPOSITS - A REVIEW
1.1 Defining coastal sand ridge deposits

1.1.1 A working definition

Coastal sand ridges have been refered to using a wide range of terms since Johnson (1919) who used the term ‘beach ridges’ referring to the low relief shore parallel ridges he observed along parts of the American coastline. Some researchers have preferred terms such as ‘dune ridges’ (Hails 1969; Mason 1992; Thom et al. 1994), ‘foredune ridges’ (Bristow & Pucillo 2006; Hesp 1999; Hesp 2006; van Heteren 2014), ‘relict foredune ridges’ (Goodwin et al. 2006; Murray-Wallace et al. 2002) and ‘aeolian beach ridges’ (Mauz et al. 2013). Otvos in his review of these coastal landforms proposed that the term “beach ridges should include all relict strandplain ridges, whether dominated by waves/ swash-built or by aeolian lithosomes” Otvos (2000 p.83). The term standplain as used by Otvos (2000) refers to a regressive barrier (Barboza et al. 2011) or prograded barrier (Roy et al. 1994). Contrary to the Otvos (2000) definition, Hesp (2006) and Barboza et al. (2011) both restrict the definition of ‘beach ridge’ to a swash built feature and distinguish foredunes and foredune ridges from ‘beach ridges’ on the basis that foredunes contain aeolian facies.

The term ‘relict foredune ridge’ used by Murray-Wallace et al. (2002) is helpful insofar as it emphasises the idea that when these ridges were actively forming, they displayed the characteristics of a foredune; having a significant aeolian component (Hesp 2006). However, the terms ‘foredune ridge’ or ‘relict foredune ridge’ may be less desirable in our nomenclature as ‘foredune ridge’ has been used by Thom (1983) to refer to a ‘stationary barrier’ (Figure 1.1.A). A ‘beach ridge plain’, ‘prograded barrier’ (or strandplain) is distinguished from a ‘foredune ridge’ or ‘stationary barrier’ by Thom (1983) on the basis that there is sequence of ridges apparent. It is here argued that the term ‘coastal sand ridges’ or ‘coastal sand ridge plain’ is a more appropriate general term instead of ‘beach ridges’ or ‘beach ridge plain’ when applied to coastal low-lying areas where a series of ridges are preserved landward of the present shoreline.

The coastal sand ridge plains studied in this thesis are composed of low relief, shore parallel, laterally persistent ridges which formed proximal to the beach and composed of marine and aeolian sands. The term ‘coastal sand ridge’ or ‘prograded barrier’ is henceforth used as general terms referring to the sites investigated in this study.
1.1.2 Coastal sand ridge formation

 Debate regarding the formation of coastal sand ridge plains has been ongoing since they were first described by the English geomorphologist Redman (1852, 1864) who used the term ‘fulls’. Since the mid 1950’s there have been many proposed explanations of coastal sand ridge formation derived from various coastal sand ridge systems around the world. Debate regarding the formation of coastal sand ridges differ in three important ways: (1) what is the nucleus of a ridge: berm (Figure 1.6, 1), emerging offshore bar (Figure 1.6, 2), attached terrace (Figure 1.6, 3) or storm surge deposit (Figure 1.2, 4), (2) are storm waves destructive or formative in ridge building and (3) does vegetation construct or preserve ridges. Such distinctions are also illustrated by Tamura (2012) who notes that differing formation processes are likely under various prevailing conditions.

 Curray et al. (1969), based on observations on the coast of Mexico, proposed that ridge formation involved an emerging longshore bar which persisted and stabilised and then accumulated aeolian material under conditions of ongoing sediment supply (Figure 1.6, 2). A narrow lagoon between each ridge would commonly form as the emergent longshore bar stabilised: such lagoons are a feature of many Mexican ridge plains. Observations of ridge development in Northern Ireland by Carter (1986), supports an emerging bar formation hypothesis. A post storm perturbation model developed by Carter (1986) showed two different modes of ridge formation depending on whether the dominant movement of sediment was alongshore or onshore. Onshore movement led to a berm ridge formed by bar narrowing and swash bar formation, whereas longshore movement led to ridge formation due to bar elongation and welding (Carter 1986).

 Psuty (1965) from observations of the extensive ridge plain at Tabasco, Mexico, produced a model of ridge development where deposition of sediment occurred during a storm surge event at the landward margin of the affected coastal zone which was preserved as summer wave conditions subsequently widened the beach. Ovtovs (2000) proposed a model of ridge formation involving three of the four models shown in Figure 1.6 and presenting the ridge formation sequence as comprising an onshore migrating bar which forms a berm ridge, which then transforms into an active foredune and is preserved and stabilised by vegetation.
CHAPTER 1: COASTAL SAND RIDGE DEPOSITS - A REVIEW

Figure 1.6: A summary of the principal theories of coastal sand ridge formation discussed in this chapter, compiled and redrawn from the sources cited.
Stapor published a suite of papers focused on the sediment budget aspects of coastal sand ridge formation highlighting the importance of littoral drift and the convergence of littoral cells for producing ridge sequences (Stapor 1971b, 1973, 1974, 1975; Stapor et al. 1991; Stapor & May 1983). Stapor and May (1983) related the geometry and parallelism of the ridges to the influence of longshore drift, whereby greater regularity and spacing with little bifurcation and amalgamation of ridges, indicated the dominance of onshore sand transport rather than longshore transport. Stapor (1975) concluded that on the sediment compartment scale, it is likely that a several processes, rather than a single process controls ridge development but that one process may take precedence due to complex internal morphodynamics.

Considering the formation processes of individual ridges, it was hypothesised that the dominant process of formation of coastal sand ridges is by swash transport during constructive swells (Tanner & Stapor 1972). The classification presented in Tanner (1995) reflects this hypothesis where the ridges are categorised into: swash built, settling lag, aeolian, storm surge. Presumably a swash-built feature forming during constructive swells would be categorised as a berm. This would broadly place the Tanner (1995) hypothesised mode of ridge formation within the stabilising berm category (Figure 1.6, 1i), however they refute the notion of a significant aeolian influence (Stapor 1971a; Tanner 1995). Instead, Holocene sea-level fluctuations are discussed as the most critical factor in forming ridges due to the tendency of a concave-up offshore profile to increase wave height and run-up when sea level fluctuates by as little as 5-30 cm (Tanner 1995). Hesp (2006) points out that Taylor and Stone (1996) in their review focused on the American literature and hence follow the Stapor definition although Taylor and Stone (1996) add that ridges may also be formed by the action of wind-blown sand.

The work of these American researchers may reflect North American situations but differ from the principal observations and ridge formation hypotheses proposed for Australian settings (Davies 1957; Thom 1964). Iconic Australian coastal sand plains such as at Moruya, NSW (Thom et al. 1981a) are undoubtedly very morphologically different to the types of ridges being described by the American researchers mentioned above, as the difference in height between the inter-ridge swale and crest of each ridge is in the order of a few tens of centimetres for sites mentioned by Tanner (1995), compared to Moruya where the difference is in the order of 1-2 metres.
Australian researchers have tended to place greater emphasis on the role of aeolian accumulation and vegetation stabilisation in ridge formation. Davies (1957) and Bird (1976) regard a ridge as a compound feature comprising aeolian and beachface sand (Figure 1.6, 1). In this model, the degree of aeolian capping may be attributed to changes in sediment supply (Bird 1976; Hails 1965; Thom 1964), beach modal state (Short & Hesp 1982) or variations in the amount of time for which a particular ridge is actively accumulating sediment (Shepherd 1987).

Hesp (1984b) considered long term ridge formation to be identical to the process of incipient dune formation whereby vegetation grows seaward and builds a ridge as it traps windblown sand. (see Figure 1.6, 3). In this model the developing ridge is not a berm but resembles rather an emerging terrace attached the backshore where the inter-ridge swale is formed as a low deposition zone behind the incipient ridge (Hesp 2002). The role of pioneer vegetation in trapping sand is fundamental to the creation of incipient foredunes in this model proposed by Hesp (1984a).

In contrasting the work of Australian and international researchers on ridge formation, Hesp made the important distinction between ‘berm nucleus’ theories and the incipient foredune theory stating categorically that “the presence of a berm is therefore not a necessary pre-requisite for foredune, or ridge formation” Hesp et al. (2005) p.498. The evidence the conclusion of Hesp et al. (2005) is twofold (1) that berms are not colonised by vegetation (Hesp 1984a; Hesp 1984b) and that dissipative beaches have no berms and yet may be backed by ridge plains (Hesp 1999). However, McLean and Shen (2006) have observed that a berm with a height of 2.3 m above MSL and a width of 30 m must exist in order for incipient foredune formation to occur at Moruya, NSW.

Researchers have also disputed the relative role of storm waves and constructive waves in forming ridge sequences. Davies (1957) proposed that storm waves would cut away any berm feature which might form a ridge and that a ridge is essentially a ‘calm weather’ feature (Figure 1.6, 1i). On the other hand Bird (1976), who agreed with Davies hypothesis that a berm is the starting point for ridge development, argued that a scarped berm and the subsequent rebuilding of the beachface, would move sand onto the relict scarp and form an incipient ridge which would then accrete and stabilise. More recently Dougherty (2009) has supported the hypothesis of Bird (1976) with the use of
Ground penetrating radar (GPR) identifying the scarp, recovery and aeolian capping units associated with this formation hypothesis.

Amongst international researchers there has been disagreement as to the role of storm waves: are they depositional (as in Psuty 1965), or do they provide a morphologic perturbation conducive to subsequent sediment accumulation. While both Carter (1986) and Curray et al. (1969) provide variations of the ‘emerging bar’ hypothesis, the model of Carter (1986) depends on the presence of a storm event and the ridge is formed by sediment being redistributed within the system, whereas the model of Curray et al. (1969) depends on the continuation of fair weather conditions where offshore sand derived from the shelf or longshore drift is moved onshore. Tanner (1995) summarising the results of American researchers concluded that coastal sand ridges are not the result of storms but rather fair-weather conditions.

1.2 Coastal sand ridge deposits: global examples

1.2.1 Distribution

Coastal sand ridge deposits occur around the world on coastlines of almost all latitudes which have some degree of exposure to waves and wind (Scheffers et al. 2011). Coastlines experiencing tropical and arid climates have coastal sand ridges as well as locations were sea-ice may be present during the winter months (Scheffers et al. 2011). However, the most favourable conditions for ridge development, and where the most extensive ridge plains exist, are in locations with low substrate angles and a high sediment supply. Such conditions are often found near the mouths of rivers and coastal sand ridges commonly form in association with delta front migration (Tamura et al. 2012). Large embayments which collect or trap sediment moving alongshore also commonly contain coastal sand ridge plains.

1.2.2 Chronostratigraphic studies

1.2.2.1 Radiocarbon dating

Reconstructing detailed barrier morphology, chronology and stratigraphy began at what are now ‘classic’ barrier island coastal areas such as Galveston Island, south east Texas (Bernard & Le Blanc 1965) and Kiawah Island in South Carolina (Moslow & Heron 1981). The work of Curray et al. (1969) at the extensive prograded barrier at Nayarit, Mexico also contributed to this important period of coastal barrier research. The use of
radiocarbon dating was instrumental in understanding the chronology of these Holocene coastal deposits, and the technique, although being less than 20 years old, successfully demonstrated the seaward building of successive ridges over the Holocene. These studies also informed the discussion at the time regarding the general formative processes of barrier islands.

Further research on barrier islands in North Carolina has been completed by Timmons et al. (2010) where radiocarbon and OSL dating, GPR, coring and marine seismic data were used to reconstruct the late Holocene deposition of the coastal landforms indicating a transition from regressive (seaward shoreline movement) to transgressive (landwards shoreline movement) conditions. Interestingly the apparent primary forcing for erosional processes was high storm frequency, rather than a rise in relative sea level (Timmons et al. 2010). On the north western coast of the USA radiocarbon dating constrained the formation of transgressive and regressive stratigraphies north and south of the Columbia River illustrating the localised effect of the large sediment discharge, where localised sediment deposition outpaced the effect of sea-level rise, but did not reach neighbouring littoral cells (Gelfenbaum & Kaminsky 2010).

Radiocarbon dating has continued as an important method for constraining the deposition of prograded barrier systems around the world. Tamura et al. (2003) used radiocarbon dating to understand the timing of deposition of beach-shoreface deposits in eastern Japan, demonstrating that progradation of this coastline has proceeded since 6000 cal yr BP. Coastal uplift in the order of 5-10 m of the Boso Peninsula, Japan was also deduced from radiocarbon dating of an extensive Holocene prograded barrier system greater than 10 km wide (Tamura et al. 2007; Tamura et al. 2010).

1.2.2.2 Luminescence dating

Thermoluminescence dating of Quaternary coastal sediments accurately reconstructed successive depositional dune ridges in southeastern South Australia (Huntley et al. 1993; Huntley et al. 1994; Huntley & Prescott 2001) and was used to constrain Holocene coastal deposition along the NSW coast (Young et al. 1993). OSL dating of coastal sand ridge sequences was first undertaken by Murray-Wallace et al. (2002) and has hence been adopted as an important chronological tool for constraining the deposition of coastal progradation around the world.
OSL dating was adopted to reconstruct the depositional history of the Holocene prograded barrier in northern Denmark (Nielsen et al. 2006). An average total dose rate of 1.33 Gy/ka for these northern European samples allows very young Holocene age samples, such as reported in this study (Nielsen et al. 2006), to avoid the problems of low signal to noise ratios common when dating samples <1000 years old (Masden & Murray 2009). Dose rates between 1-3 Gy/ka are common for coastal Holocene quartz samples from this part of the world (Lindén et al. 2006; Masden et al. 2005; Mauz & Bungenstock 2007).

Luminescence dating of coastal progradation for the southwest Baltic sea coastline (Reimann et al. 2011) revealed progradation and spit growth in a series of ridges punctuated by phases of erosion evidenced by foredune instability. These phases of instability correlate with Little Ice Age type events and periods of increased aeolian activity in North and West Europe over the past ~4000 years (Reimann et al. 2011).

Application of luminescence dating to prograded portions of barrier islands in Florida, USA enabled depositional reconstruction in these environments and, due to the unique multi-depth sampling of each ridge, provided and indication of ridge accumulation rates (Rink & López 2010). This multi-depth sampling of each ridge demonstrated that vertical accumulation of ridges continues, albeit at a slower rate, even once stranded behind newly forming ridges (López & Rink 2008; Rink & López 2010).

The depositional history of a prograded barrier in southeastern Brazil was investigated by Guedes et al. (2011) using OSL dating, who demonstrated that slower barrier growth rates coincided with erosional events. A relative sea-level fall in this region from around 7000 years ago to present, while mobilising sediment for progradation, did not primarily control sediment retention within the barrier system; rather it was the pre-existing bedrock topography (pre-Cainozoic hills) which dictated where the sediment traps were, and hence where sediment accumulated (Guedes et al. 2011).

In the central Mekong River delta, OSL dating successfully distinguished ridge ages to such a degree as to allow centennial to multi-decadal shoreline changes to be mapped (Tamura et al. 2012). Discontinuous shifts in the position of the shoreline in the order of 5 km were caused by the formation of a delta front bar/island every 200-600 years (Tamura et al. 2012). The use of OSL dating for young Holocene sediments, even those less than 1000 years old (Madsen & Murray 2009), has exciting prospects for bridging
our understanding between the longer term records of coastal deposition and historical data sets if centennial and multi-decadal changes are distinguishable as in Tamura et al. (2012).

1.2.3 Ground penetrating radar studies

Ground penetrating radar (GPR) has been used in recent years to image the subsurface structures of prograded barrier deposits around the world. The development of this technique for understanding coastal barrier deposition was pioneered in studies such as Roy et al. (1994), Smith et al. (1996), Neal and Roberts (2000) and Neal (2004). This research noted the applicability of this geophysical technique for imaging subsurface structures in sandy environments and considered the specific dialectic and conductivity characteristics of coastal substrates.

Following these initial investigations detailed stratigraphic reconstructions of prograded barrier deposits were completed, such as at Massachusetts, USA (Dougherty et al. 2004). This work involved an intensive GPR survey pattern in order to capture the complex Holocene history of this barrier and detailed ground truthing with cores indicated that the strong curved beachface reflectors were related to storm lag deposits (Dougherty et al. 2004). Pleistocene prograded barrier deposits have also been successfully imaged with GPR (Dougherty & Nichol 2007). Bristow and Pucillo (2006) imaged a sequence of beachfaces at Guichen Bay, SA and were able to calculate sediment volumes above the basal limit of these reflectors. Roy et al. (1994) using a 100 MHz antenna showed the seaward succession of the barrier stratigraphy at Forster, NSW.

Over the last 5-10 years there has been an upsurge in the use of GPR for prograded coastal barrier subsurface investigation around the world including Japan (Tamura 2008; Tamura et al. 2010), Brazil (Boski et al. 2015; Dillenburg et al. 2011; Hein et al. 2013, 2014) and the USA (Buynovich et al. 2004; Timmons et al. 2010). These studies demonstrate the utility of GPR data for understanding coastal progradation and for extracting palaeoclimatic records stored within these coastal landforms (Cunningham et al. 2011; Tamura 2012).
1.3 Coastal sand ridge deposits in Australia

1.3.1 Distribution and environmental setting

Holocene coastal sand ridge plains are found in many locations around the Australian mainland although they vary in size and character (Figure 1.7). While the most well studied ridge plains are those of southern and eastern Australia, by far the most extensive are those in the northwest of Australia. These systems can be greater than 5km wide and 10’s of kilometres long. The more accessible locations such as in NSW are smaller and generally less imposing, although distinctive.

Figure 1.7: The location of coastal sand ridge plains around Australia studied in the literature. Numbering corresponds to Table 1.1. Map data from Geoscience Australia.
Coastal sand ridge plains are formed in a variety of geomorphic settings and can vary in composition from >90% quartz sands to >90% carbonate sands. They are often found at the mouth of rivers where there is a large sediment supply. Coastal compartments divided from proximal areas of coastline by prominent headlands also act as sediment trap for sand moving alongshore which promoted coastal progradation. They are most commonly found in mid to low energy regimes (Short 1988), but always require a low offshore profile to supply sediment to the shoreface and beachface (Davies 1957; Taylor & Stone, 1996). Figure 1.8 shows a schematic representation of the divisions used in this thesis for the components of the coastal system. This nomenclature is derived from Eliot and Clarke (1982) and Cowell et al. (1999a) where the terms offshore, beachface and shoreface were most clearly used in relation to the coastal geomorphic system.

Figure 1.8: Coastal zone definitions used in this thesis applied to a typical morphology of a coastal sand ridge plain in NSW. Adapted from Eliot and Clarke (1982) and Cowell et al. (1999a).

### 1.3.2 Early Australian research

At the end of the 19th Century scientists began to investigate the coastal geomorphology of Australia. Examples of the early work include Carne (1895) who investigated beach sand deposits surrounding the Esk River (a northern tributary of the Clarence River) and Jerusalem Creek (just to the north of the Esk). This is a Pleistocene backbarrier sequence (Goodwin et al. 2006) where low sand dunes are interspersed with swamps. This is likely the first scientific description of a Pleistocene coastal sand ridge sequence in Australia, although this terminology is not used.

Between the 1890’s to 1950’s much of the coastal research in Australia focused on mining exploration, in particular beach sand and heavy mineral deposits e.g. (Carne
1895, 1896; Connah 1948) Much of this work is summarised by Gardener (1955) in a bulletin for the Bureau of Mineral Resources: Geology and Geophysics, Department of National Development titled “Beach-sand heavy mineral deposits of eastern Australia”. There is no explicit description of coastal sand ridges in this work although doubtless the research undertaken and reviewed by this report would have involved investigation of such environments.

Andrews (1912) described what he considered to be emerged “low and ball” features of the Botany Bay shoreline. Johnson (1919) explained the term “low and ball” as referring to a series of subaqueous ridges and troughs of considerable distance which lie parallel to the shoreline. This term had been used with some confusion in the 1890’s to 1950’s according to Evans (1942). Johnson (1919) makes no reference to Andrews (1912) but clearly describes the mode of coastal sand ridge formation as not emerged ‘low and ball’ features.

Burges and Dover (1953) commented on emerged the “low and ball” hypothesis of Andrews (1912) citing evidence from a coastal sand ridge plain at Woy Woy, NSW where soil profile development indicated a chronology not consistent with recent emergence of subaqueous ridges. This work appears to be the first chronological study of coastal sand ridges in Australia. Burges and Drover (1953) assumed that the ridge sequence was approximately 4000 years old, citing evidence from Cotton (1926) who studied drowned coastal valleys in Australia concluding that sea-level reached stability close to present levels, between 3000-5000 years ago. From this assumption a chronology based on calcium carbonate leaching and podzol formation was developed whereby the ridge plain was thought to have prograded at a rate of around 1 yard (0.9m) per year (Burges & Dover 1953).

Sprigg (1952) in a Bulletin of the Geological Survey of South Australia examined the coastal deposits of the Naracoorte region including the Pleistocene shorelines and more contemporary ridge plains such as the Guichen Bay. While later advances in dating allowed chronological analysis of these Quaternary shoreline features, soil analysis was the only method for chronological investigation during this early phase of coastal geomorphic research in Australia. For example Blackburn et al. (1967) in his work for the CSIRO mapped soils across the Pleistocene ridges in south western Victoria commenting on the age of these features in terms of soil type and development.
Sprigg (1952) also commented on the ridge formation hypothesis of Andrews (1912) and proposed a ridge formation mechanism involving oscillations in the height of wave attack due to sea level, tides or storms. The more contemporary Holocene ridge plains in this region of South Australia, such as at Kingston, seemed to be actively forming at the beginning of the last century: “on the property of William Barnett just north of Kingston, two and half additional beach ridges had formed since the property was originally fenced along the then shoreline in the 1880’s” (Tindale 1954 p.228). Thus in this region of Australia there is a full spectrum of Quaternary coastal deposition; from Pleistocene shorelines, to late Holocene deposition (Murray-Wallace et al. 2002).

A discussion regarding coastal sand ridges and their formation was started by Davies (1957) with his paper; “The Importance of Cut and Fill in the Development of Sand Beach Ridges” in which he studied a number of ridge plains in south-eastern Tasmania. Davies (1957) suggested that a ridge was developed from a beach berm which became stranded behind a new incipient berm and accumulated windblown sand to form a low ridge. This process was dependent on calm weather so as not to “cut” away the accumulating berm or the incipient berm at either stage (Davies 1957). Davies (1957) repeatedly refers to Johnson (1919) supporting his hypothesis that the most fundamental requirement for ridge building is a shallowing or flattening of the offshore profile. However, Davies (1957) made a new distinction between ridges composed of sand and ridges composed of gravel (more common in Europe and North America) proposing that storm waves tended to throw up pebbly material landwards to form ridges but to cut away sand, destroying a berm, and thus in his mind, preventing a sandy ridge from forming. Hails (1969) describing the ridge sequence at Woy Woy, NSW, agreed with the of hypothesis Davies (1957) that ridges are formed as persistent berms become stabilised by vegetation and collect a wind-blown sand capping.

In commenting on the age of the coastal sand ridge systems studied by other Australian researchers Davies (1957) noted that the similarity of Tasmanian ridges to those of New South Wales, Victoria and South Australia, means it was likely that they were of similar age: post-glacial and most likely within the “mid-Recent” (Holocene) period. Gill and Banks (1956) also agreed with a Holocene age estimate after studying the Black River ridge sequence in Tasmania.
Table 1.1: Holocene coastal sand ridge plains reported in the literature around Australia with their location, dating method/s, number of dates, youngest and oldest age and references.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Site Name</th>
<th>(No. of ridges approx.)</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Dated dates</th>
<th>(No. of dates)</th>
<th>Method</th>
<th>Youngest Date</th>
<th>Oldest Date</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td><strong>New South Wales</strong></td>
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<tr>
<td>1</td>
<td>Jerusalem Creek</td>
<td>29°15’ S 153°21’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Carne 1985; Gardner 1955; Roy &amp; Thom 1981)</td>
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<tr>
<td>2</td>
<td>Iluka-Woody Bay</td>
<td>29°22’ S 153°22’ E</td>
<td>Yes (°C-15, OSL-8)</td>
<td>13°C OSL</td>
<td>345 ± 42 230 ± 50</td>
<td>4753 ± 245 1690 ± 200</td>
<td>(Goodwin et al. 2006)</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>Forster/ Tuncurry</td>
<td>32°7’ S 152°30’ E</td>
<td>Yes (32)</td>
<td>13°C</td>
<td>1100 ± 200</td>
<td>8520 ± 790</td>
<td>(Melville 1984; Nielsen &amp; Roy 1981)</td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>Myall Lakes</td>
<td>32°29’ S 152°22’ E</td>
<td>Yes (4)</td>
<td>13°C</td>
<td>870 ± 65</td>
<td>7280 ± 110</td>
<td>(Thom 1965; Thom et al. 1981c)</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Fens Emplacement</td>
<td>32°39’ S 152°11’ E</td>
<td>Yes (13)</td>
<td>13°C</td>
<td>3480 ± 260</td>
<td>6000 ± 270</td>
<td>(Shepherd 1974; Thom et al. 1978; Thom et al. 1981a,b; Thom 1965)</td>
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<tr>
<td>6</td>
<td>Newcastle Bight</td>
<td>32°47’ S 152°3’ E</td>
<td>Yes (11)</td>
<td>13°C</td>
<td>360 ± 160</td>
<td>6890 ± 310</td>
<td>(Thom et al. 1981a)</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>Wool Woy Woy</td>
<td>33°31’ S 151°19’ E</td>
<td>Yes (32)</td>
<td>13°C</td>
<td>1340 ± 280</td>
<td>7110 ± 220</td>
<td>(Thom et al. 1981a)</td>
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<tr>
<td>8</td>
<td>Seven Mile Beach</td>
<td>34°49’ S 150°45’ E</td>
<td>Yes (20)</td>
<td>13°C</td>
<td>720 ± 170</td>
<td>6640 ± 240</td>
<td>(Thom et al. 1981a)</td>
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<tr>
<td>9</td>
<td>Callala Beach</td>
<td>35°1’ S 150°41’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Thom 1987)</td>
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<tr>
<td>10</td>
<td>Batemans Bay</td>
<td>35°42’ S 150°11’ E</td>
<td>Yes (15)</td>
<td>13°C</td>
<td>700 ± 160</td>
<td>4220 ± 350</td>
<td>(Thom et al. 1981a)</td>
<td></td>
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<tr>
<td>11</td>
<td>Moruya</td>
<td>35°53’ S 150°9’ E</td>
<td>Yes (°C-37, OSL-11)</td>
<td>13°C OSL</td>
<td>2450 ± 270 7220 ± 390</td>
<td>6530 ± 250 390 ± 60</td>
<td>(Thom et al. 1981a; Oliver et al. 2015)</td>
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<tr>
<td>12</td>
<td>Wondabyne</td>
<td>37°16’ S 149°57’ E</td>
<td>Yes (15)</td>
<td>13°C</td>
<td>950 ± 210</td>
<td>8650 ± 330</td>
<td>(Thom et al. 1981a)</td>
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<tr>
<td><strong>Victoria</strong></td>
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<tr>
<td>13</td>
<td>Lakes Entrance</td>
<td>37°53’5.5” S 147°38’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Bird 1960)</td>
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<tr>
<td>14</td>
<td>Sperm Whale Head</td>
<td>37°59’ S 147°41’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Bird 1961)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tasmania</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>15</td>
<td>Lavinia Point</td>
<td>39°41’ S 144°6’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Jennings 1959)</td>
<td></td>
<td></td>
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<tr>
<td>16</td>
<td>Anthonys Beach</td>
<td>40°48’ S 145°14’ E</td>
<td>Yes (3)</td>
<td>13°C</td>
<td>1310 ± 160</td>
<td>7210 ± 80</td>
<td>(Gill &amp; Banks 1956; Thom et al. 1981)</td>
<td></td>
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<tr>
<td>17</td>
<td>Black River</td>
<td>40°51’ S 145°20’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Gill &amp; Banks 1956; Davies 1961)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Bakers Beach</td>
<td>41° 9’ S 146°35’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Davies 1961; Davies 1972)</td>
<td></td>
<td></td>
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<tr>
<td>19</td>
<td>Greens Beach</td>
<td>41° 5’ S 146°45’ E</td>
<td>Yes (4)</td>
<td>13°C</td>
<td>3650 ± 270 38320 ±5400</td>
<td>(Davies 1961; Thom et al. 1981a)</td>
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<td>20</td>
<td>Nine Mile Beach</td>
<td>42° 5’ S 148° 9’ E</td>
<td>Yes (6)</td>
<td>13°C</td>
<td>6130 ± 260 11350 ± 130</td>
<td>(Davies 1961; Thom et al. 1981a)</td>
<td></td>
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<td>21</td>
<td>Rheban Spit</td>
<td>42°39’ S 147°57’ E</td>
<td>Yes (7)</td>
<td>13°C</td>
<td>770 ± 150</td>
<td>5570 ± 270</td>
<td>(Thom et al. 1981a; Bowman 1986)</td>
<td></td>
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<tr>
<td>22</td>
<td>Marion Bay</td>
<td>42°49’ S 147°52’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Davies 1957; Davies 1959)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>23</td>
<td>Seven Mile Beach</td>
<td>42°50’ S 147°33’ E</td>
<td>Yes (1)</td>
<td>13°C</td>
<td>4500</td>
<td>4500</td>
<td>(Thom et al. 1981a)</td>
<td></td>
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<td>24</td>
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<td>42°55’ S 147°30’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Davies 1957; Davies 1958; Davies 1959)</td>
<td></td>
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<td></td>
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<tr>
<td>25</td>
<td>Ralph Bay</td>
<td>42°58’ S 147°29’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Davies 1959)</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>26</td>
<td>Beachport</td>
<td>37°30’ S 140° 5’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Sprigg 1952)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Guichen Bay</td>
<td>37° 7’ S 139°49’ E</td>
<td>Yes (°C-8, OSL-12)</td>
<td>13°C OSL</td>
<td>180 ± 180 51 ± 5</td>
<td>8110 ± 210 5400 ±230</td>
<td>(Thom et al. 1981a; Murray-Wallace et al. 2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Kingston</td>
<td>36°47’ S 139°52’ E</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(Tindale 1954)</td>
<td></td>
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## CHAPTER 1: COASTAL SAND RIDGE DEPOSITS - A REVIEW

<table>
<thead>
<tr>
<th></th>
<th>Lefevre Peninsula</th>
<th>34°48' S 138°30' E</th>
<th>Yes (96)</th>
<th>14C</th>
<th>(Bowman &amp; Harvey 1986; Harvey 2010)</th>
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<tr>
<td>29</td>
<td>Western Australia</td>
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<tr>
<td>30</td>
<td>Rockingham (&gt;100)</td>
<td>32°22' 115°45' E</td>
<td>Yes (56)</td>
<td>14C</td>
<td>565 ± 170 7920 ± 105 (Searle et al. 1988; Searle &amp; Woods 1986)</td>
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<tr>
<td>31</td>
<td>Cervantes (&gt;50)</td>
<td>30°29' 115°4' E</td>
<td>Yes (3)</td>
<td>14C</td>
<td>3000 ± 70 6000 ± 70 (Shepherd &amp; Eliot 1995)</td>
</tr>
<tr>
<td>32</td>
<td>Green Head (&gt;100)</td>
<td>30°4' 115°59' E</td>
<td>Yes (1)</td>
<td>14C</td>
<td>6702 ± 67 6702 ± 67 (Shepherd &amp; Eliot 1995)</td>
</tr>
<tr>
<td>33</td>
<td>Desperate Bay (5)</td>
<td>29°31' 114°59' E</td>
<td>No</td>
<td></td>
<td></td>
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<tr>
<td>34</td>
<td>Cliff Head (5)</td>
<td>29°30' 115°00' E</td>
<td>Yes (2)</td>
<td>14C</td>
<td>1992 ± 59 2633 ± 70 (Jahnert et al. 2012)</td>
</tr>
<tr>
<td>35</td>
<td>Shark Bay (5)</td>
<td>26°23.5' 114°10'</td>
<td>Yes (31)</td>
<td>14C</td>
<td>380 ± 28 960 ± 77 (Shepherd &amp; Eliot 1995)</td>
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<tr>
<td>36</td>
<td>Admiral Bay (50)</td>
<td>18°48' 121°59' E</td>
<td>Yes (27)</td>
<td>14C</td>
<td>780 ± 50 8260 ± 60 (Engel et al. 2015)</td>
</tr>
<tr>
<td>37</td>
<td>Smith Point (6)</td>
<td>11° 8' 132°10' E</td>
<td>Yes (2)</td>
<td>14C</td>
<td>1520 ± 105 2200 ± 185 (Woodroffe et al. 1992)</td>
</tr>
<tr>
<td>38</td>
<td>Quantas Spit (11)</td>
<td>13°48' 115°00' E</td>
<td>Yes (15)</td>
<td>14C</td>
<td>330 ± 10 6450 ± 100 (Olley et al. 2004)</td>
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<tr>
<td>39</td>
<td>Edward River (5)</td>
<td>14°35' 141°24' E</td>
<td>Yes (5)</td>
<td>14C</td>
<td>160 ± 80 6450 ± 100 (Rhodes et al. 1980)</td>
</tr>
<tr>
<td>40</td>
<td>Wonga (13)</td>
<td>16°20' 145°25' E</td>
<td>Yes (26)</td>
<td>OSL</td>
<td>40 ± 10 4550 ± 250 (Forsyth et al. 2012)</td>
</tr>
<tr>
<td>41</td>
<td>Port Douglas (26)</td>
<td>16°33' 145°29' E</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Cairns (50)</td>
<td>16°56' 145°45' E</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Mulgrave River (29)</td>
<td>17°13' 145°58' E</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>Cowley Beach (29)</td>
<td>17°39' 146°8' E</td>
<td>Yes (28)</td>
<td>OSL</td>
<td>200 ± 10 5740 ± 400 (Nott 2010)</td>
</tr>
<tr>
<td>45</td>
<td>Tully Heads (19)</td>
<td>18°3' 146°2' E</td>
<td>Yes (23)</td>
<td>OSL</td>
<td>10 ± 20 5010 ± 240 (Forsyth et al. 2010)</td>
</tr>
<tr>
<td>46</td>
<td>Herbert River (19)</td>
<td>18°36' 146°20' E</td>
<td>Yes (1)</td>
<td>OSL</td>
<td>4300 ± 380 4300 ± 380 (Olley et al. 2004)</td>
</tr>
<tr>
<td>47</td>
<td>Joskeleigh (30)</td>
<td>23°24' 150°48' E</td>
<td>Yes (11)</td>
<td>OSL</td>
<td>&lt;60 1460 ± 125 (Brooke et al. 2008b)</td>
</tr>
<tr>
<td>48</td>
<td>Beachmere (7)</td>
<td>27° 6.5' 153°4' E</td>
<td>Yes (7)</td>
<td>OSL</td>
<td>140 ± 50 1700 ± 130 (Brooke et al. 2008a)</td>
</tr>
</tbody>
</table>

*Many Pleistocene dates are published. Holocene barrier dates only are reported in this table.
*Other references describe other aspects of these sites. Only the papers which publish the original dates or discuss them in detail are referenced.
*Older dates are reported for lower transgressive sand deposit and estuarine mud deposits. The oldest date reported in this table relates to the progradational facies.
*Other young samples were collected but were simply stated as modern or contemporary. This date is the youngest age.

The mode of ridge formation proposed Davies (1957) led to a number of other researchers proposing alternatives. McKenzie (1958) argued that a berm was not a suitable nucleus for a ridge because it was too unstable, proposing instead that seaward growth of vegetation formed a terrace (in some cases up to 2 metres above the beach level) stabilised by vegetation and functioning to trap wind-blown sand. Bird (1960) supported Davies (1957) hypothesis citing evidence from Lakes Entrance, Victoria where entrance modifications in 1889 have provided suitable conditions for recent ridge formation. At this site the ridges are approximately 3 metres high and coastal grasses...
are growing on the ridge crests but not in the inter-ridge swales (Bird 1960). Bird (1960) also indicated that the spacing and geometry of the ridges cannot be explained by McKenzie (1958)’s terrace theory and concluded that these ridges must lie upon earlier berms.

### 1.3.3 Coastal sand ridge plains as sea-level indicators

Alongside the discussion of coastal sand ridge formation during this time, Australian researchers were also exploring the possibility of using Holocene coastal sand ridge sequences as indicators of past sea-level changes. It was thought that by analysing the height of the ridge crests and inter-ridge swales that a trend in sea level could be established. This idea was discussed by Johnson (1919) who explained that there were a number of qualifications on using ridges for this purpose as the height of a given ridge or sequence of ridges will be related to past sea level differently depending on the proposed mode of formation: if the height of a ridge is a function of the amount of aeolian decoration, then ridge height does not have a definite relation to past sea level.

Davies published a paper applying linear regression analysis to ridge crest and inter-ridge swale heights in order to indicate trends in past sea level (Davies 1958a). He also argued for higher sea-levels in the recent past, citing as evidence raised shorelines just east of Hobart, and correlating them with the timing and formation of the Seven Mile ridge plain on which is built Hobart airport (Davies 1959). In 1961 another paper published by Davies continued the linear regression work of the 1958 paper adding more locations from around Tasmania and hypothesising that there is a greater correlation with a fall of sea-level on ridge systems protected from prevailing winds, as they have less aeolian capping on the ridge and are more dominated by wave-built facies (Davies 1961).

Thom (1964) commented on Davies work proposing that the drop in ridge height across a barrier may be due to reduction in thickness of the aeolian ridge capping produced by a reduction in sediment supply. This suggestion was not supported by Shepherd (1987) who proposed that as sediment supply is reduced, ridge height actually increased rather than decreased. Shepherd (1987) proposed that rapid low relief ridges would form under conditions of high sediment supply as constant delivery of large amounts of sand to the shoreface would result in rapid build-out and a short ‘formation time’ for each ridge. Conversely, lower sediment supply to the shoreface would result in slower shoreline
build-out and a longer ‘formation time’ for each ridge and hence the ridges would be larger having accumulated more of the available sediment as dune facies (Shepherd 1987).

1.3.4 Radiocarbon dating

Following the use of radiocarbon dating for constructing depositional age models of barrier islands in north and central America in the 1960’s (Bernard & LeBlanc 1965; Curray et al. 1969; Psuty 1965), the use of radiocarbon dating of barriers in southeastern Australia commenced in the late 1970’s. Radiocarbon dating on the southeast coast of NSW led to the formulation of a conceptual model of prograded barrier morphology and chronology, whereby progradation was thought to have initiated at around 6500 years BP, when sea level reached at or near its present height (Thom & Chappell 1975) at the end of the Post-Glacial Marine Transgression (PGMT), and progressed with varying degrees of continuity until between 3000 and 1000 years BP (Thom 1978; Thom et al. 1981b; Thom et al. 1978). The variation in age of termination of progradational facies for these systems has convinced those who studied these sites that their chronological and morphological history is complex and involves the interplay of numerous other local factors; especially the volume and consistency of sediment supply (Figure 1.9) (Thom 1983). A synthesis of results of radiocarbon dating on prograded barriers for southeastern Australia and an evaluation of its contribution to our understanding of these geomorphic systems is here given.

Radiocarbon dating of coastal barriers requires samples of organic material, commonly shell, wood or charcoal. After the preparation and counting stages, derived ages must be corrected for isotopic fractionation and marine reservoir (for shell) effects. The isotopic fractionation correction yields an apparent or conventional radiocarbon age. The marine reservoir correction involves accounting for the long residence time of carbon in the oceans (as the aragonite of the shells dated is derived from dissolved marine bicarbonate) and the magnitude of this effect varies over the earth’s surface due to ocean circulation patterns (Stuiver et al. 1998).
A broad scale research project in the late 1970’s documented the morphology and chronology of barriers along the southeast coast of Australia (Thom et al. 1981b) (Figure 1.9, Table 1.1). From this research, a series of detailed monographs (Thom et al. 1978; Thom et al. 1981b) were produced, along with numerous papers in the late 1970’s and 1980’s (Thom 1978; Thom 1983; Thom et al. 1981a; Thom et al. 1981c; Thom & Roy 1985).

This research utilised an uncased solid flight power auger to core to depths of up to 40 m into each barrier (Thom et al. 1981b). This technique allowed the recovery of 20-40 cm of sample every 2-4 m (Thom et al. 1981b). For the recovery of shallower samples,
a sludge pumping technique was used which involved hand auguring to water table and then pumping the water saturated sand to the surface and sieving to collect shell material for dating (Thom et al. 1981b).

The majority of material collected for radiocarbon dating was shell hash, with occasional samples of organic mud, peat, charcoal and wood (Thom et al. 1981b). A ‘nearshore shelly sand’ unit containing abundant shell hash material was usually encountered between 5-10 m depth. The upper portion of the ridge plain was composed of quartz rich dune sand which had little or no shell material. While an extensive geographic coverage of sites was investigated and local variation was evident (Figure 1.9), a reasonably coherent picture of Holocene barrier development was apparent from the radiocarbon dating of barriers along the southeastern Australian coastline (Table 1.1).

With the exception of Batemans Bay, NSW and Rheban Spit in southeastern Tasmania (Table 1.1), the oldest radiocarbon dates for each of the sites studied by Thom et al. (1981b) fall within an age range corresponding to the cessation of the PGM when sea level reached at or near its present height. Variations in Holocene prograded barrier deposition were thought to be caused by localised factors such as bedrock accommodation space and topography, the volume and continuity of sediment supply, barrier aspect in relation to swell direction and offshore seabed topography controlling wave propagation. The cessation of progradation for most of the barriers studied by Thom et al. (1981a) was hypothesised as due to the expiry of sediment supply (Cowell et al. 2003b).

In contrast to the barrier system of eastern and southern Australia, the barrier systems of South Australia and Western Australia are rich in carbonate sands, making interpretation of radiocarbon dating difficult due to the problems of reworking and recrystallisation. At Guichen Bay, SA the sands were 90% calcium carbonate and therefore during the initial dating by Thom et al. (1981b), only shell material from a single species was used for dates. These radiocarbon chronologies for coastal sand ridge plains in southeastern Australia have made a significant contribution to our understanding the Holocene evolution of this coastline.
1.3.5 Luminescence dating

Thermoluminescence (TL) dating, developed in the late 1970’s and early 1980’s, was used in a number of locations around Australia, such as the Pleistocene coastal dune sequence between Robe and Naracoote, South Australia (Huntley et al. 1993, 1994; Huntley & Prescott 2001) and the Holocene dune field on Groote Eylandt, Northern Territory (Shulmeister et al. 1993). In addition Young et al. (1993) used TL dating from along the southern and central NSW to constrain Holocene coastal evolution. OSL dating (Huntley et al. 1985), which has been used to date coastal deposits worldwide (Jacobs 2008), was first applied to Holocene coastal sand ridge sequences by Murray-Wallace et al. (2002). This pioneering work was also the first direct comparison of a radiocarbon and OSL chronology for a coastal sand ridge plain. It is appropriate that this comparison was first completed for an Australian site, given the rich history and global significance of chronological and morphostratigraphic research on Holocene barrier deposition in Australia. In addition Holocene sands from Australia have been shown to have excellent luminescence properties and are thus ideally suited to OSL dating (Fitzsimmons et al. 2010).

Eight coastal sand ridge plains around Australia have been dated using OSL techniques. Many of these sites have complex histories of sediment delivery over the Holocene e.g. Guichen Bay (Murray-Wallace et al. 2002; Bristow & Pucillo 2006) and Woody Bay (Goodwin et al. 2006). Three sites in Queensland show an OSL chronology stretching from ~5000 years to present; Wonga, Cowley Beach and Tully Heads (Table 1.1 entries 40, 44, 45) (Forsyth et al. 2010, 2012; Nott et al. 2009). Two sites from mid and southern Queensland have very young ridge sets ranging from 1500 to present (Brooke et al. 2008a,b).

Guichen Bay and Iluka-Woody Bay have been dated using both the radiocarbon and OSL technique and therefore offer important insights into progradation trends and the difference between these two techniques for chronological investigation of coastal barriers (Goodwin et al. 2006; Murray-Wallace et al. 2002). At Guichen Bay, SA there is good agreement between the radiocarbon and OSL age estimates in the seaward portion of the barrier, however there are significant discrepancies in the landward portion, where the OSL ages are considerably younger than the radiocarbon ages (Murray-Wallace et al. 2002). This study presents OSL ages for the Moruya and
Wonboyn prograded barriers in NSW, both of which have radiocarbon chronologies (Figure 1.9) and therefore this work will provide additional comparisons between these two geochronological techniques.

1.3.6 GPR

The first use of GPR for an Australian coastal sand ridge plain was at Tuncurry, NSW where a 100 MHz antenna was used to image the successive beachface reflectors (Figure 1.10) interpreted as heavy mineral lag deposits and changes in sediment sorting and packing (Baker 1991; Roy et al. 1994). This GPR data was used for informing models of Holocene shoreface deposition (Cowell et al. 2003a).

![Figure 1.10: Example of GPR from Tuncurry, NSW collected with a 100 MHz antenna from Roy et al. (1994).](image)

This technology, offers the potential to unravel issues of ridge formation as well as reconstruct detailed stratigraphic relationships e.g. the Holocene ridge sequence at Shark Bay, Western Australia (Jahnert et al. 2012). The GPR technique has been employed at other prograded barriers around Australia to image beachface reflectors e.g. Bristow and Pucillo (2006). More recently, a prograded barrier at North Stradbroke Island, Queensland was imaged with a 250 MHz antenna indicating the potential of this site to provide a record of late Holocene sea-level and storm frequency (Gontz et al. 2014).
1.4 Summary

Coastal sand ridge deposits are found on many different coastlines around the world and variation of morphology and composition is evident in different regions. The term ‘beach ridge’ has received substantial criticism when it has been used to refer to ridge systems not solely built by swash action (Hesp 2006). Instead, the general terms of ‘coastal sand ridge’ and ‘prograded barrier’ are used in the southeast Australian context.

It is not surprising, considering the variation of coastal settings where prograded barriers have formed, that researchers have disagreed considerably in defining the formative processes of these coastal landforms. The debate has centred on the relative importance of wind versus waves, the influence of storms and the role of colonising vegetation. However, the importance of ongoing supply of sediment to a coastal embayment has been common to all models of ridge formation.

Dating of prograded barriers has been completed at several locations around the world with radiocarbon dating and OSL being the most common methodologies. In southeastern Australia, extensive radiocarbon dating was undertaken during the late 1970’s and early 1980’s for many prograded barrier deposits. In more recent years, OSL dating has been used to constrain the depositional age of coastal sand ridges and researchers have emphasised the role of these coastal landforms as a repository of paleoclimatic data (Tamura 2012).

Ground penetrating radar has also been used in Australia and around the world to characterise the subsurface structure of prograded barrier deposits to a degree of detail not possible with coring techniques. Reconstruction of coastal sediment deposition, especially of storm lag deposits and the elevation of swash facies, have led to the use of prograded barriers for the reconstruction of coastal storm histories as well as records of sea-level change.
1.5 Thesis objective

This thesis investigates the Holocene deposition of the Moruya (Bengello Beach), Wonboyn and Callala Beach prograded barrier systems on the NSW south coast using OSL dating, LiDAR elevation data and GPR. OSL dating of individual ridges in each barrier sequence will be used to constrain the depositional history of each barrier. LiDAR data will be used to capture the morphology of each ridge sequence and GPR will be used to image subsurface structures along shore normal transects. These techniques combined allow the calculation of volumes of sand accumulated in each barrier sequence. This thesis also aims to better understand the emplacement, morphology and subsurface structure of the large foredunes evident on the seaward margin of these prograded barriers.
CHAPTER 2: METHODS
2.1 Introduction

This chapter presents the methodology used in this thesis to examine the Holocene progradation of three coastal sand ridge plains: Moruya, Wonboyn and Callala Beach. OSL dating was used to constrain the timing of deposition of the low-relief shore parallel coastal sand ridges on each barrier. GPR was collected in order to characterise the subsurface structures relating to these prograded coastlines and better understand the processes of ridge formation and the role of storm events. LiDAR data for each site was used to delineate ridge elevation, spacing and amplitude and provide a general picture of broader scale morphology of each embayment. The calculation of volumes of sediment accumulated on each barrier was completed by integrating these techniques. The morphology and subsurface structure of the larger modern foredune at these sites was examined.

2.2 OSL methods

2.2.1. Introduction

OSL dating is a method that can be used for determining the elapsed time since quartz grains were buried after being exposed to sunlight (Huntley et al. 1985; Aitken 1998). Upon exposure to sunlight, electrons are released from traps in the crystal lattice of the mineral grains and the latent OSL signal is reset. During burial, grains are exposed to ionising radiation from the decay of $^{238}\text{U}$, $^{235}\text{U}$, $^{232}\text{Th}$ (and their daughter products) as well as $^{40}\text{K}$ and $^{87}\text{Rb}$ in the surrounding sediment. Cosmic rays also contribute a radiation dose proportional to grain burial depth. Consequently, charge accumulates in traps within the crystal lattice of luminescent grains at a rate that is proportional to the flux of such ionising radiation in the surrounding sediment and cosmic rays. This rate is termed the ‘environmental dose rate’ and is measured by either determining the total output of various forms of radiation with techniques like gamma spectrometry and thick source alpha counting, or determining the amounts of radioactive isotopes like $^{238}\text{U}$ and calculating a radioactive output from the proportions of these isotopes. Grains are then stimulated optically in the laboratory the stored energy is released and photons are emitted (hence ‘optically stimulated luminescence’). This ‘luminescence’ from a given sample is measured and used to calculate the ‘equivalent dose’ ($D_e$) absorbed by the grain during burial. The burial age is then calculated by dividing the $D_e$ in (Gy) by the dose rate (Gy/ka).
OSL dating of coastal barriers and relict foredune ridge plains has been undertaken at many locations globally (Jacobs 2008; Mallinson et al. 2008; Nielsen et al. 2006; Reimann et al. 2010; Reimann et al. 2011; Rendell et al. 2007; Rink & Forrest 2005; Rink & Lopez 2010; Roberts & Plater 2007; Tamura et al. 2011, 2012). OSL has also been used to date coastal sand ridge plains in Australia since the early 2000’s (Brooke et al. 2008a,b; Forsyth et al. 2010; Forsyth et al. 2012; Goodwin et al. 2006; Murray-Wallace et al. 2002; Nott et al. 2009). These studies demonstrate the applicability of this technique for dating coastal sediments.

2.2.2 Preliminary testing of OSL dating at Moruya

Three samples (see Table 2.1) collected at Moruya spread evenly across the barrier from west to east were measured using single grain techniques prior to multigrain aliquot methods being applied to the samples analysed in this study (see Table 2.2). For each of these initial three samples, 500 individual quartz grains were measured (180/180 preheat combination) allowing the identification and elimination of those grains with unsuitable OSL properties. This method also enabled issues of incomplete bleaching and post-depositional mixing to be assesed prior to age calculation. The results from these three samples served to assess the suitability of using multigrain aliquots to determine ages for coastal barriers in this region. The results from these initial three samples demonstrated that the barrier sands at Moruya had excellent luminescence characteristics and hence a multigrain aliquot procedure was adopted for all subsequent samples in Table 2.2.

Table 2.1: Sample details of those collected at Moruya by Dr. Amy Dougherty and dated by Dr. Luke Gliganic also at the University of Wollongong optical dating facility. These samples were collected and dated prior to those collected and dated in this study.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Date collected</th>
<th>Date measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seaward</td>
<td>June 2012</td>
<td>October 2012</td>
</tr>
<tr>
<td>Middle</td>
<td>June 2012</td>
<td>October 2012</td>
</tr>
<tr>
<td>Landward</td>
<td>June 2012</td>
<td>October 2012</td>
</tr>
</tbody>
</table>
2.2.3 OSL Sample collection

Twenty-five samples were collected and dated at the luminescence dating facility at the University of Wollongong from three sites along the NSW south coast (Table 2.2). Each sample was collected from a depth of between 70-100 cm of the undisturbed aeolian facies (>80% quartz) of the relict foredune ridges. The technique for collecting these samples was developed in the field by Dr. Christine Neudorf and Dr. Amy Dougherty. Cores were extracted by auguring to a depth of 70 cm with a 100 mm diameter sand auger head. Following this a 1 m section of PVC pipe, 50 mm in diameter, was hammered until flush with the surface of the ground containing the remaining 30 cm of sample. A void space was created adjacent to the PVC tube with a smaller 50 mm sand auger to a depth of 1 m. Cores were capped while in situ and then removed from the ground by extracting the tube under cover light impenetrable black plastic to ensure the preservation of light-safe grains. Cores were wrapped in light impenetrable black plastic in the field and then stored in a refrigerated cold storage laboratory until opened under light-safe conditions. Sampling of each barrier was mostly carried out adjacent to beach access tracks and thus for Moruya and Callala, transects are offset part way across the barrier.

Table 2.2: OSL sample list for this study, collected at three prograded barriers on the NSW south coast. Note: all samples for Moruya, except MorLAND, were collected by Dr. Amy Dougherty and Dr. Christina Neudorf.

<table>
<thead>
<tr>
<th>UOW code</th>
<th>Sample name</th>
<th>Date collected</th>
<th>Date measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moruya</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UOW-1201</td>
<td>Mor1</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1221</td>
<td>Mor2</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1222</td>
<td>Mor3</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1223</td>
<td>Mor4</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1224</td>
<td>Mor5</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1228</td>
<td>Mor6</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1231</td>
<td>Mor7</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1232</td>
<td>MorLAND</td>
<td>June 2012</td>
<td>Nov 2013</td>
</tr>
<tr>
<td>UOW-1672</td>
<td>Mor-FD1</td>
<td>Feb 2015</td>
<td>Nov 2015</td>
</tr>
<tr>
<td>UOW-1673</td>
<td>BM2-REC78</td>
<td>Feb 2015</td>
<td>Nov 2015</td>
</tr>
<tr>
<td>UOW-1674</td>
<td>BM2-Mod</td>
<td>Feb 2105</td>
<td>Nov 2015</td>
</tr>
<tr>
<td>Wonboyn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UOW-1249</td>
<td>Won1</td>
<td>Oct 2013</td>
<td>Sep 2014</td>
</tr>
<tr>
<td>UOW-1251</td>
<td>Won2</td>
<td>Oct 2013</td>
<td>Sep 2014</td>
</tr>
<tr>
<td>UOW-1252</td>
<td>Won3</td>
<td>Oct 2013</td>
<td>Nov 2014</td>
</tr>
<tr>
<td>UOW-1370</td>
<td>Won4</td>
<td>Feb 2014</td>
<td>Nov 2014</td>
</tr>
</tbody>
</table>
2.2.4 Sample preparation and dating

All samples were prepared using standard laboratory techniques (Wintle 1997) to isolate the 180-212 µm grain size fraction of quartz. Under dim red-light conditions the top and bottom 4cm of material was extracted and utilized to estimate the environmental dose rate for each sample and provide an indication of in situ water content. The light-safe grains were wet sieved to isolate the 180-212 µm grain size fraction and then treated with 15% HCl to remove carbonates and 15% H₂O₂ to remove any organic material. Each sample was then put through two iterations of sodium polytungstate separation at densities of 2.7 and 2.62 to remove heavy minerals and feldspars respectively. The pure quartz samples were etched with a 40% HF solution for 45 minutes to remove any remaining feldspars and the outer 5-10 µm of quartz grains. Each sample was then dried in a 50°C oven and dry sieved to remove any grains outside the 180-212 µm size fraction. Multigrain aliquots were prepared by attaching the grains to a stainless steel disc using silicon spray as an adhesive. A 3 mm mask size resulted in around 50-60 grains in the centre of each disc.

Appropriate regenerative and test dose preheat combinations were determined using preheat plateau (Aitken 1998) and dose recovery experiments (Murray & Wintle 2003; Roberts et al. 1999) prior to further measurement procedures. Eight preheat combinations were assessed using preheat plateau experiments and two of these (180/160 and 180/180) combinations were subsequently assessed using dose recovery experiments. The combination 180/160 was selected as most appropriate for measurement of each samples equivalent dose. The latter experiment also serves to
assess the suitability of the SAR procedure and to aid accurate test dose determination for these samples.

Twenty-four discs for each sample were loaded onto a Risø TL/OSL reader for stimulation, measurement and irradiation according to standard procedures Gliganic et al. (2012a,b). $D_e$ values were estimated using a modified single-aliquot regenerative-dose (SAR) procedure (Murray & Wintle 2000). To ensure the suitability of the SAR procedure for each aliquot, standard tests were applied, including a recycling ratio test, recuperation test (Murray & Wintle 2000) and OSL-IR depletion radio test (Duller 2003). For each of the 24 aliquots of a given sample, $D_e$ was calculated using the sum of the first 0.8 seconds of signal minus a background derived from the final 8 seconds. Dose response curves were fitted with a “exponential+linear fit” curve for the highest accuracy, although little or no curvature was evident from a visual inspection of each dose response curve. The final $D_e$ and overdispersion (spread in $D_e$ data beyond that expected based on the standard error of each $D_e$ value) values for each sample were calculated using the central age model (CAM) (Galbraith et al. 1999).

For all samples in Table 2.2, ICP-MS analysis (completed by Intertek Genalysis) was used to measure uranium, thorium, and potassium concentrations. Dose rates were calculated using the conversion values of Guérin et al. (2011) and despite a laboratory measurement of water content being obtained, an assumed water content of $5 \pm 2.5\%$ was used for all samples. This decision was taken due to the uncertainty associated with water content estimations in free-draining sandy facies. All measured water contents were between 1-4 % and the adjustment to an assumed value of $5 \pm 2.5\%$ did not change the ages outside of the 1 sigma error margins. The cosmic dose for each sample was calculated taking into consideration geographic position, sediment density, altitude and depth of overburden following Prescott and Hutton (1994).

Of all samples measured, two required additional aliquots: samples 14 and 18 (Table 2.2). These samples had unacceptably high overdispersion values and were re-measured in order to understand possible sources of error. The overdispersion value of Sample 18, from the northern foredune at Wonboyn, reduced significantly when another series of 24 discs with their respective $D_e$ values was added to the CAM. The overdispersion value for Sample 14, after re-measurement, remained unacceptably high, even after the addition of 24 additional aliquots with associated $D_e$ values.
2.3 Radiocarbon recalibration and reporting

The radiocarbon ages reported by Thom et al. (1981a) for Moruya and Wonboyn were calibrated to sidereal years according to the procedure of Stuiver and Reimer (1993) using Calib 7.0.2. A Delta R of 11 ± 85 yr was adopted for this calibration based on studies by Gillespie and Polach (1979) who collected and analysed modern shell material from the southeastern coastline of NSW. All radiocarbon ages are reported in cal yr BP and rounded to the nearest 10 years. It should be noted that all radiocarbon ages represent years before 1950 (Gillespie 1984), so there is a 63-year offset between radiocarbon and all OSL ages.

2.4 GPR methodology

2.4.1 Introduction

Ground penetrating radar (GPR) is a geophysical technology which can image subsurface structures and stratigraphy by propagating electromagnetic pulses through a substrate. The high frequency (MHz) electromagnetic waves are emitted by the antenna transmitter and recorded by the receiver antenna as they reflect or ‘bounce back’ off various subsurface structures (Figure 2.1). These subsurface structures are often called reflectors. The time in nanoseconds (ns) between transmission and receiving of a pulse (two-way travel time), and the strength or amplitude of the reflector is recorded by the GPR equipment.
Figure 2.1: The mode of GPR data recording where a transmitted electromagnetic signal from A1 is reflected off subsurface stratigraphy and received by the A2 receiver antenna and then displayed and recorded by the computer system. Schematic after Neal (2004).

The longer the travel time down to any given reflector, and back to the antenna, the deeper the reflector is within the substrate. Hence the vertical axis of GPR data when displayed in 2D is ‘two-way travel time’ in nanoseconds. The reflectors in the substrate recorded by the GPR system, are changes in dielectric permittivity ($\varepsilon$), electrical conductivity ($\sigma$) and magnetic permeability ($\mu$) (Neal 2004), which in turn arise from changes in water content, sediment type, grain size, grain shape and orientation, sediment sorting, porosity, sediment compaction and organic material (Jol & Bristow 2003). However, as an electromagnetic wave travels through a substrate it attenuates at a rate proportional to the conductivity of that substrate. Signal penetration and return quality is best in non-conductive materials such as unsaturated sand and gravel and worst in highly conductive materials like silt, clay and saline water (Jol & Bristow 2003). Thus coastal sand ridge plains are ideal locations for using GPR to image subsurface stratigraphy provided there is no saltwater intrusion into the water table when working close to a shoreline.
As well as controlling the depth of penetration and signal quality, the character of the subsurface environment will also control the speed or velocity of the signal as it propagates through that substrate. The primary control on signal velocity passing through a substrate is dielectric permittivity, which is in turn primarily a function of water content. Hence in most cases where GPR is used in coastal sand ridge settings, the presence of a non-saline ground water table will halve the velocity of the GPR signal as it travels downward.

The other factor which dictates the depth of signal penetration is the frequency of the antenna. Higher frequency antennas have shallower penetration and higher data resolution. Conversely, lower frequency antennas have far greater penetration depth but lower data resolution. Higher frequency antennas suffer from greater signal attenuation due to increased electrical and scattering losses, however, their shorter wavelength enables the detection of more closely spaced changes in the substrate. Lower frequency antennas suffer less signal attenuation due to scattering and electrical losses, but due to their longer wavelength, do not capture small-scale changes in the substrate. 200 MHz or 250 MHz frequency antennas have been widely used in coastal environments (Gontz et al. 2014) and seem to provide a good balance between penetration and detail when working with sandy coastal environments.

GPR antennas may be shielded or unshielded. Shielded antennas are generally preferable in environments where there is the potential for interference of the GPR signal from above-ground features such as trees and buildings. A shielded antenna has a protective cover, which attempts to reduce the background electromagnetic noise. Such shielded antennas were well suited to the thickly vegetated coastal sand ridge plains encountered in this study.

2.4.2 GPR data acquisition

GPR data was collected at all three sites examined in this study: Callala, Moruya and Wonboyn. The data was collected with a Mala ProEx system and three frequencies of antenna (100, 250 and 500 MHz) were tested at Seven Mile Beach (see Figure 2.2), a coastal sand ridge plain around 50 km south of Wollongong. Significant ‘ringing’ was evident in the data using the 100 MHz antenna likely due to interference from trees proximal to transect locations. Further testing of this antenna has not been attempted in this study and it appears that others using the same antenna have encountered this same
‘ringing’ problem (personal comm. S. Nichol). The 500 MHz antenna produced ‘clean’ data at Seven Mile Beach and also at Callala where additional testing took place. However, upon processing it was seen that while high detail was evident in the upper 2-3 metres of the GPR traces, the depth of penetration was only around 4 m. This meant that few subsurface structures related to the beachface were evident. The most reliable antenna which imaged the subsurface stratigraphy with the most clarity, was the 250 MHz shielded antenna. However, on some occasions, some horizontal ringing was present in the data from this antenna at Moruya.

Suitable transects for the collection of GPR data were selected based on field surveys and close inspection of LiDAR and aerial imagery. Beach access footpaths linking parking areas with the beach and 4WD roads (see example in Figure 2.2) seemed to provide the best results in terms of data clarity and signal penetration. Such tracks generally also had little topographic modification. Little success was had when attempting to penetrate through bitumen road surfaces as data clarity was severely compromised. Transect locations on such foot and 4WD tracks were also selected.

Figure 2.2: Photo of the Mala ProEx GPR system with a 500 MHz antenna during testing at Seven Mile Beach.
according to how shore normal their orientation was. A GPR transect which crosses ridge crest strikes at acute rather than 90 degree angles introduce errors in the geometry of beachfaces imaged by the GPR equipment. This principal is also seen in that beach profiling is done as perpendicular to the beach alignment as possible, so as to avoid distortions in the profile topography.

Wherever possible, the greatest width of the barrier was captured by GPR data so as to have the most complete data record for each site. However, as much of these coastal sand ridge plains contain ecologically sensitive flora and fauna the decision was taken not to manually cut a path for GPR data collection. Therefore, only at Moruya, is the full width of ridges covered by GPR transect. At Moruya and Callala, due to the presence of beach access footpaths, some attempt was made to collect data from both the northern and southern ends of the barrier. At Moruya, this effort was restricted to the incipient ridges in the north, and the foredune in the south, as there were no suitable tracks available which were perpendicular to the ocean over the older ridges. At Callala a suitable beach foot track was identified at the north end but was only covered using the 500 MHz antenna.

Collecting data with the Mala ProEx system was in common offset mode (Neal 2004) where the transmitter and receiver antenna remain a fixed distance apart and are moved simultaneously across the ground surface. For all sites the sampling frequency was set as 15 multiplied by the frequency of the antenna, which for the 250 MHz antenna was roughly 3750. Sampling interval was set to 0.2 m, such that a pulse is sent from the transmitter antenna every 0.2 m. Distance was metered and applied to the trace data using a wheel on the cart that carried the equipment (see GPR set up in Figure 2.2).

During GPR data acquisition at Callala and Wonboyn, an auger hole was used to verify the depth of the water table so that a correct velocity could be applied during the processing stage. Common midpoint survey (CMP) is often used to determine velocity profiles in coastal substrates, however this was not possible with the Mala 250 MHz antenna. At Moruya, an auger hole to water table was not taken at the time of the GPR survey, but testing of a Pulse Ekko GPR system prior to processing meant that a CMP survey was completed for this site. This CMP survey indicated a velocity of 12 cm/ns above the water table and 0.65 cm/ns below the water table for the region near to the modern foredune. Therefore for the Moruya GPR processing a 12 cm/ns and 0.6 cm/ns
above and below water table velocity respectively was adopted. These velocity values were also adopted for Wonboyn and Callala as they resulted in an accurate depth for the water table verified by the auger holes.

2.4.3 GPR Processing

Processing of raw GPR data is necessary in order to accurately reconstruct subsurface structures in coastal environments. Flexible testing of processing parameters is necessary in order to develop an overall processing routine which is best suited to a particular site, as each site may vary in substrate character in terms of sediment composition and grain size range. The GPR processing functions found in most GPR processing software packages, are adapted from common seismic data processing, and hence their applicability to GPR datasets, must be carefully considered (Neal & Roberts 2000). Close examination of the literature reviewed in Chapter 1 demonstrates that there is no ideal processing routine to be universally applied (Bristow & Pucillo 2006; Neal & Roberts 2000; Neal 2004; Neal et al. 2002). Indeed most papers do not disclose the particular parameters used for a given function; instead simply stating that a particular function was applied. However, it is clear from these studies that individual datasets require individual testing to produce the most satisfactory results.

GPR data collected with the Mala system was processed using RadExplorer version 1.41. This software package is distributed by Mala Geosciences and is designed for geological applications. The processing routines found in RadExplorer have been designed to be used in the order in which they are presented below. While other configurations were tested, the most satisfactory results were achieved when the routines were applied in the order specified by the RadExplorer software. The available processing routines include ‘DC removal’, ‘Time Zero Adjustment’, ‘Trace Edit’, ‘Spatial Interpolation’, ‘Background Removal’, ‘2D Spatial filtering’, ‘Amplitude Correction’, ‘Predictive Deconvolution’, Background Filtering’, ‘Stolt F-K Migration’, ‘Reflection Strength’ and ‘Topography’. Each of these processing routines were tested by trial and error on samples of field data from each site to understand their effects and benefits or limitations. This trial and error testing process allowed the determination of a specific suite of processes which were applied to the data for each site. The function and resultant changes evident in a given GPR data set for each process are explained in detail in Appendix A alongside justification for applying or not applying each of these
processes. Below is outlined the final processing routine as adopted after testing of each processing component.

2.4.4 Final processing scheme

GPR data processing routines always require appraisal for each new data set and there are very few ‘standard’ procedures which are always applied (Neal 2004). A summary of the processing applied here is seen in Figure 2.3, which for the sake of cross site consistency and comparison, have been applied to all GPR collected in this study.

Figure 2.3: Adopted processing routine for all data presented in this study. See Appendix A for additional details relating to each step.
GPR processing is also very user specific and different operators are likely to prefer different tools, software programs and settings. An attempt has been made to eliminate some of these differences by, where possible, using the default settings provided by RadExplorer. No doubt other processing routines could be applied to this data and various settings in the different tools could be tweaked to produce slightly different results. However, by using most basic processing routine with standard settings, the data presented here is in the most replicable form.

2.5 LiDAR analysis

2.5.1 Introduction

Airborne Light Detection and Ranging (LiDAR) is an active remote sensing method which, using a aircraft mounted sensor, collects detailed information about the elevation of the land surface and vegetation by emitting laser pulses which reflect off objects and produce a backscatter recorded by the sensor. In addition to a ‘travel time’ for each pulse and subsequent return signal, an intensity of reflectance is also often measured. LiDAR data has been used extensively for meteorological applications for many years as well as by Forestry departments for its ability to measure tree heights and crown diameters. However, the ability of LiDAR also to penetrate tall vegetation means it is of great benefit for capturing the topographic detail of coastal sand ridge plains on the NSW south coast, which are commonly covered in tall dry sclerophyll forest.

2.5.2 LiDAR processing

LiDAR data, flown in 2012 by the NSW Government Land and Property Information (LPI), was acquired for all three sites (Callala, Moruya and Wonboyn) in order to better understand barrier morphology. Initial processing was completed by LPI NSW, who produced a classified xyz point file (LAS file) differentiating ground surface from vegetation (low, medium and high) and identifying buildings, bridges and water as separate classes. This classification process involved an automated classification, ground anomaly removal and manual ground correction. Metadata supplied with this data specified that heights were referenced to the Australian Height Datum 1971 (AHD71) using AUSGeoid09 and further corrected to a local Geoid model according to LPI practice. Vertical accuracy was reported as ± 0.3 m and horizontal accuracy as ± 0.8 m for all data provided. Average point density for these data sets was 1.6 points/ m².
For each site, the points classified as ‘ground’ or ‘bare earth’ were extracted and a Digital Elevation Model (DEM) was produced using the Triangular Irregular Network (TIN) method in ArcGIS 10.2. For all further analysis using these LiDAR data sets, the decision was taken not to further convert the TIN DEM’s to raster layers. This conversion process involves a subtle but significant interpolation step, where any given raster cell is assigned a height value based on a linear or nearest neighbor (within a specified distance) calculation. Thus any further calculations of height etc. based on a raster layer derived from the TIN DEM would have additional errors proportional to the ‘accuracy’ of the interpolation used to produce the said raster.

2.5.3 Digitisation and interpretation of geomorphic units

The crests of ridges and geomorphic unit boundaries were digitised from a DEM surface for Moruya and Wonboyn with the aid of georectified aerial photography. Digitising was completed at between 1:500 and 1:2000 scales. Field inspection, involving ridge crest counting along shore-normal transects, indicated good agreement between the DEM and the location of ridge crests. For a small number of crest locations, for example in the Moruya aerodrome, aerial photography was used, as flattened topography meant that LiDAR did not capture the ridge locations. In this area, each ridge crest is distinguished as a lighter coloured sandy, less vegetated shore parallel feature (Figure 2.4). The alignment of these structures was cross-checked against LiDAR identified ridge crests adjacent to the aerodrome precinct and good agreement was apparent.
Figure 2.4: Ridge crest locations in the Moruya aerodrome identified as the shore parallel lighter coloured, sandy less vegetated features. Map data Google Earth and DigitalGlobe.

At Callala, the top two thirds of the barrier has been modified for housing and road infrastructure, thus the ridge topography has been modified. Digitisation at this site was therefore not attempted. For Wonboyn, some ridge crests were difficult to discern in one portion of the ridge sequence due to thick undergrowth and hence few LiDAR ground points. However, an approximation of crest location was still possible. Thick undergrowth was also an issue in preventing LiDAR ground points at the southern end of the Callala foredune. In a 300 m section the height of the foredune according the LiDAR TIN model is not an accurate estimation of it’s true height.

The resolution of the LiDAR data also allowed the observation and digitisation of features not easily reconisable from aerial imagery as they were obscured by dense or tall vegetation. Numerous narrow foot tracks not visible in aerial imagery were identified at Callala, Moruya and Wonboyn which later served as locations for GPR surveys.
2.5.4 Barrier volume analysis

Calculation of volumes of sediment accumulated on each barrier derived from LiDAR data has not been attempted in the published literature. Bristow and Pucillo (2006) used GPR profiles and a single topographic survey coupled with OSL dating by Murray-Wallace et al. (2002) to estimate progradation volumes for the Guichen Bay ridge plain, near Robe, SA. The basal limit of their volume calculation was the shoreface which had an elevation close to 0 m AHD for much of the barrier sequence (Bristow & Pucillo 2006). The thickness of the material above this basal surface was derived from an elevation profile across the centre of the barrier and assumed for the entire length of the embayment. A volume was then calculated by multiplying the thickness of sediment by the planform area of each ridge set. Volumes of sediment accumulated over the late Holocene were reported for Iluka Bay Woody Head coastal plain in northern NSW (Goodwin et al. 2006) although it is not clear how these values were generated. The approach adopted in this study was to calculate a volume of sand above a specified reference plane representing the transition from beachface facies to dune facies at each site, up to the topographic surface derived from LiDAR data. This was completed for all sites and the chosen elevation at all sites of 3 m AHD broadly represented the upper limit of wave action and beach sediment. This elevation was derived from examination of the modern beach profile and the GPR data which imaged the elevation of beachface reflectors.

For each site, polygons defining segments or slices of the barrier were digitised by following ridge inter-ridge swales alongshore (see example for Moruya in Figure 2.5). These polygons defined the portion of the barrier accumulated in a specified time period. The polygon volume tool was used in ArcGIS 10.2 to calculate the volume of sediment between the LiDAR derived DEM and the reference plane in the area specified by each slice. This resulted in a volume in m$^3$ for each ‘slice’ where slices are separated by a vertical bounding line. This volume was then plotted with respect to age to understand the pattern of ridge accumulation over time. The adopted method using the LiDAR data was considered appropriate for volume calculations of aeolian sediment where the offset between a vertical bounding line and dune structures present is minimal. The offset between a vertical bounding line and a typical low-angle beachface or shoreface is far more significant.
Figure 2.5: Moruya barrier divided into sections in order to calculate aeolian sediment volumes over the Holocene.
At Moruya, two small sections of sandy substrate at the southern end of the barrier were omitted from the volume calculations as these may have been modified by tidal processes and not directly related to coastal progradation (Figure 2.5). At Callala, tracing a ‘volume slice’ alongshore was impeded by the removal of the ridge topography due to urban development. Error for the volume of each age slice was calculated by applying multiplying 0.3 m (LPI specified ± 0.3 m vertical error for LiDAR data) by the surface area calculated by the polygon volume tool to get ± m³ error value for each ‘slice’. When plotting cumulative barrier volume through time, cumulative error was also accounted for in the error bars on each graph.

2.5.5 Foredune height and volume analysis

To systematically analyse the height and volume of the foredune at each site a series of shore normal transects were constructed at regularly spaced intervals of 50 metres along the length of the barrier. Some short sections were omitted due to human modification to the foredune e.g. bulldozing for car parks. These transects covered the entire foredune complex at each site. At Moruya the seaward limit of each transect was the top of the obvious late 1970’s storm scarp and the landward limit was the inter-ridge swale immediately landward of the foredune. The erosional line of the 1978 storm scarp, rather than the inter-ridge swale to the seawards was selected as the limit for each profile as it ran roughly parallel to the present day beach and therefore allowed for the most consistent profile with respect to alongshore variations of the foredune morphology. The inter-ridge swale had a consistently curving nature alongshore with respect to the current shoreline. For Wonboyn and Callala the inter-ridge swales either side of the foredune were selected as the most laterally persistent and easily identifiable limits for each shore normal foredune transect.

Assuming a 1 metre wide transect, a volume was calculated for each transect using the ‘Polygon Volume’ tool in ArcGIS 10.1. This tool measures the volume above or below a given reference plain to a defined surface within an area specified by a polygon. In this case the volume was calculated above the reference plane of 3 m AHD up to the LiDAR derived TIN surface in the area defined by each transect. Each transect varied in length alongshore according to the changing width of the foredune. A 1 metre wide transect was selected so as to be comparable to the measurements of beach volume
change measured at Moruya over the past ~40 years (McLean & Shen 2006) which report volume in m$^3$ per metre of beach. The reference plane of 3 m AHD was selected so as to only calculate aeolian deposited material. Error for each profile was estimated by multiplying ± 0.3 m vertical error (specified by LPI) with the surface area of the LiDAR defined by each 1 metre wide transect. Foredune height was extracted from the LiDAR derived DEM at this same 50 metre interval by identifying the highest point on each foredune transect.
CHAPTER 3: MORUYA (BENGELLO BEACH)
3.1 Introduction

This chapter presents the findings for the Moruya coastal sand ridge plain behind Bengello Beach, NSW. This site has been well studied in past years with extensive drilling and radiocarbon dating as well as a long-running beach monitoring program which is still underway.

A description of the general physiographic setting of Moruya and a synthesis of past research is followed by the results of OSL dating for the sand ridges across the central portion of the barrier. GPR collected for this site characterises the subsurface structures and demonstrates the progradation of successive beachfaces. Analysis of ridge morphometrics including height, spacing and amplitude as well as the broader morphology of the embayment is presented. OSL dating, LiDAR data and the existing drilling, enabled the calculation of volumes of sand accumulated in the barrier. Analysis of the high foredune fronting this barrier is followed by a summary of the overall Holocene deposition of the coastal sand ridge plain at Moruya.

3.2 Site characteristics

3.2.1 Physiographic setting

The Moruya coastal plain behind Bengello Beach is located on the tectonically stable coast of NSW, approximately 240 km south of Sydney (Figure 3.1). The Palaeozoic bedrock backing and underlying the site is a turbidite sequence comprising siltstone, claystone, sandstone, quartzite and chert (Rose, 1966). This Palaeozoic formation is characteristic of the Lachlan Fold Belt which lies south of the Sydney Basin geological province. The southern border of the Sydney Basin lies just north of Batemans Bay, approximately 30 km north of the Moruya barrier. The Lachlan Fold Belt has generally shore-parallel fold structures, high coastal relief, small river catchments and narrow embayments (Roy & Thom, 1981). The modern Bengello Beach is comparatively long beach for this region of NSW measuring a little over 6 km. Most beaches of this region would be less than 4km long and commonly in the order of 0.5-2 km (Short 2007).

The Moruya coastal plain itself, spans a maximum width of almost 2 km and consists of ~60 coastal sand ridges (Figure 3.1) which are low relief (1-2 m crest to inter-ridge swale), laterally persistent features comprising a composite of beach sands with an aeolian capping (Thom & Roy, 1985).
Figure 3.1: A) A digital elevation model (DEM) derived from LiDAR data. B) Interpreted geomorphology for the Moruya barrier. Sampling location numbers correspond to Table 3.2. GPR example section refers to parts B and C in 3.7. C) Air photo from 2015 of the Moruya barrier and surround. Map data from Google Earth.
Behind the ridge sequence are a number of freshwater swamps, the largest of which, Waldrons Swamp, still connects to the ocean on occasion via a narrow channel (Figure 3.1). At the southern end of the barrier, the Moruya River (upstream named the Deua River) connects to the ocean through breakwalls, which were completed in 1954. The Moruya River, along with the Clyde, Tuross and Bega Rivers are the largest in this region, with catchments in the order of 1000-3000 km². Sediment contribution to coastal embayments from these rivers in considered minimal over the Holocene due to both catchment size and moderate rainfall (1000-1500 mm/ year). Sediment incorporated into barrier along this coastline is primarily from offshore sources (Roy et al. 1994).

3.2.2 Past studies

Details of the ridge sequence at Moruya were first described by Thom et al. (1978) who undertook topographic surveying to document the barrier morphology and drilling to extract sediments for stratigraphic and age reconstructions using radiocarbon dating. The stratigraphy of the Holocene infill comprises a series of facies; the uppermost ‘beach-ridge and dune sand’ overlies ‘nearshore shelly sand’, under which is a shelly sand with gravel layer interpreted as an early Holocene transgressive unit; an estuarine clay and organic mud layer occurs at the base of the sequence (Thom et al. 1981b). Samples for radiocarbon dating were collected from the ‘nearshore shelly sand’ as identified in cores, and distinct from the overlying 'beach-ridge and dune sand' (Thom et al. 1981b).

Radiocarbon dating was carried out in laboratories at Sydney University and the Australian National University, with results published in a series of papers and reports which explored the Holocene deposition of this part of the Australian coastline (Polach et al. 1979; Roy & Thom 1981; Thom et al. 1981a; Thom 1983). The resulting age model placed the commencement of barrier progradation at ~6500 cal yr BP (calibrated ages are corrected for marine reservoir effects), with progradation culminating around ~3000-2500 cal yr BP. The overall rate of progradation was considered to have decelerated after ~5000 cal yr BP (Roy et al. 1994) and was interpreted as due to a decreasing volume of sand on the shoreface and offshore (Cowell et al. 2000). This decrease in sand supply is thought to have been caused either by the shoreface progressing toward equilibrium state, or due to bed armouring by a surface lag deposit
Soils along the central Moruya transect were investigated by Bowman (1989) who observed good agreement between soil characteristics and the radiocarbon based age model.

The large foredune adjacent to the modern beach is approximately 3-4 metres higher than previous ridge crests for most of its length. While the published radiocarbon chronology for the central transect indicated that progradation ceased around 3000-2500 cal yr BP, a charcoal sample from the large foredune close to the northern transect gave an age of 720 ± 270 cal yr BP (Thom et al. 1981b) recalibrated according to Stuiver and Reimer (1993). This age aligns closely with the radiocarbon chronology for the northern transect where a date of ~1000 cal yr BP was recorded beneath the large foredune (Thom et al. 1981a, b). This disparity between transects is reflected in the progradation rates for Moruya in Figure 4.18 in Roy et al. (1994) and was also highlighted by Thom et al. (1981b).

3.2.3 Radiocarbon recalibration of existing radiocarbon ages

The recalibration of 21 samples collected and dated by Thom et al. (1981b) was completed as there has been significant progress in the refinement of marine calibration curves. The recalibrated ages are not significantly different to the calibrated ages previously reported (Polach et al. 1979; Thom et al. 1981b) as the Delta R values (Gillespie & Polach, 1979) for the marine reservoir correction are the same as those used by Thom et al. (1981b) in the original calibration. The recalibrated radiocarbon ages from Thom et al. (1981b) are presented in Table 3.1. All but two of these age estimates were from the dating of ‘shell hash’ which were composed of mixed species.
Table 3.1. Radiocarbon samples from Thom et al. (1981b) ordered landward to seaward and shallowest to deepest. ‘Radiocarbon Age’ is the ‘Laboratory age’ and is corrected for isotopic fractionation only. The calibrated age is presented in cal yr BP according the calibration of Stuiver and Reimer (1993) using CALIB REV 7.0.1. The Delta R of 11 ± 85 yr used for the calibration is taken from Gillespie and Polach (1979).

<table>
<thead>
<tr>
<th>Ref. No.</th>
<th>Sample Code</th>
<th>Facies*</th>
<th>Sample Depth (m)</th>
<th>Dated Material</th>
<th>Radiocarbon Age (yr BP)</th>
<th>Radiocarbon Cal. Age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ANU-1117</td>
<td>NSS</td>
<td>7</td>
<td>Shell hash</td>
<td>6100 ± 80</td>
<td>6530 ± 250</td>
<td></td>
</tr>
<tr>
<td>2) ANU-1118</td>
<td>NSS</td>
<td>9</td>
<td>Shell hash</td>
<td>5920 ± 70</td>
<td>6340 ± 260</td>
<td></td>
</tr>
<tr>
<td>3) ANU-1197</td>
<td>NSS</td>
<td>16</td>
<td>Shell hash</td>
<td>5820 ± 90</td>
<td>6200 ± 270</td>
<td></td>
</tr>
<tr>
<td>4) ANU-1198</td>
<td>NSS</td>
<td>8</td>
<td>Shell hash</td>
<td>5820 ± 70</td>
<td>6220 ± 250</td>
<td></td>
</tr>
<tr>
<td>5) ANU-1116</td>
<td>NSS</td>
<td>9</td>
<td>Shell hash</td>
<td>4930 ± 70</td>
<td>5200 ± 300</td>
<td></td>
</tr>
<tr>
<td>6) ANU-1199</td>
<td>NSS</td>
<td>14</td>
<td>Shell hash</td>
<td>5120 ± 80</td>
<td>5460 ± 270</td>
<td></td>
</tr>
<tr>
<td>7) ANU-1200</td>
<td>NSS</td>
<td>21</td>
<td>Shell hash</td>
<td>6290 ± 80</td>
<td>6730 ± 290</td>
<td></td>
</tr>
<tr>
<td>8) ANU-1400</td>
<td>NSS</td>
<td>22</td>
<td>Shell hash</td>
<td>5410 ± 90</td>
<td>5790 ± 280</td>
<td></td>
</tr>
<tr>
<td>9) ANU-1135</td>
<td>NSS</td>
<td>9</td>
<td>Shell hash</td>
<td>4100 ± 60</td>
<td>4130 ± 280</td>
<td></td>
</tr>
<tr>
<td>10) ANU-1137</td>
<td>NSS</td>
<td>13</td>
<td>Shell hash</td>
<td>3760 ± 60</td>
<td>3690 ± 270</td>
<td></td>
</tr>
<tr>
<td>11) ANU-1138</td>
<td>NSS</td>
<td>17</td>
<td>Shell hash</td>
<td>5180 ± 60</td>
<td>5520 ± 230</td>
<td></td>
</tr>
<tr>
<td>12) ANU-1139</td>
<td>NSS</td>
<td>22</td>
<td>Shell hash</td>
<td>5150 ± 60</td>
<td>5500 ± 220</td>
<td></td>
</tr>
<tr>
<td>13) ANU-1140</td>
<td>SSG</td>
<td>28</td>
<td>Shell hash</td>
<td>8490 ± 170</td>
<td>9040 ± 460</td>
<td></td>
</tr>
<tr>
<td>14) ANU-1141</td>
<td>SSG</td>
<td>33</td>
<td>Shell hash</td>
<td>9130 ± 210</td>
<td>9920 ± 550</td>
<td></td>
</tr>
<tr>
<td>15) ANU-1133</td>
<td>ECOM</td>
<td>44</td>
<td>Organic mud</td>
<td>8960 ± 80</td>
<td>9740 ± 350</td>
<td></td>
</tr>
<tr>
<td>16) ANU-1114</td>
<td>NSS</td>
<td>11</td>
<td>Shell hash</td>
<td>3810 ± 80</td>
<td>3760 ± 310</td>
<td></td>
</tr>
<tr>
<td>17) ANU-1398</td>
<td>NSS</td>
<td>20</td>
<td>Shell hash</td>
<td>4920 ± 80</td>
<td>5180 ± 310</td>
<td></td>
</tr>
<tr>
<td>18) ANU-1399</td>
<td>NSS</td>
<td>7</td>
<td>Shell hash</td>
<td>2740 ± 70</td>
<td>2450 ± 270</td>
<td></td>
</tr>
<tr>
<td>19) ANU-1397</td>
<td>NSS</td>
<td>25</td>
<td>Shell hash</td>
<td>4950 ± 100</td>
<td>5240 ± 330</td>
<td></td>
</tr>
</tbody>
</table>

*NSS – Nearshore Shelly Sand, SSG – Shelly sand with gravel, ECOM – Estuarine clay with organic mud
3.3 OSL dating

3.3.1 Introduction

OSL dating was completed for 14 samples from selected coastal sand ridges across a transect spanning the central portion of the Moruya coastal plain. Details regarding the methodology can be found in chapter 2. Samples were collected from the upper portion of each ridge and the relation to the radiocarbon ages from deeper in the barrier is discussed.

3.3.2 Dating results

The samples for OSL dating from the Moruya coastal plain generally had good luminescence properties. The single grain measurements for the three preliminary samples indicated that these deposits do not suffer from post-depositional mixing or partial bleaching. Consequently, multi-grain aliquots can be used to estimate $D_e$ values for samples from this study area. Combined, these results demonstrate that young marine sands from SE Australia are ideally suited to OSL dating (Jacobs 2008). The preheat plateau results suggest that multiple preheat combinations could be selected for age determinations (Figure 3.2A) suggesting that samples were thermally stable, which is advantageous as it implies that age determinations have a high level of confidence. Of the possible preheat combinations, two were selected as most appropriate: 180/160 and 180/180 (Figure 3.2B) and were used for a dose recovery experiment. Both preheat combinations could be used to accurately recover a known dose in the laboratory (Figure 3.2B) and were therefore both suitable for $D_e$ estimation. OSL age data is presented in Table 3.2.
Figure 3.2. (A) Preheat plateau experiment for 24 aliquots of sample 2 (Table 3.2). 180/160 denotes regenerative dose preheat = 180°C, cut heat = 160°C. The mean $D_e$ value (in Gy) and associated error (grey shading) is plotted as a dotted line. (B) Dose recovery experiment on 12 aliquots of sample 2 (Table 3.2). Aliquots are plotted according to the ratio of measured dose/ given dose and divided into the two pre-heat/ cut heat combination categories. (C) A typical decay curve of the OSL signal of an aliquot and an associated dose recovery curve taken from sample 11 (Table 3.2). The dotted lines on the decay curve indicate the integration intervals for calculating the $D_e$ where the first 0.8 s was used for the OSL signal and the final 8 s for the background correction. The dose response curve shows linearity, also typical of the other samples, and higher doses were unnecessary due to $D_e$ values all being less than 6 Gy. (D) A radial plot of the $D_e$ distribution for sample 11 (Table 3.2) which is typical of all other samples. The shaded band is centered on the $D_e$ value determined using the CAM and the relative error is less than 3% and precision greater than 30 for all 24 aliquots.
Table 3.2. OSL ages for coastal sand ridges across the Moruya Barrier, NSW. All samples include an internal dose rate contribution of 0.03 ± 0.01 Gy/ka assumed based on measurements made on Australian quartz (Bowler et al. 2003). Note: samples 1, 6 and 10 (Seaward, Middle and Landward) were dated by Dr. Luke Gliganic using single grain techniques (see Chapter 2: Methods).

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Beta (Gy/ka)</th>
<th>Gamma (Gy/ka)</th>
<th>Cosmic (Gy/ka)</th>
<th>Total Dose Rate (Gy/ka)</th>
<th>(D_x) (Gy)</th>
<th>Over-dispersion (%)</th>
<th>OSL Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Seaward*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.53 ± 0.03</td>
<td>0.27 ± 0.01</td>
<td>0.18 ± 0.02</td>
<td>1.00 ± 0.05</td>
<td>0.39 ± 0.05</td>
<td>23 ± 3</td>
<td>390 ± 60</td>
</tr>
<tr>
<td>2) Mor1</td>
<td>0.24 ± 0.01</td>
<td>1.12 ± 0.04</td>
<td>0.83 ± 0.02</td>
<td>0.64 ± 0.02</td>
<td>0.27 ± 0.01</td>
<td>0.18 ± 0.02</td>
<td>1.12 ± 0.04</td>
<td>0.93 ± 0.02</td>
<td>11 ± 1.7</td>
<td>820 ± 40</td>
</tr>
<tr>
<td>3) Mor2</td>
<td>0.20 ±0.01</td>
<td>1.04 ±0.04</td>
<td>0.65 ± 0.01</td>
<td>0.50 ± 0.02</td>
<td>0.22 ±0.003</td>
<td>0.18 ± 0.02</td>
<td>0.94 ± 0.03</td>
<td>1.31 ± 0.03</td>
<td>10 ± 1.6</td>
<td>1400 ± 60</td>
</tr>
<tr>
<td>4) Mor3</td>
<td>0.21 ±0.01</td>
<td>1.17 ±0.05</td>
<td>0.58 ± 0.01</td>
<td>0.45 ± 0.02</td>
<td>0.21 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>0.88 ± 0.03</td>
<td>1.82 ± 0.02</td>
<td>6 ± 0.9</td>
<td>2070 ± 90</td>
</tr>
<tr>
<td>5) Mor7</td>
<td>0.23 ±0.01</td>
<td>1.27 ±0.05</td>
<td>0.55 ± 0.01</td>
<td>0.44 ± 0.02</td>
<td>0.21 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>0.87 ± 0.03</td>
<td>2.24 ± 0.04</td>
<td>8 ± 1.2</td>
<td>2580 ± 110</td>
</tr>
<tr>
<td>6) Middle*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.79 ± 0.05</td>
<td>0.35 ± 0.01</td>
<td>0.18 ± 0.02</td>
<td>1.34 ± 0.07</td>
<td>3.17 ± 0.06</td>
<td>8 ± 3</td>
<td>2380 ± 150</td>
</tr>
<tr>
<td>7) Mor6</td>
<td>0.20 ±0.01</td>
<td>0.87 ±0.03</td>
<td>0.52 ± 0.01</td>
<td>0.41 ± 0.02</td>
<td>0.18 ±0.003</td>
<td>0.18 ± 0.02</td>
<td>0.80 ± 0.03</td>
<td>2.89 ± 0.05</td>
<td>7 ± 1.2</td>
<td>3610 ± 160</td>
</tr>
<tr>
<td>8) Mor5</td>
<td>0.25 ±0.01</td>
<td>1.19 ±0.05</td>
<td>0.62 ± 0.01</td>
<td>0.49 ± 0.02</td>
<td>0.23 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>0.93 ± 0.03</td>
<td>4.45 ± 0.1</td>
<td>11 ± 1.7</td>
<td>4770 ± 220</td>
</tr>
<tr>
<td>9) Mor4</td>
<td>0.25 ±0.01</td>
<td>1.12 ±0.04</td>
<td>0.75 ± 0.01</td>
<td>0.58 ± 0.02</td>
<td>0.26 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>1.04 ± 0.04</td>
<td>5.20 ± 0.06</td>
<td>5 ± 0.8</td>
<td>4980 ± 210</td>
</tr>
<tr>
<td>10) Landward*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.52 ± 0.03</td>
<td>0.28 ± 0.01</td>
<td>0.17 ± 0.02</td>
<td>1.02 ± 0.06</td>
<td>5.59 ± 0.17</td>
<td>18 ± 3</td>
<td>5500 ± 360</td>
</tr>
<tr>
<td>11) MorLAND</td>
<td>0.20 ±0.01</td>
<td>0.82 ±0.03</td>
<td>0.30 ± 0.01</td>
<td>0.25 ± 0.01</td>
<td>0.13 ±0.002</td>
<td>0.18 ± 0.02</td>
<td>0.60 ± 0.03</td>
<td>4.31 ± 0.11</td>
<td>12 ± 1.8</td>
<td>7220 ± 390</td>
</tr>
<tr>
<td>12) Mor-FD1</td>
<td>0.24 ±0.01</td>
<td>1.10 ±0.04</td>
<td>0.63 ± 0.01</td>
<td>0.50 ± 0.02</td>
<td>0.23 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>0.93 ± 0.03</td>
<td>0.17 ± 0.01</td>
<td>27 ± 5</td>
<td>180 ± 15</td>
</tr>
<tr>
<td>13) BM2-REC78</td>
<td>0.32 ±0.01</td>
<td>1.38 ±0.06</td>
<td>0.49 ± 0.01</td>
<td>0.41 ± 0.02</td>
<td>0.20 ±0.004</td>
<td>0.18 ± 0.02</td>
<td>0.83 ± 0.03</td>
<td>0.04 ± 0.003</td>
<td>35 ± 7</td>
<td>43 ± 4</td>
</tr>
<tr>
<td>14) BM2-Mod</td>
<td>0.29 ±0.01</td>
<td>1.28 ±0.05</td>
<td>0.93 ± 0.02</td>
<td>0.71 ± 0.03</td>
<td>0.31 ±0.01</td>
<td>0.19 ± 0.02</td>
<td>1.24 ± 0.04</td>
<td>0.02 ± 0.002</td>
<td>7 ± 1</td>
<td>15 ± 1</td>
</tr>
</tbody>
</table>
The example OSL signal decay curve (Figure 3.2C) is typical of all samples tested. The sensitivity corrected dose response curve shows linearity typical for $D_e$ values below 6 Gy (Figure 3.2C). The spread in $D_e$ data is low (overdispersion values between 5 and 23%), as indicated by an example $D_e$ distribution (plotted as a radial plot; Figure 3.2D) for sample 11 (Table 3.2). These overdispersion results (Table 3.2) are within the normal bounds expected for well-bleached marine quartz samples (Olley et al. 2004). All samples experienced similar environmental dose rates (weighted mean of 0.96 ± 0.04 Gy/ka) and there is no discernible trend either seawards or landwards in the total dose rates (Figure 3.3).

![Figure 3.3: Total dose rate in Gy/ka plotted for all samples arranged according to distance from the shore.](image)

3.3.3 A chronology of coastal progradation

The OSL age estimates from Moruya show a distinctly different pattern of Holocene shoreline progradation than that inferred from radiocarbon ages reported by Thom et al. (1981b) (Figure 3.4, 3.5). The radiocarbon chronology suggested an initially rapid phase of progradation, which then slowed until eventually ceasing ~2500 cal yr BP (Figure 3.4, 3.5) (Thom et al. 1981a). After ~2500 cal yr BP the last 10% of the barrier formed, mostly comprising the large foredune adjacent to the present day beach (Roy et al. 1994).
CHAPTER 3: MORUYA (BENGELLO BEACH)

Figure 3.4. A comparison between the published radiocarbon chronology (Table 3.1) and associated facies model according to Thom et al. (1981b), and the OSL age estimates presented in this study. The topographic barrier profile is extracted from LiDAR data and was taken close to the OSL sampling sites, which is in the central portion of the barrier (see Figure 3.1). *Refers to OSL age estimates determined using single grain techniques.

In contrast, the OSL chronology shows a linear rate of shoreline progradation. The sequence of ridges according to OSL dating spans from 7220 ± 390 yr ago to 390 ± 50 yr ago at an average linear rate of 0.27 m/yr (Figure 3.5). The youngest age of 390 yr ago indicates that the large foredune is only a few hundred years old. The linear progradation trend according to the OSL ages is especially pronounced in the seaward 40% of the barrier indicating neither cessation, nor slowing, of shoreline progradation over the past 3000 years.

This linear pattern of progradation demonstrated by the OSL ages is more consistent with radiocarbon dates along the northern transect at Moruya which shows progradation beginning at ~6000 cal yr BP and ceasing at ~1000 cal yr BP (Figure 3.5) (Roy et al. 1994; Thom et al. 1981b). The oldest OSL age of 7220 yr ago and the innermost
shoreface radiocarbon age of 6530 ± 250 cal yr BP, while differing, both indicate sea level close to present around this time and that there was a sufficiently shallow shoreface profile to trigger shoreline progradation (Cowell et al. 2003a).

Figure 3.5. Radiocarbon ages for the south, central and northern transects (Thom et al. 1981a,b; Roy et al. 1994) and OSL age estimates plotted against dimensionless barrier width for the Moruya Barrier. A linear regression and corresponding $R^2$ value has been defined for the OSL age estimates. Errors correspond to 1 sigma.

The OSL ages presented here do not support the suggestion that there was an initially rapid ‘adjustment phase’ of progradation (Thom et al. 1981a) following culmination of the post-glacial sea-level rise around 7500-8000 cal yr BP (Lewis et al. 2013; Sloss et al. 2007). Such an ‘adjustment phase’ seems to be evident from other radiocarbon chronologies in NSW e.g. Woy Woy and Fens; Roy et al. (1994). It was hypothesised that the initial rapid accumulation of sand at Moruya according to the radiocarbon ages was caused by an “adjustment of nearshore gradients to an equilibrium configuration” (Thom et al. 1981a p.324). However, the OSL ages indicate no such rapid initial progradation of the shoreline; if anything, the trend of the first three OSL ages would indicate a slightly slower rate of progradation than the overall linear trend from ~7000 to ~400 years ago.

A more extended discussion of possible explanations for the difference in OSL dates reported this study and the existing radiocarbon chronology for this site may be found in Oliver et al. (2015). However, some brief additional comments are provided. The disparity between the OSL chronology of this study and the radiocarbon ages of Thom
et al. (1981b) for the central Moruya transect may have several plausible explanations. First, radiocarbon dating of shell hash from nearshore shelly sand may result in a general trend of overestimation of ages, due to the higher probability that older reworked shell fragments would be included in a sample; thus biasing the age (Thom et al. 1981b; Roy 1991).

Another consideration is the uncertainty involved in projecting isochrones to the surface based on ages from sample material collected from depths of 10 to 30 m within the nearshore shelly sand unit. The validity of Thom et al. (1981b)’s method relies on the accurate reconstruction of palaeo beachface and shoreface geometry. GPR data collected for this site (see below) while providing useful information about subsurface structures above 0 m AHD, does not penetrate to the depths necessary in order to inform the drawing of such isochrones. However, section 3.6 below presents a series of revised isochrones based on the GPR reflector geometry above MSL and idealized shoreface geometries considering recent work by Kinsela et al. (2016).

Each of the 60 ridges in this sequence had an average “lifetime” of ~110 years, that is they were, on average, active for this length of time. This is comparable to the average lifetime of 80 years inferred for each ridge for the linear portion of the Holocene ridge sequence at Guichen Bay (Murray-Wallace et al. 2002). This longer ridge “lifetime” is also reflected in the progradation rate of 0.3 m/yr which is than many progradation rates inferred for other coastal sand ridge plains in Australia that have been dated using OSL. This formation time of approximately 110 years per ridge requires further examination with additional dates, especially multiple dates along individual ridges. Given the estimated formation time 110 years per ridge, it will be important to continue the beach monitoring program that has been conducted at Bengello Beach for the past 40 years (McLean & Shen 2006; McLean et al. 2010) if the full estimated lifetime of individual ridges is to be observed. A recent review, which considers this monitoring program in the context of longer term records of progradation from around the world, reinforces the uniqueness of this record and indicates that progradation may still be continuing today (Tamura 2012).

The OSL dating sequence does include one age reversal; samples 5 and 6 (Figure 3.4, 3.5 and Table 3.2). These two samples are separated by one large compound ridge with deep inter-ridge swales on either side. Considering the average ridge ‘lifetime’ of 110
years and the 1 sigma error on each of the two ages (samples 5 and 6, Table 3.2) of 110 and 150 years respectively, they are not statistically separable.

Another uncertainty exists between samples 8 and 9 where the ages overlap at the 1 sigma error, yet the distance between the sample locations is around 300 m spanning 7 identifiable ridge crests. Despite this, the linearity of the sequences of ages is still apparent (Figure 3.5). More OSL dates on individual ridges along the dating transect presented in this paper might resolve the question of whether there were episodes of rapid progradation, however the errors associated with OSL dating of samples (especially older than ~2000 yrs) makes it likely that such episodes would remain masked by dating uncertainties. However, further OSL dating north and south along specific ridges would enhance the precision of ridge formation time and shed light on problems of alongshore variation of progradation patterns first identified by the three radiocarbon dating transects for this site (Thom et al. 1981b).

3.4 GPR across the Moruya barrier

3.4.1 Introduction

GPR data at Moruya was collected across the entire barrier width at it widest point (almost 2 km) and is shown below in a series of nine 200 m portions. Such a continuous record of subsurface structure across a prograded barrier has not yet been presented in published literature. The discussion that follows these results will focus on the character of the shallow subsurface stratigraphy and provide some insights into the ridge formation processes. In addition, an examination of the elevation of the subsurface structures in the GPR data will be made with reference to their possible use a palaeo-sea-level indicators.

3.4.2 Characterising the subsurface structures

The GPR results are proximal to the OSL dating transect in section 3.3 above (see Figure 3.4) and the nine ~200 m sections are denoted A through to I. The location of the OSL dates from section 3.3 above have been included in these sections at their respective depths on each ~200 m section to relate specific structures to particular time periods in the barrier history.
CHAPTER 3: MORUYA (BENELLO BEACH)

Figure 3.6: The geographic locations of each of the GPR sections with respect to the barrier morphology. The DEM is a TIN model derived from LiDAR of ground returns.

GPR section (A) (Figure 3.6) was collected along a slightly winding foot track descending from the truncated bedrock structure at the rear of the barrier (Figure 3.6). The transition from bedrock to barrier sands was surprisingly obvious in the field. As can be seen in Figure 3.7A, the 250 MHz antenna has delineated the bedrock surface which dips seaward. Beneath this reflector no stratigraphy is evident. Moving seaward across section (A) a series of reflectors with similar seaward dip angles are present. Some reflectors above the water table may indicate incipient ridge building. Some apparent storm cut and recovery features appear to be evident between 40 and 60 metres along section (A) (Figure 3.7A). The beach cut, recovery and progradation ‘activity’ is occurring at an elevation of between 2-4 m AHD with the infant ridge crests at a height of around 5 m AHD.

Section (B) (Figure 3.7B) of the GPR shows the most stratigraphic detail of any of the profiles with a series of evenly spaced strong seaward-dipping reflectors which are slightly concave-up. These reflectors are surprisingly uniform in geometry with respect to one another in this portion of the data. There is also some evidence of incipient ridge crests at around 5 m. There is one particularly strong reflector spanning close to 100 m
in length and reaching from 4 m to 0.5 m AHD in elevation. It is difficult to ascertain whether this reflector is evidence of a particularly intense storm event, or whether its strength is related to an increase in penetration depth of the antenna. Perhaps the surrounding reflectors, which have similar geometry, have this same character but have not been imaged by the GPR to this depth. A series of cores down to this reflector would reveal the specific substrate characteristics which have produced this strong signal in the GPR data. While there appears to be a significant degree of regularity in the spacing and geometry of the reflectors in section (B) (Figure 3.7B), there is also some variation in dip angle which may be related to variability in the strength and nature of storm activity.

Strong seaward-dipping reflectors continue into Section (C) (Figure 3.7C) and appear to maintain a similar geometry and concave-up character. However, in this section the reflectors above the water table also resemble their counterparts below the water table, rather than changing to a convex-up geometry as seen in section (A) and (B).

Section (D) (Figure 3.7D) has clear structures for the first 100 metres, after which horizontal ringing has masked much of the subsurface structure. Some examples of cut and recovery of the beach face are still evident between 2-3 m AHD at around 450 m (Figure 3.7D). The severe horizontal ringing continues throughout section (E) (Figure 3.7E) and for much of section (F) (Figure 3.7F), although in this later section more structure can be seen. The reasons for such ringing are unknown, but are potentially related to a particularly compacted track surface in this region; although no obvious change was evident in the field.

At the start of section (F) between 800 m to 825 m convex-up reflectors are apparent which appear distinctive when compared with the other sections. From around 900 m onwards in section (F) the reflectors are close in character to what was evident in previous sections.

Section (G) (Figure 3.7G) contains a series of regular reflectors below the water table of varying geometry, some concave-up and some short convex-up reflectors indicative of cut and fill progradation. Above the water table there is evidence of both concave-up erosional like reflectors, as well as convex-up reflectors indicating ridge vertical building. A series of landward-dipping reflectors at 1125 m and 2-3 m AHD complicate this section as they downlap unconformably onto a strong seaward-dipping reflector.
Section (H) (Figure 3.7H), taken along the roadside just north of the Moruya Aerodrome (Figure 3.6), shows significant ringing over the first 100 m due to the compacted gravel road surface. Between 100 m and 200 m subsurface structures are apparent as there was more available unvegetated areas for walking >2 m away from the road edge. This meant better imaging was possible. The structures in this landward portion of section (H) are strong seaward-dipping reflectors between 0 and 4 m AHD. There are no ridge building structures above these reflectors as in other sections, because the topmost surface over the barrier has been smoothed slightly during road construction. Thus, while it may appear that the beachface reflectors have risen in elevation; this is not the case. They are in fact at an elevation similar to all other landward GPR sections.

Section (I) (Figure 3.7I) continues on from Section (H) with a series of regular seaward-dipping reflectors. This section is well imaged, as off road walking was possible. The shore-parallel sections of the transect (see Figure 3.6) were removed during the processing stage. Reflectors continue until around 260 m where there appears to be a buried ridge surface with landward-dipping reflectors capping the foredune (see section 3.7.2. below for further discussion of this foredune stratigraphy). The foredune is not as high in this location (7 m AHD) as at areas nearby, for example just to the north where the crest height is around 8-9 m AHD. This transect location was selected due to accessibility; other surrounding areas of the foredune are quite thickly vegetated. At 325 m the scarp associated with the 1974 and 1978 storms is evident. Some short reflectors in the two incipient ridges are apparent between 3-4 m AHD likely evidence for small storm events.
3.4.3 Significance of the GPR data for understanding progradation

The GPR results presented above are an almost continuous record of subsurface structure across the barrier at its widest point. The record is broken only by horizontal ringing in some instances although some structures are still evident in these areas. All subsurface structure presented above is higher than 0 m AHD placing it in the upper beachface zone of activity. The intention was for the GPR to also image shoreface reflectors; in order to inform the relationship between the radiocarbon ages of Thom et al. (1981b) and the OSL ages in this study. However, this data nevertheless provides important insights into the ridge-building processes over the barrier history as well as implications for the debate about higher sea-levels during the late Holocene.

The first important trend to note is the drop in water table height over the entire GPR profile. For sections (A) through to (D) the water table has an elevation of 3.5 m AHD, from (E) through to (G) an elevation of 3 m AHD and for section (H) an elevation of 2 m AHD. It then rises to 3 m AHD for section (I); most likely due to the rise in elevation associated with the higher foredune. Such an overfall drop in water table elevation is expected as proximity to the ocean is reduced and a similar lowering of water table elevation was observed for the Seven Mile Beach prograded barrier system in Tasmania (Donaldson 2010).

It appears from the GPR data, that incipient ridge building has occurred at the same elevation (between 4-5 m AHD), as these modern incipient ridge building processes, for the entire barrier sequence. The convex-up reflectors, concave-up truncations and ‘tops’ of upper beachface reflectors evident at this elevation (4-5 m AHD) in many of the sections (A) through to (I), demonstrate that the incipient ridge seen on the beach today is at a similar elevation with respect to imaged beachface reflectors. A mechanism is therefore required not only for the current incipient ridge, but for all ridges in the sequence which explains how ridges attain heights of ~6 m i.e. how does an incipient ridge ‘grow’ into a ridge in the sequence. The obvious conclusion is that each incipient ridge and inter-ridge swale couplet builds higher by accumulating sediment over time. The average ridge ‘lifetime’ of 110 years is informative in understanding the timing of
such a process of accumulation. If the current incipient ridge has attained a height of 4.8 m AHD in the ~35 years since the 1974 and 1978 storm events, it has another 75 years of accumulation yet to occur. One can envisage it attaining an elevation of around 6 m AHD over this time while another incipient ridge may form on its seaward margin. It has also been demonstrated for a barrier island coast in Florida, that during the process of ridge building “up to approximately one order of magnitude lower sedimentation rates occur after an initial period of more rapid aeolian accumulation” (Rink & Lopez 2010 p.341).

A related point concerning the elevation of beachface reflectors over the barrier width is that there is no apparent decrease in height of these structures. Across the barrier width the upper limit of the preserved beachface reflectors with a concave-up seaward-dipping geometry occur between the 3-4.5 m AHD with no obvious decreasing trend. However the exact height (within 0.3 m, which is the vertical error associated with the LiDAR data used for topographically correcting the GPR) of these upper limits is debateable, especially as they commonly coincide with the elevation of the water table.

Some insights into ridge-building processes are seen in the GPR profiles presented above. Beneath the ridges in the barrier sequence are a series of seaward-dipping reflectors of varying size and geometry. However, there is no apparent trend of strong reflectors being associated with topographically high ridges. Some resemblance to the published model of coastal sand ridge development proposed by Bird (1976) may be seen in the GPR data. The model as presented by Bird (1976) involves the accumulation of sand on and behind the berm forming a low ridge often occupied by Spinifex grasses. This low ridge is then scarped by storms, and the resultant slumping of the scarp and accumulation due to wind and wave action ‘repairs’ the scarp and a undulating morphology is produced (Figure 3.8). However, the GPR suggests that a complex suite of storm events of differing strength are involved in this process at Moruya, rather than a single storm event as shown in the Bird (1976) schematic in Figure 3.8.
Figure 3.8: The top box shows the development of a coastal sand ridge sequence after Bird (1976) where a berm (A) grows into a foredune covered by grasses (B) which is subsequently scarped (C) and recovers to form a higher foredune with a new berm in front (D). The bottom box shows selected beach profiles from Moruya coloured according to year by Tamura (2012).

The GPR data for across the historical ridges indicates that the process of storm erosion and recovery seen at Moruya over the past 40 years (McLean & Shen 2006) has occurred throughout the barriers progradational history. Furthermore, examining the profiles presented by Tamura (2012) for this site (Figure 3.8) from the profiling dataset of (McLean & Shen 2006), the complex suite of beachface geometries appears to be similar to the complexity of beachface reflectors observed in the GPR data. Thus it is likely that the processes of storm erosion and recovery, which have produced the incipient ridge evident currently at Moruya (Figure 3.8), have been responsible for ridge development in the past. However, if we consider the average ridge lifetime to be in the order of ~100 years we may suppose that we have observed in the beach monitoring at this site roughly 40% of a ridge-building time period. It is not known whether the
incipient ridge seen on the front of the Moruya beach face currently will develop into a ridge of comparable height and morphology to those seen in the Holocene sequence.

It appears that a complex series of storm events, likely to be of varying magnitude facilitate ridge building on the Moruya barrier. However, storm cut and recovery processes are recorded in beach profiling records for numerous other beaches along this coastline, which are not backed by a Holocene prograded barrier sequence. Therefore the process of storm cut and recovery alone does not produce a prograded barrier of ridges.

![Figure 3.9: Schematic after Woodroffe (2003) showing storm cut and recovery processes where negative, neutral and positive sediment budget result in coastal recession, stability or accretion.](image)

The critical factor is a positive long-term sediment budget, so that volume of the recovery after a storm event is greater than that which was cut away (Figure 3.9). The process of storm cut and recovery is a well-known process occurring on many NSW beaches but the process itself does not produce a ridge sequence, rather, it is an ongoing positive sediment budget. This point has rarely been emphasised in the published literature on coastal sand ridge formation where process models abound. It must be reiterated: coastal processes do not form a prograded barrier. A positive sediment budget does.
3.5 Morphology of the barrier

3.5.1 Introduction

With the aid of LiDAR data, the morphology of the Moruya barrier can be examined in detail, including heights of individual ridges, variation in the amplitude and spacing of the ridge sequence and truncations, bifurcations and coalescing of ridges. In addition, other geomorphic features of the barrier complex can be discerned, for example, freshwater swamps, small creeks which incise through the barrier, and the bedrock structures around the landward margin of the barrier. LiDAR data was able to penetrate the tall vegetation covering the majority of this coastal plain and provides a new opportunity to examine it’s morphologic features.

3.5.2 Ridge morphometrics

Individual ridge heights at Moruya vary considerably; both in shore parallel and shore normal directions. There is a general trend for each ridge to increase in height towards the northern end of the barrier, although there is a slight decrease again close to the small island just inland from Broulee Island. This increase is in the order of 1-2 metres with heights at southern end being commonly around 4.5 – 6 m and at the northern end around 6.5 - 7.5 m (Figure 3.10). The increase in height occurs gradually and the maximum height of each ridge is attained just north of the small creek flowing out from Waldrons swamp (Figure 3.10). The same pattern is apparent for inter-ridge swales, which also seem to increase in height northwards, although to a lesser degree (in the order of 0.5-1.5 m).

This general increase in height northward is hypothesised to result from an increase in dune building activity northwards along the embayment leading to greater aeolian decoration capping each ridge. An increase in dune building activity in the northern end of the embayment is attributed to the generally flatter beach profile common for the northern ends of embayments and observed at Moruya (Wright et al. 1979), where there is greater potential for the entrainment and transport of aeolian material (Short 1999; Short & Hesp 1982). This flatter beach profile in the north results from the generally finer sands in the north compared to the south of embayments along the southeastern coast of Australia, for example at Seven Mile Beach (Wright 1970). This generally
accepted grain size difference within embayments is due to the winnowing of finer grained material northwards as it has greater transport potential.

The differential in dune development in the north and south of the Moruya embayment may be conceptualised by examining Figure 2 from Psuty (1992): the northern end of the Moruya embayment is likely to be experiencing a more positive ‘foredune budget’ than the southern end. Wright (1970) observed at Seven Mile Beach, that incipient foredune accretion increased dramatically up to 40 cm in one year at the northern end of the embayment.

The crest height for any given ridge, while increasing northward gradually, is nevertheless highly variable alongshore. Interpolating crest heights from the LiDAR data reveals that the crest height may vary by up to 1 metre over just 200-300 metres despite the general increasing height trend. This is also true for inter-ridge swales, which may vary to a similar amount over the same distance. The position of the crest maximum height and inter-ridge swale minimum height in planform also shifts subtly on an east-west plane. The amplitude of this slight ‘wiggle’ in crest or inter-ridge swale strike is commonly around 10-15 m.

Some ridges seem anomalously high in comparison to others when examining a shore normal transect, as can be seen in Figure 3.10. Particularly high ridges may be accompanied by ridges of small or moderate size ridges on either side. Larger ridges may have a single high crest or may be wider and have multiple small crests of a similar height 15-20 metres apart. Large ridges do not seem to occur in sets and neither to smaller ridges.
Ridge amplitude and spacing also seems highly variable across the barrier complex. Ridge amplitude is here defined as the difference in height between a ridge crest and an inter-ridge swale and ridge spacing as the length in metres between ridge crests. The example in Figure 3.10 of the central profile shows a subtle but significant increase in ridge amplitude in a seaward direction (excluding the modern foredune and incipient ridge). The increase in amplitude for this particular profile is approximately 1 metre. There also appears to be a trend of closer ridge spacing especially in the zone from 1400 – 1800 metres (Figure 3.10). This general trend of closer spaced, higher amplitude ridges closer to the present shoreline appears to be evident on close inspection of other shore normal profiles to the north and south. However these amplitude and spacing trends could potentially be a product of ridge degradation over time, which is

Figure 3.10: A series of five profiles across the Moruya barrier extracted from LiDAR derived DEM. The bottom profile is a detailed examination of profile 4 (where the barrier is at it widest) and corresponds to where the OSL samples were collected.
commonly seen in Pleistocene ridges (van de Geer 1981). Although, the time differential from the most landward ridges is in the order of a few thousand years, rather than hundreds of thousands of years common for ridges from MIS 5 for example. Davies (1957) was first to suggest that an increase in ridge amplitude implies a slower rate a ridge development, an idea which was reinforced by Shepherd (1987). However, the OSL ages do not support a slowing trend in ridge building rate.

The incipient ridge which is actively receiving aeolian sand is 4.8 metres high, which is lower than any other ridges in the sequence. While it is probable that this incipient ridge will continue to increase in height, assuming it is not removed by a large storm event as documented by McLean and Shen (2006), its height above the inter-ridge swale immediately landward seems an ‘appropriate’ amplitude considering the rest of the profile. However, the questions of why there is such a large foredune and why there is a inter-ridge swale of only 3 metres compared with 4.5 – 5 m inter-ridge swale heights for the rest of the profile do not yet have satisfactory answers. Davies (1957) observed this same ‘problem’ when examining the ridge sequence of Seven Mile Beach in southeastern Tasmania (Figure 3.11) where the current summer beach berm formed at an elevation significantly lower than that required to build the ridge sequence. At Moruya, it appears that the incipient ridge is forming at a similarly low elevation with respect to the rest of the ridge sequence. However the GPR data collected at Moruya reveals that incipient ridge building has occurred at elevations of 4-5 m for the whole barrier sequence and that vertical accretion of each ridge must occur over longer time scales to produce relict ridges with crest heights of 6-7 m. The observations of McLean and Shen (2006) at Moruya, indicate that the current incipient ridge has accreted vertically between 1980 and 2004 at least 2 m. This corresponds to a rate of ~80 cm/yr, which, with the average ridge formation time is 110 years would build a ridge in the order of 8-9 m.
Figure 3.11: The frontal portion of the ridge sequence at Seven Mile Beach, southeastern Tasmania showing the difference in elevation of the past and present high water mark in relation to the heights of the older ridges and the modern day beach berm. Modified after Davies (1957).

When following a single ridge crest alongshore, bifurcation and coalescing is common. This occurs throughout the entire barrier sequence; an example is seen in Figure 3.12. Two distinct ridges separated by an inter-ridge swale may coalesce to from a single ridge for some distance and continue as a single crest alongshore, or often bifurcate and an inter-ridge swale will appear. Remarkably, a single ridge cannot be tracked topographically for more than several hundred metres before it either bifurcates into two separate ridges, or is joined by another ridge which continues as the initial ridge fades away.
Another feature of the ridge morphology at Moruya can be seen just landward of the Moruya airport (Figure 3.1A) where there is a distinct change in ridge alignment. A series of 3-4 ridges appear to bend seaward to form a SE to NW alignment. This indicates the presence of a small structural control, either a subaqueous offshore reef or low-lying island. As it is now covered by marine sands, it must have been topographically subtle but yet significant enough to affect ridge alignment. Interestingly the drilling profile by Thom et al. (1981b) shows a distinct rise in bedrock in this region to approximately -5 m AHD. It is possible that this rise, perhaps in the form of a submerged reef, could have realigned the ridge sequence due to its affect on wave refraction. A similar bedrock topographic rise is present in the drilling transect for the northern end in Thom et al. (1981b) although the rise is less significant, reaching a maximum of – 10 m AHD. There is no evidence of ridge realignment at the northern end as a result of this feature.
3.5.3 Broader morphology of the barrier

Along the landward margin of the Moruya barrier are a series of now freshwater swamps. The largest is Waldrons Swamp which connects to the ocean in the northward portion of the barrier through an incised channel. The landward curvature of the ridges proximal to this channel suggest that it has advanced as the barrier has prograded rather than incising as a subsequent event. A second channel flowing from a smaller back barrier swamp terminates just landward of the Moruya airport and has a similar morphology. There are a number of other swamps that do not have outflow channels. These swamps formed as marine sand was reworked across the inner shelf during the post glacial marine transgression impounding small barriers around ~7500 years ago. These small barriers would have resembled barrier islands in their morphology and the swamps would likely have experienced saline conditions. Preliminary cores from a number of these swamps have confirmed the presence of marine shells in the basal layers (B. Thom, personal communication, unpublished data). The timing of the switch from marine to freshwater for these swamps is unknown but it is likely that after several thousand years, their ephemeral nature would have resulted in little marine influence, as their catchment size is not sufficient to maintain a permanently open channel to the ocean.

Another feature to note regarding the two creeks incised through the ridge sequence is their distinct southward migration, and then, for the northern channel, subsequent northwards migration (Figure 3.13). The OSL dating results above reveal that the timing of the southward turn for both of the channels is ~2000 years ago. The morphology of the barrier at the time of this switch is significant as at this time a more permanent tombolo would have connected the barrier to the smaller island just west of the more prominent Broulee Island (see Figure 3.1). The formation of such a tombolo would have altered the nearshore wave propagation patterns as well as nearshore drift patterns. The hypothesis suggested here is that such a series of changes may have caused the southward migration of the two creeks. Confirmation of this hypothesis would require nearshore wave modelling involving significant assumptions regarding the character of the offshore profile during this time and beach regime, both of which are uncertain. However, using appropriate offshore data and additional dating, as in Goodwin et al. (2006), a picture of such sediment movements could be established.
The more recent northward migration of the northerly of the two creeks (Figure 3.13) occurred, according to the OSL dating above, around ~400 years ago, and is potentially coeval with the formation of the high foredune. It is possible that the development of the high foredune ‘blocked’ the outflow the creek and forced it to migrate to the north and it burst through the developing foredune during a high magnitude flood event. Further investigation including dating and sediment analysis around these creeks would help to resolve some of these questions and likely prove useful in understanding the morphodynamics of these smaller scale sub-systems involved in the overall barrier deposition.

Figure 3.13: Three-dimensional view of the Moruya barrier with a northwesterly aspect. Red circles show the location of truncated bedrock headlands.

The truncated bedrock features present around the landward margin of the barrier are another feature of the barrier morphology evident from a LiDAR derived DEM. Four truncated bedrock structures are evident in Figure 3.13 where the marine sand transitions to bedrock within a matter of metres. The slopes of these truncated bedrock features are steep in comparison the rest of the barrier. The most satisfactory hypothesis for the formation of these features involves marine erosion during the higher sea-levels of the late Pleistocene during MIS stage 5. During this period, and especially during MIS 5e, sea levels ~2 metres higher than present, may have formed a series of small pocket beaches infilling small bedrock embayments separated by sections of cliff as can
be seen nowadays at South Durras just north of Batemans Bay or at Garie Beach and surrounds. There is also evidence from drill cores near the base of these truncated bedrock features at Moruya of relict shore platforms presumably also formed during a period of higher than present sea level in the Pleistocene (Figure 3.13).

### 3.6 Barrier volumes and sediment accumulation rates

#### 3.6.1 Introduction

This section presents the results of the estimation of volumes of sediment deposited in the Moruya barrier over the Holocene using LiDAR data. Volumes above 3 m AHD are reported which accounts for the aeolian facies of the barrier. In addition, calculation of barrier volume for the central transect based on new interpreted isochrones was completed which considers the aeolian, beachface and shoreface facies. These results are then discussed in the context of other reported prograded barrier volumes. The limitations of these calculations are also considered.

#### 3.6.2 Aeolian sediment volumes

Volumetric analysis above 3 m AHD demonstrated that, relatively consistent amounts of sediment have accumulated in the aeolian portion of the barrier as it prograded. However, some shorter-term complexity is also superimposed on the longer-term trend. The data in Figure 3.14A showing cumulative aeolian volume over the Holocene was fitted with a linear trend line ($R^2 = 0.94$), which demonstrates a consistent pattern of ridge formation over the Holocene. Using this trend line the aeolian accumulation rate is shown to be $\sim 3600$ m$^3$/yr, which at the current embayment length equates to $\sim 0.6$ m$^3$/m/yr. Thus over the ~40 years the beach surveying program at Moruya has been running, an overall increase in aeolian sediment of $\sim 20-30$ m$^3$/m should have occurred. A calculation from the beach profiling redrawn in Tamura (2012) (see Figure 3.8) reveals that the envelope of sediment above 3 m AHD stored in the recovery from the 1978 storms and the recent incipient ridges is $\sim 40$ m$^3$/m.

The two separate lines of best fit applied to the embayment length data in Figure 3.14B demonstrate that from $\sim 7000 – 2500$, embayment size is rapidly increasing, and from $\sim 2500 – 0$ embayment size is slowly decreasing. Despite this significant change in the trend of embayment length, an overall steady aeolian sedimentation rate has occurred over the Holocene.
Figure 3.14: (A) Cumulative barrier volume results for the Moruya barrier above 3 m AHD, delineated according to the OSL ages across the ridge sequence. Vertical error bars indicate cumulative error of volume calculation and horizontal error bars reflect error for each OSL age. (B) Embayment length over the Holocene according to the pattern of OSL ages.

3.6.3 Shoreface reconstruction volumes

At Moruya, where there has been extensive drilling and radiocarbon dating, the OSL ages presented above provided an opportunity to reconstruct paleoshorefaces which could reconcile the difference between the radiocarbon chronology of the shoreface facies and the OSL dates from the aeolian dune facies. A new series of isochrones were drawn which were modified from the known shoreface profile depicted in Thom et al. (1981b) (see Figure 3.4 above). Modelled shoreface profiles incorporated the curvature of the GPR imaged beachfaces above MSL and extended deeper into the barrier profile based on the general pattern in Figure 7 of Roy and Thom (1981) where during Holocene progradation an initially lower-angle shoreface transitions to a higher-angle shoreface. Consideration was also given to the recent work of Kinsela et al.
(2016) in the drawing of interpreted shoreface isochrones. These reconstructed shorefaces produced a far more robust agreement between the OSL ages and the radiocarbon ages than was evident from the original isochrones (Figure 3.4) seen in Thom et al. (1981b) and also in Figure 3 of Thom and Roy (1985). A modelled reconstruction of relict shorefaces after Kinsela et al. (2016) at Moruya would be of great benefit at this site in the future.

Figure 3.15: A) Moruya central transect stratigraphy modified from Figure 3.4 with interpreted isochrones with reconstructed shoreface geometry. B) Discrete volumes (assuming a 1 m wide transect) for each time period defined by the isochrones in part A. C) Cumulative volume over time calculated using the discrete values in part B with a linear fit applied.
Volumes of material added to the barrier could then be calculated in $m^3/m/yr$ from 7000 years ago to present (Figure 3.15B) based on these interpreted isochrones. Despite some variability in the volumes for each time slice (Figure 3.15B) a consistent trend of barrier accumulation for the Moruya central transect based on these interpreted isochrones is demonstrated (Figure 3.15C) at a rate of $5.7 \ m^3/m/yr$. This rate of barrier volumetric growth is comparable to the volumes calculated for the Tuncurry barrier by Kinsela et al. (2016). In the optimal simulation of Kinsela et al. (2016) the rate of overall barrier growth declined during the simulation from around $8 \ m^3/m/yr$ to $2 \ m^3/m/yr$ despite shoreline progradation rate remaining relatively constant. Modelling of relict shorefaces at Moruya, where now both the shoreline and shoreface progradation is chronologically constrained, offers a unique opportunity to better define the Holocene progradation and the interplay between the shoreface and shoreline.

3.6.4 Uncertainty of barrier volume calculations

In the calculation of aeolian volume at Moruya, there is a difference between a vertical line used by the ‘polygon volume tool in ArcGIS and the GPR imaged subsurface structures in the aeolian facies. However Figure 3.15 demonstrates that this difference above $3 \ m \ AHD$ is minimal compared to the error in the beachface and shoreface zones where a much lower-angle surfaces exists. Subsurface structure above $3 \ m \ AHD$ in the GPR for Moruya are characterised by more complex hummocky reflectors rather than distinct concave-up bounding surfaces representing relict beachfaces below $3 \ m \ AHD$.

Both the aeolian volume calculation volumes and the central transect shoreface reconstruction volumes at Moruya include an assumption of negligible sea-level change during the progradation history. Kinsela et al. (2016) found that during simulation of shoreface response throughout the Holocene, a sea-level fall could not account for the observed volumes of accumulation. Furthermore, there is ongoing debate regarding the nature and level of a late Holocene sea-level curve for NSW (Lewis et al. 2103; Sloss et al. 2007).
3.7 The foredune

3.7.1 Foredune morphology

The large foredune at Moruya is seen to be a much more recent feature of the barrier than previously indicated by radiocarbon dating. The foredune stands on average 3-5 metres higher than the crests of older ridges across the barrier sequence. There is a general trend of increasing volume and height toward the north until just north of the Waldrons Swamp creek outflow (4500-5000 m distance in Figure 3.16), after which a small decrease in height and volume occurs (Figure 3.16). A hypothesis for this height and volume trend, involves the interaction of wave climate and refraction patterns over the late Holocene forming a confluence zone of sediment drift patterns. This pattern of maximum foredune height between 4500-5000 metres along the barrier (from south to north) is also a feature of all other ridges in the Holocene sequence, and is hypothesised as due to the an increase in dune building activity in this region of the barrier, related to beach state and grain size variation.

The foredune seen from above using LiDAR data appears to be significantly lobed along its landward edge. These lobes have a tendency to truncate earlier proximal ridges as can be seen in Figure 3.16 (c), (d) and (e) and appear to indicate the cascading of aeolian material over existing ridge topography. Thus, during formation of the foredune, is appears that there has been deposition of aeolian material landwards to a degree not observed in older ridges. This foredune is therefore indicative of a phase of unprecedented dune activity in the past ~400 years and the age of 180 ± 15 (see Figure 3.17) from the crest of the feature near the northern end of the airport confirms this. This sample taken from ~1m deep within the dune indicates that this feature formed around this time. The greater height and development of the foredune further to the north suggests that accretion of this feature may have continued after 180 ± 15 years ago.

The storm scarp, evident in the DEM in Figure 3.17 and the DEM’s in Figure 3.16 (a)-(f), was caused by the significant storms in the mid and late 1970’s (McLean & Shen, 2006), it is noteworthy that the geographic position of the current foredune is well landward of the scarp. In fact on close inspection it is possible to discern one, or in some cases several, ridges between the scarp position and the foredune crest (see profile
in Figure 3.17). The most seaward of these ridges appears to be truncated by the 1978 storm scarp and it is this ridge that is seen in the left of the photo in Figure 3.18.

Figure 3.16: Top: foredune volume (above 3 m AHD) and height plotted from south to north; derived from LiDAR data. Bottom: DEM models (a) - (f) show approximately 1 km sections of the foredune in greater detail. The elevation classification of the DEM’s (a) to (f) is identical to all other Figures showing the LiDAR data.
Figure 3.17: Large scale view of a section of the Moruya foredune using a LiDAR derived DEM showing critical elements of morphology. Four OSL ages are also plotted with the northern two located on McLean and Shen (2006)'s Profile 1.

As is demonstrated by the photo in Figure 3.18, these ridge features just seaward of the larger foredune were present at the time of the 1970’s storms and where truncated by this erosional activity. Therefore the formation of the foredune is not related to these storm events and rather reflects an earlier episode of increased dune activity.
Figure 3.18: Looking northwards from profile 3 (McLean & Shen 2006) on Bengello Beach on 25th May 1974. After this date, the erosional scarp continued to migrate landwards into the vegetated foredune on the left. Photo from McLean et al. (2010).

3.7.2 Foredune subsurface structure

Foredune subsurface structure has been examined using GPR across three transects at the southern, central and northern parts of the foredune. While the northern and southern transect locations were constrained by the location of access tracks, thinner vegetation allowed the central GPR transect location to align with the OSL dating transect and GPR was collected across an undisturbed portion of the foredune. The GPR data for all three transects: south, middle and north, is dominated by seaward-dipping reflectors of varying geometry which commonly truncate one another indicating a complex pattern of sedimentation over the past ~400 years. A peculiar feature of the central GPR transect over the foredune crest seen Figure 3.17 is the presence of landward-dipping reflectors lying unconformably on an undulating surface interpreted as a buried ridge-inter-ridge swale surface (Figure 3.19). These landward-dipping reflectors are composed of aeolian sand and appear from the GPR to have cascaded landwards and downlapped onto the buried ridge surface. No other comparable landward dipping reflectors were observed in the GPR record for this barrier implying a unique formative processes for the foredune.
Figure 3.19 (above): GPR data across the central portion of the Moruya foredune (location in Figure 3.17). This transect was collected using a 250 MHz antenna and referenced to mean sea level (AHD) using a topographic profile derived from LiDAR data. The horizontal dotted line denotes the water table and interpreted sediment packages have been coloured and lettered a – r. OSL ages are also plotted (see Figure 3.17 for sample locations).

Figure 3.20: Location on a LiDAR DEM of the A) southern GPR transect location and B) northern GPR transect location. The southern transect (A) traverses over the foredune location but in an area where it has been smoothed during the building of the Moruya airport. The northern transect (B) does not traverse the foredune but still provides useful information regarding the nature of recent deposition of the barrier.

Examining GPR profiles from the northern and southern ends of the Moruya barrier (Figure 3.20) reveals a similarly complex pattern of sediment accumulation in recent centuries. Such complexity is to be expected and reflects the measured complexity of beach change at this site (Figure 3.8) (Tamura 2012). The depositional and erosional structures preserved demonstrate that sediments in this frontal zone of the barrier are consistently reworked by wave and wind (Tamura 2012). Such reworking and poor
preservation potential is expected when the average ‘lifetime’ of 110 years is considered.

A close inspection of the southern GPR transect shows a series of seaward-dipping reflectors of varying geometry (Figure 3.21). A series a low-angle beachfaces may be seen in the profile between 1 - 2 m AHD and persist till 30-40 m along the profile reaching an elevation of around 0.5 m. There appears to be a seaward migrating berm like structure at around 1.5 m AHD between 0 and 20 metres along the transect which downlaps onto the low angle beachfaces. A possible truncation at 28 m at an elevation of between 4-0.5 m AHD could be the stratigraphic signature of the 1978 storm event as its distance along the transect matches the position on the LiDAR DEM in Figure 3.20. A clear steep truncation can be seen at around 52 m which cuts into an existing incipient ridge. The recovery from this scarp has formed a second low ridge just visible in the topography in Figure 3.20A and is laterally persistent alongshore.
Figure 3.21: GPR transect for the southern end of the Moruya barrier (location in Figure 3.20A). The crest structures of the foredune in this transect have not been captured due to levelling of the ground surface for construction of the airport.

The northern GPR transect (location in Figure 3.20B), does not capture the formative processes of the high foredune, nevertheless shows the recent progradation structures of the barrier. The position of the 1978 scarp on the LiDAR DEM has been located in its position in the GPR profile at around 43 m. There is a possible truncation of the seaward-dipping reflectors in this location which might indicate scarping activity. However in both these GPR transects (Figure 3.21 and Figure 3.22) the difficulty in imaging a beach scarp, which is essentially a vertical topographic feature, is apparent.
Figure 3.22: GPR transect for the northern end of the Moruya barrier (location in Figure 3.20B). This transect does not capture the foredune but cover the incipient ridges behind the present day beach as well as traversing the 1978 scarp. The dotted line on the interpreted transect is the 1978 storm scarp preserved as a truncation. Its position in the profile agrees with the topographic position determined from the LiDAR DEM in Figure 3.20B).

3.7.3 Explanations for foredune development

The GPR and LiDAR data relating to foredune fronting the Moruya prograded barrier presents compelling evidence for a process of foredune formation involving the landward migration of aeolian sediments burying two established older ridges. A similar example of a buried ridge sequence has been observed from GPR data at Fens, NSW (personal communication, A. Dougherty, unpublished data). However, the question remains as to the causes of such an event and the origin of such aeolian material. As can be seen from the GPR above, no such landward-dipping, downlapping features have been observed for any other ridges in the entire Holocene sequence. A change in wave
climate and storm magnitude and frequency has been proposed as a possible driver of rapid foredune accretion along this coastline (Goodwin et al. 2015).

Examining the morphology and subsurface structure of this foredune at Moruya in the context of published models of barrier deposition and dune development reveals some fascinating insights. First the barrier model proposed by Roy et al. (1994) (Figure 3.23A) suggests that distinct barrier types such as prograded barriers and stationary barriers have a characteristic morphology and stratigraphy where the primary mode of sediment accumulation in the former is seawards and in the later is upwards. This model highlights the anomalous behaviour of the Moruya barrier in recent times as the barrier has accumulated sediment vertically and laterally in a landwards direction to create a foredune feature not observed in the Holocene history of the barrier. Another model of barrier evolution proposed by Psuty (1992) (Figure 3.23B) suggests that such movements of sediment and the resulting barrier morphologies are due to specific sediment budget conditions; either positive or negative beach and foredune budgets. This model suggests that an accreting foredune has a separable time series of vertically accreted layers, whereas a ridge series has a horizontally sequential time series. The Moruya barrier appears to contain both such models, as the OSL ages clearly demonstrate a sequential time series for the ridges (Figure 3.23D), and the GPR data for the foredune shows evidence of a two-stage vertical building process not evident for other ridges. Obviously the ridge-building mechanism for other ridges in the sequence involves a time series of events as is seen in the development of incipient ridges on the modern beach (McLean & Shen 2006). However the buried ridge surface overlain with aeolian landward-dipping reflectors is evidence of a time series of events dissimilar and more separable than previous ridge-building processes.

Shepherd (1987) (Figure 3.23C) suggested, after examining ridge systems in New Zealand and Western Australia, that rapidly prograding coastlines would result in low-relief ridges, whereas slowly prograding coastlines would result in higher-relief broader spaced ridges and that a prograded coast which is now receding would result in a high modern foredune. This suggestion is closely in accord with the evidence and discussion of Tasmanian eroding ridge systems studied by Davies (1957) (Figure 3.23E). Davies (1957) was first to suggest that a high foredune fronting a prograded barrier is evidence of an eroding coastline, adding that such morphology is typical of many Tasmanian ridge systems. Davies (1972) also noted that the clearing of vegetation for pasture on
many ridge systems has resulted in secondary blow-out dunes (Figure 3.24). Bird (1976) (Figure 3.23F) also associated a morphology where landward migrating dune covers existing shore parallel ridges, with a receding or eroding coastline. These two models (Figure 3.23E,F) appear to closely accord with the morphology and subsurface structure of the foredune at Moruya presented above.

![Diagram](image)

**Figure 3.23:** A) Models of prograded and stationary barrier stratigraphy and morphology according to Roy et al. (1994), B) The relationship between beach budget and foredune budget and its control on barrier morphology according to Psuty (1992), C) Models for the morphology of prograding coastlines of New Zealand and Western Australia after Shepherd (1987), D) a topographic profile extracted from LiDAR for the Moruya barrier showing the sequence of OSL ages and the high foredune just landwards of the incipient ridge and modern beach, E) a profile of the frontal portion of the Seven Mile Beach barrier system in southeastern Tasmania from Davies (1957) and F) the character of a prograded barrier if aeolian material is moving landward behind the present day beach after (Bird 1976).
Figure 3.24: On the left is an oblique aerial photo taken looking northeast over Bakers Beach, Tasmania from Davies (1972). On the right is a DEM of LiDAR data. Secondary blowout dunes are clearly evident in both images. The red circled blowout dune is the same feature in both images.

After examining the morphology and subsurface structure of the Moruya foredune and comparing it with the models discussed above; a logical explanation is that the deposition of the high foredune reflects a phase of increased dune activity where sediment accumulation has occurred vertically and laterally landwards. However, it must be noted that this feature does not appear to be currently active. Furthermore, the foredune does not appear to be connected with the last major stormy period from 1974 to 1978, which eroded a significant amount of material from the present beach, as the foredune is generally more than 30 metres landward of the scarp position and the OSL date of 180 ± 15 indicates a substantial time period between the events. As well as this, those who surveyed the beach throughout the 1970’s storms, never associated this severe erosional event with foredune building (McLean & Shen 2006). Any possible explanation for the presence of this foredune must therefore account for its distinctive morphology and subsurface structure as well as its apparent present inactivity. Considering its timing and emplacement in the barrier morphology, it seems that a discrete phase of increased dune activity now replaced by a seemingly stable phase of barrier growth must be invoked. The causes of such an episode of dune activity phase in the recent past are unknown. One possibility noted by Davies (1957) and expanded by Goodwin et al. (2015) a change in storm frequency and intensity coupled with a change in modal wave climate which may produce a discrete phase of foredune development.
3.8 A summary of Holocene barrier deposition

This section is a synthesis of the major findings of this chapter bringing together these three data sets to form a cohesive picture of the Holocene deposition of the Moruya barrier. The coastal sand ridges forming the Moruya barrier are demonstrated to have accumulated between ~7200 and ~400 years ago with an overall linear trend of barrier growth in the central portion of the barrier. This pattern of Holocene progradation is significantly different to the pattern indicated by the radiocarbon dating by Thom et al. (1981a,b). The OSL dating also demonstrates that Moruya has experienced a comparatively slow average rate (0.27 m/yr) of progradation over the entire Holocene barrier history and that the average ridge ‘lifetime’ is around 110 years. These findings are especially significant considering the long-term beach monitoring program currently operating at Bengello Beach.

A DEM derived from LiDAR data shows that the consistent rate of seaward accumulation of the barrier is reflected in a regular sequence of shore-parallel ridges. Calculating volumes of sediment accumulated over the Holocene reveals a linear trend of barrier growth above 0 m AHD at an average rate of 7400 m$^3$/yr. However, plotting the pattern of volume accumulation for individual time slices demonstrates that there is some variation in sediment supply over time, despite the errors associated with the OSL ages.

GPR data covering the entire width of the barrier characterises the processes of ridge formation at this site. The model proposed by Bird (1976) of cut and recovery and capping of an accumulating backshore ridge appears to be the most appropriate mode of ridge formation at Moruya considering the GPR data. However, the GPR data reveals a complexity of storm events superimposed on this general model, as evidenced by the beach monitoring program at this site. What must be emphasised is that the critical factor leading to a prodgrading coastline is not a certain unique processes, rather an ongoing supply of sediment to the embayment available for working onshore, so that during the cut and recovery process, a greater volume of sand is recovered than is cut.

An issue highlighted by the LiDAR data was that the current height of the incipient ridge and inter-ridge swale couplet behind the present day beach was at a lower elevation that the previous ridges. This was first noticed on Tasmanian sites by Davies (1957). However, the GPR data reveals that incipient ridge formation involving cut,
recovery and aeolian capping has occurred at this elevation for the entire barrier sequence. Therefore a process of ongoing accumulation of these incipient ridges must occur: likely over an interval of ~110 years as demonstrated by the OSL chronology. Incipient ridges must persist and accumulate sand for a much longer period of time than has so far been observed in the beach monitoring program in order to become relict features of the barrier.

A secondary conclusion relating to the elevation of beachface reflectors is that there does not appear to be any distinct fall in their height during Holocene barrier deposition. Therefore this data does not support a Holocene higher sea-level, although the strength of this conclusion rests on the appropriateness of palaeo beachfaces as robust indicators of sea-level change.

A final consideration relating to the Holocene deposition of the Moruya coastal plain is the high foredune fronting the ridge sequence. LiDAR data highlights the anomalous height of this feature in comparison to the rest of the ridges, as well as revealing some distinctive characteristics in its morphology, in particular its apparent lobed landward side, which indicates it has transgressed landwards across pre-existing ridges.

OSL dating reveals that this feature of the barrier is <400 years old, which is considerably younger than previously supposed. GPR data demonstrates that its subsurface structure is unlike other ridges in the sequence, as the reflectors in the capping of the ridge have an obvious landward dip and lie unconformably on a buried ridge surface. The cause of this feature of the barrier morphology is unknown, especially as similar high foredunes are apparent on many other prograded barriers in southeastern Australia. It seems that a boundary condition change is needed to explain this morphologic feature of so many similar coastal environments across such a wide geographical area. Further discussion of this foredune and those of the other sites in this study will be presented in Chapter 6: Discussion.
CHAPTER 4: WONBOYN
4.1 Introduction

This chapter presents the findings from investigation of the prograded barrier at Wonboyn, on the far south coast of NSW (Figure 4.1). This site has an existing radiocarbon chronological data set reported in Thom et al. (1981b), which constrained the deposition of the ridge sequence and described the general stratigraphic and morphologic character of the embayment. Therefore OSL ages reported below serve as a comparative dataset of coastal progradation.

![Figure 4.1: Air photo of Wonboyn barrier and surrounds with OSL sample locations (see Table 4.2). Map data from Google Earth.](image)

GPR data covering the front half of the barrier is presented which imaged a series of beachface reflectors, and when coupled with the OSL dating, demonstrates the sequential deposition of sediment through the Holocene. Analysis of the ridge and broader barrier morphology using DEM derived from LiDAR data is then presented. Volumes of progradation were calculated from this same DEM. An analysis and discussion of the high foredune fronting this barrier combines the LiDAR, GPR and OSL dating. An overall picture of Holocene barrier deposition concludes this chapter.
4.2 Site characteristics

4.2.1 Physiographic setting

Wonboyn barrier is located approximately 20 km S of Eden in Disaster Bay on the far south coast of NSW. The barrier is separated into a northern and southern portion by Bay Cliff, which is part of the Worange Point Formation (Figure 4.2). On the northern side of this bedrock control, Wonbyon Lake, a mature barrier estuary (Roy et al. 2001), connects to Disaster Bay. Green Cape projects seaward to form the northern promontory of Disaster Bay and likely functions as a substantial trap of northward moving sediment sourced from the continental shelf or from longshore transport from Cape Howe. The Wonbyon River, which flows into the Wonboyn Lake estuary, has a small catchment 335 km$^2$ compared with say the Moruya River (1423 km$^2$). The estuary has a maximum depth of 5.5 m in the central portion of the main basin area. The bedrock embayment surrounding the Holocene deposited sediments is composed of Late Devonian sedimentary and volcanic rocks. The sedimentary units contain massive mudrock and sandstones as well as fluvial sandstones with mudrock and conglomerate. The volcanics are silicic with ignimbrites and minor lavas.

Figure 4.2: Map showing the geology surrounding Wonboyn barrier and modern sedimentary units
4.2.2 Past studies

There is little published work on the Wonboyn prograded barrier. The primary investigations involving radiocarbon dating and initial stratigraphic and morphologic data collection were compiled in early 1980’s (Thom et al. 1981a,b). Fifteen radiocarbon ages date the seaward deposition of the barrier expressed in a series of low relief ridges (Figure 4.3A). A complete topographic profile across the barrier accompanies these dates and indicates the heights of the ridges above MSL (Figure 4.3A). These ages cover the portion of the barrier south of the entrance of the Lake Wonboyn (Figure 4.3C). The northern side has no chronological, stratigraphic or morphologic information. Apart from the most landward sample, which was taken to be an anomalously old due to reworking of older shell material, the ages were plotted with two linear relationships against barrier width, one from ~6000 to ~4000 from ~4000 to ~1000 years BP (Figure 4.3B) (Thom et al. 1981b).

Figure 4.3: Summary of data for Wonboyn barrier after Thom et al. (1981b). (A) Radiocarbon ages plotted on a topographic profile, (B) Radiocarbon ages plotted against barrier width (C) Radiocarbon dating transect location with sample codes (see also Table 4.1) and general barrier morphology.
This pattern of progradation inferred from the radiocarbon ages for Wonboyn was unusual, compared with other other barriers of southeastern Australia (Thom et al. 1981a). The primary difference was that less than half of the barrier was less than 3000 years old (Figure 4.3 A,B), whereas for other sites such as Moruya, according to the radiocarbon chronology, the barrier was at 85% of its full width by 3000 years ago (Thom et al. 1981b) (see Figure 1.9). The trapping of northward moving sand by Green Cape, from sources such as Cape Howe was proposed as a possible explanation for the Wonboyn barrier’s unique progradation history which implied a greater supply of sediment in the last 3000 years (Thom et al. 1981a,b).

4.2.3 Recalibration of existing radiocarbon dates

Fifteen radiocarbon samples, collected and dated by Thom et al. (1981b), were recalibrated according to the procedure of Stuiver and Reimer (1993) for this study. All of these age estimates are from the dating of ‘shell hash’. The recalibrated radiocarbon ages from Thom et al. (1981b) are presented in Table 4.1 also seen in Figure 4.3 above.

Table 4.1: Radiocarbon Samples from Thom et al. (1981b) ordered landward to seaward (‘Sample Code’ corresponds to Figure 4.3C). ‘Radiocarbon Age’ is the ‘Laboratory age’ and is corrected for isotopic fractionation only. The calibrated age is presented in cal yr BP according the calibration of Stuiver and Reimer (1993) using CALIB REV 7.0.1. The Delta R of 11 ± 85 used for the calibration is taken from Gillespie and Polach (1979).

<table>
<thead>
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<th>Sample Code</th>
<th>Radiocarbon Age (yr BP)</th>
<th>Radiocarbon Cal. Age (cal yr BP)</th>
</tr>
</thead>
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<td>GX-3635</td>
<td>9100 ± 150</td>
<td>9840 ± 400</td>
</tr>
<tr>
<td>SUA-900</td>
<td>5770 ± 80</td>
<td>6150 ± 240</td>
</tr>
<tr>
<td>ANU-1585</td>
<td>5930 ± 90</td>
<td>6340 ± 290</td>
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<tr>
<td>SUA-899</td>
<td>4140 ± 70</td>
<td>4190 ± 300</td>
</tr>
<tr>
<td>SUA-898</td>
<td>3750 ± 80</td>
<td>3670 ± 400</td>
</tr>
<tr>
<td>GX-4461</td>
<td>3760 ± 130</td>
<td>3710 ± 400</td>
</tr>
<tr>
<td>SUA-897</td>
<td>3230 ± 70</td>
<td>3040 ± 270</td>
</tr>
<tr>
<td>ANU-1396</td>
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<tr>
<td>SUA-896</td>
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</tr>
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<td>SUA-893</td>
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<td>SUA-892</td>
<td>1450 ± 70</td>
<td>990 ± 230</td>
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</table>
CHAPTER 4: WONBOYN

4.3 OSL dating

4.3.1 Introduction

OSL dating was completed for 9 samples from a transect across the southern portion of the Wonboyn barrier close to the location of radiocarbon dating transect of Thom et al. (1981b) above. Details regarding the methodology are found in chapter 2. Below are the dating results and discussion of their significance in the context of the existing radiocarbon chronology at this site.

4.3.2 OSL dating results

Samples for OSL dating were collected from the crests of 9 ridges in the sequence spanning the width of the barrier. The quartz grains used for dating from these samples had generally good luminescence characteristics, similar to that of Moruya. The pre-heat and cut-heat combinations used for these samples were 180/160 and 180/180 respectively; the same as the Moruya OSL samples. The decay curve results for the Wonboyn barrier sands demonstrate that no alternations were necessary to the heating combinations. Linear dose response curves were observed for all samples as was expected for samples with equivalent doses less than 5 Gy. Overdispersion values for the 9 samples were varied, with 5 samples having values less than 20%, 3 samples between 20 - 30% and one sample (Won5) with an overdispersion value of ~60% (Table 4.2). This sample was not given an age due to this anomalously high value. Sample WN-Fdune from the northern foredune required remeasuring so the overdispersion value was acceptable.
Table 4.2: OSL ages for coastal sand ridges across the Wonboyn Barrier, NSW. The samples are ordered according to sample position with respect to the ocean, so that the first sample listed in the table corresponds to the sample closest to the shore (except WN-Fdune, see Figure 4.1). All samples include an internal dose rate contribution of 0.03 ± 0.01 Gy/ka assumed based on measurements made on Australian quartz (Bowler et al. 2003).

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Beta (Gy/ka)</th>
<th>Gamma (Gy/ka)</th>
<th>Cosmic (Gy/ka)</th>
<th>Total Dose Rate (Gy/ka)</th>
<th>D2 (Gy)</th>
<th>Over-dispersion (%)</th>
<th>OSL Age (years)</th>
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<td>Won7</td>
<td>0.15 ± 0.01</td>
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<td>0.14 ± 0.002</td>
<td>0.19 ± 0.02</td>
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<td>0.29 ± 0.02</td>
<td>30 ± 5</td>
<td>450 ± 40</td>
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<td>0.3 ± 0.01</td>
<td>0.24 ± 0.01</td>
<td>0.12 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.58 ± 0.03</td>
<td>0.70 ± 0.02</td>
<td>13 ± 1.9</td>
<td>1200 ± 70</td>
</tr>
<tr>
<td>Won5</td>
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<td>0.26 ± 0.01</td>
<td>0.13 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.61 ± 0.03</td>
<td>5.14 ± 0.64</td>
<td>59 ± 9</td>
<td>-</td>
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<tr>
<td>Won1</td>
<td>0.16 ± 0.01</td>
<td>0.76 ± 0.03</td>
<td>0.32 ± 0.01</td>
<td>0.26 ± 0.01</td>
<td>0.13 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.61 ± 0.03</td>
<td>1.82 ± 0.09</td>
<td>23 ± 3</td>
<td>3010 ± 200</td>
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<tr>
<td>Won2</td>
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<td>0.86 ± 0.03</td>
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<td>0.22 ± 0.01</td>
<td>0.12 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.56 ± 0.03</td>
<td>1.87 ± 0.06</td>
<td>16 ± 2</td>
<td>3350 ± 200</td>
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<tr>
<td>Won3</td>
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<td>0.25 ± 0.01</td>
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<td>2.08 ± 0.05</td>
<td>7 ± 2</td>
<td>3900 ± 210</td>
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<tr>
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<td>0.19 ± 0.01</td>
<td>0.17 ± 0.01</td>
<td>0.10 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.48 ± 0.02</td>
<td>2.17 ± 0.04</td>
<td>7 ± 1.4</td>
<td>4480 ± 250</td>
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<td>Won8</td>
<td>0.21 ± 0.01</td>
<td>1.02 ± 0.04</td>
<td>0.28 ± 0.01</td>
<td>0.24 ± 0.01</td>
<td>0.14 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.60 ± 0.03</td>
<td>4.63 ± 0.08</td>
<td>8 ± 1.3</td>
<td>7770 ± 400</td>
</tr>
<tr>
<td>WN-Fdune</td>
<td>0.21 ± 0.01</td>
<td>0.91 ± 0.04</td>
<td>0.54 ± 0.01</td>
<td>0.42 ± 0.02</td>
<td>0.19 ± 0.003</td>
<td>0.19 ± 0.02</td>
<td>0.83 ± 0.03</td>
<td>0.06 ± 0.01</td>
<td>28 ± 5</td>
<td>70 ± 5</td>
</tr>
</tbody>
</table>

*All sample dose rates were measured with ICP-MS (U and Th) and ICP-OES (K) and calculated using the conversion values of Guérin et al. (2011).

**A water content of 5% ± 2.5 % was assumed for all samples.
Total does rates for these Wonbyon samples were remarkably consistent with respect to one another with a mean of 0.58 Gy/ka (Figure 4.4). The sample collected from the foredune in the northern section of the barrier was an exception to this with a dose rate of 0.83 ± 0.03 Gy/ka (Table 4.2). A higher potassium percentage appears responsible for this higher dose rate (Table 4.2). In comparison to the Moruya total dose rates, which varied about a mean of 0.96 Gy/ka, the Wonboyn results are significantly lower. This lower dose rate is due to lower concentrations of Uranium, Thorium and Potassium (Table 4.2) compared with the Moruya samples (c.f. Table 3.2 in Chapter 3). There is also far less variability (i.e. scatter) in the total dose rate results compared with Moruya c.f. Figure 3.3.

Figure 4.4: Total dose rate plotted with respect to distance from Disaster Bay. The red dotted square highlights the total dose rate for the sample from the foredune in the northern portion of the barrier and is not on the transect from which the other samples were collected.

The OSL ages demonstrate the seaward progradation of the barrier from ~7770 to ~450 years ago (Figure 4.5). These ages span the entire barrier width with the oldest age taken from the most landward ridge and the youngest age from just behind the seaward foredune. There are no age reversals across the barrier and only two ages (Won1 and Won2, Table 4.2) overlap slightly at the 1 sigma error level. The age for the large foredune in the northern section of the barrier was 70 ± 5 years.
The exclusion of sample Won5 (Table 4.2) from the age sequence due to its unacceptably high overdispersion value, leaves a significant gap in the OSL chronology for this site (Figure 4.5). An attempt was made to remeasure this sample to eliminate the possibility of an accidental error in the laboratory or measurement procedures. The second preparation and measurement of this sample produced similarly high overdispersion values and thus it is reasonable to suppose that this sample has some unexplained issues. Careful examination of the aliquot data revealed that around 20% of the aliquots had a $D_e$ value appropriate to produce an age which would be in accord with the sequence of the other ages across the barrier (~2000 years). The other 80% of the aliquots had very high $D_e$ values in the order of 5 Gy (see Table 4.2). No single grain work was been undertaken to examine in more detail the complexities of this sample, such as, whether there was any coeval heavy mineral lag deposit which is not accounted for in this samples dose rate.

Figure 4.5: OSL ages for the Wonboyn ridge sequence. The missing age is Won5 from Table 4.2. Bathymetric data for Lake Wonboyn (from OEH, NSW) and a DEM derived from LiDAR characterise the embayment.
4.3.3 A chronology of Holocene progradation

The OSL results from the Wonboyn ridge sequence are significant with regards to the Holocene barrier deposition at Wonboyn and also when compared with the radiocarbon ages reported by Thom et al. (1981b). Comparing the OSL ages for the Wonboyn barrier with the existing radiocarbon chronology, there appears to be a consistent pattern of Holocene progradation (Figure 4.6).

Figure 4.6: Top; OSL and radiocarbon ages from Figure 4.3 and Table 4.1 plotted against barrier width. Bottom; OSL and radiocarbon ages from Table 4.1 and 4.2 plotted on a topographic profile extracted from LiDAR data.

At the landward edge of the transect below the first ridge (50 m along the x axis of the topographic profile in Figure 4.6) the radiocarbon age of 9840 ± 400 cal. yr BP, which was discounted as anomalously old by Thom et al. (1981b) and supposed to be reworked shell material, is still anomalously old with respect to the OSL age of 7770 ± 400 for this same ridge. These two ages are separated by 1270 years taking into
consideration their associated error margins. This older radiocarbon age may be from reworked shell material, however an alternative explanation would be that this most landward ridge has a ‘core’ or transgressive material deposited during the late stages of sea level transgression during around 10,000 years ago. No sedimentological data has been collected from this ridge to resolve this issue, and no GPR was collected over this ridge as any field activity in this region is severely impeded by thick vegetation. The OSL age of 7770 ± 400 from 70-100 cm below the ridge crest surface, may be regarded as a culmination age for this first ridge in the sequence.

Lewis et al. (2013 p.131) concluded that around Australia, “sea-level reached present levels somewhat earlier, between 7500 and 8000 cal. yr BP”, which is slightly older than previously thought: a shift which is a result of improvements to radiocarbon calibration practices as well as additional dating using uranium series and Amino Acid Racemisation. This range of 7500 too 8000 cal. yr BP accords closely with the OSL age of 7770 ± 400 for the most landward ridge and indicates that this ridge likely formed during the period where sea-level attained at, or near, its present height. The radiocarbon chronology, OSL chronology and the conclusions of Lewis et al. (2013) demonstrate that barrier progradation began during this time period in the Holocene. It is also likely, considering the broader geomorphological context at Wonboyn (Figure 4.1, 4.2 and 4.5), that this first ridge formed a youthful barrier estuary (Roy et al. 2001: Figure 5) and created what is now Lake Wonboyn. This first ridge is also likely to have extended further in a NE direction towards to bedrock valley margin and has since been truncated by estuary entrance processes (Figure 4.5).

Comparing the OSL ages in relation to the existing radiaocarbon chronology (Thom et al. 1981b) in some cases the OSL overlap with the radiocarbon ages considering their error margins (Figure 4.6). However, the most seaward age the OSL is ~500 years younger ($^{14}$C 990 ± 210, OSL 450 ± 40). The OSL ages appear to support the two rates of progradation at Wonboyn originally proposed by (Thom et al. 1981b). A progradation rate according the linear trend of the OSL ages from ~4500 to present is ~0.3 m/yr. The average ridge lifetime for this linear trend is 130 years. While further dating is needed to establish with greater confidence an earlier phase of slower progradation, a rate calculation reveals a value of ~0.1 m/yr and a ridge lifetime ~410 years over this period. The radiocarbon age of 9840 ± 400 cal. yr BP has not been
included in the calculation of this slower phase of progradation as its depositional
environment, i.e. transgressive or prograded is not known (Figure 4.6).

The similarity of the radiocarbon and OSL ages at Wonboyn is especially significant
considering the substantial difference between these two techniques that was apparent
for the central transect at Moruya. The most plausible explanation for this difference
between Moruya and Wonboyn is sampling depth. Depths for the Wonboyn shell hash
samples (excluding the deeper core to bedrock at around 1000 m along the transect in
Figure 4.6) are between 0 and 3 m AHD. At Moruya, the series of dill holes to bedrock
or estuarine clay units provide invaluable stratigraphic information, however shell hash
samples from the nearshore shelly sand collected from depths between 0 and -20 m
AHD do not directly relate to a chronology of the aeolian ridge crests. These shallower
radiocarbon ages at Wonboyn have a more robust association with a surface position
and hence with the OSL age estimates unlike Moruya where there is uncertainty
regarding how to correspond an age from say -10 m AHD to a surface location.

While this explanation of shallower sampling goes along way in explaining the
difference in chronological data at the these two sites, it does not completely resolve the
issue as the one age of 3500 ± 400 cal. yr BP from deeper in the barrier at Wonboyn (-5
m AHD) is still in reasonable accord with the OSL ages. This is not the case at Moruya,
where radiocarbon ages at a similar depth and in a similar location with respect to
barrier progradation have a discrepancy of around ~2500-3000 years. Thus sampling
depth does not fully explain why the two dating techniques at Moruya should be so
dissimilar, and be so similar at Wonboyn.

An alternative explanation for the discrepancy between OSL and radiocarbon ages at
Moruya, was that the radiocarbon ages constrain the early emplacement of a shoreface
sand unit to form a shallow offshore profile and the upper portion of this unit has
subsequently been worked onshore into the ridge sequence over the time period defined
by the OSL ages. If this hypothesis were true, one would expect that at Wonboyn,
samples from deeper in the barrier would produce older ages representing this same
earlier emplacement of shoreface sand. There has been no deeper sampling of the
barrier to test a multi-stage shoreface and beachface emplacement hypothesis.
4.4 GPR

4.4.1 Introduction

The GPR data spans approximately half (~640 m) the width of the southern ridge sequence. This data set, while not covering the entire barrier width, nevertheless provides important insight into the subsurface structures present in the Wonboyn ridge plain. The results are presented in a series of three approximately 200 m sections. The discussion that follows these results will focus on interpreting the shallow subsurface structures and comparing and contrasting these results with the Moruya GPR record as well as other published GPR data for prograded sand barriers.

4.4.2 Characterising the subsurface structures

The three ~200 m GPR data sections are denoted A, B and C and were collected with a 250 MHz antenna close to the OSL dating transect (see Figure 4.7) along the foot track running shore normal from a carpark to the beach. The OSL dates are shown at their appropriate depths on each of the three ~200 m sections to relate specific structures to particular time periods during barrier deposition.

Section A (Figure 4.8A) has a regular series of seaward dipping reflectors which produce a complex subsurface structural pattern. A series of ‘stacked’ reflectors indicating vertical ridge accretion are seen above 3 m AHD at numerous locations along the profile e.g. at 75 and 120 m. Some reflectors which may indicate storm cut and recovery are evident at 1 m AHD between 140 and 160 metres along the transect (Figure 4.8A). The seaward accumulation of sediment over time is demonstrated by the regular succession of beachface reflectors between 0 and 2 m AHD.
Section B (Figure 4.8B) again has a series of seaward dipping reflectors showing the progradation of the beachface over time. While the water table here is 0.5 - 1 m higher than in the previous profile, the change from concave-up to convex-up reflectors is still occurring at around 2.5 m AHD. In section B some reflectors can be traced which contain both convex-up and concave-up elements in a continuous profile. For example, the reflector starting at 245 m and 4 m AHD and extending to 296 m and 1 m AHD and the reflector starting at 325 m and 4 m AHD and ending at 375 m and 1 m AHD. Both theses examples have a convex-up geometry between 4 and 2.5 m AHD and a concave-up geometry between 2.5 and 1 m AHD. Examples of vertical ridge building can also be seen in Section B where a series of ‘stacked’ reflectors demonstrate the accumulation of material (likely wind blown).

Section C (Figure 4.7C) displays a regular series of seaward-dipping reflectors which vary in geometry above and below the water table. Those above the water table display a generally convex-up geometry, while those below the water table are generally convex-up. This pattern is consistent with profiles A and B and the elevation of the
change in geometry is approximately 2.5 m AHD similar to profiles A and B. Profile C, unlike A and B, has two OSL ages shown corresponding to their position within the barrier sequence. The other OSL sample collected in the region covered by this GPR transect had an unacceptably high overdispersion and thus has no age estimate.
4.4.3 Interpretation of the imaged subsurface structures

All subsurface structure presented in the three profiles above is higher than 0 m AHD placing it in the beachface zone. The zone of ridge building activity is at an elevation of 3-5 m AHD which is similar to the Moruya GPR data. Thus the same issue, highlighted by the Moruya GPR data is apparent here: how do incipient ridges of an elevation of 3-5 m AHD become relict ridges in the barrier sequence at an elevation of around 6 m AHD? Clearly, like Moruya, a process of ridge vertical accumulation must be invoked over a ridge lifetime of 130 years (similar to Moruya’s 110 years). It must be noted that the GPR transect at Wonboyn was collected along a beach foot track which was ‘cut’ (<0.5 m) through the crests of some ridges and that there was also a degree of compaction from human traffic along the path. Therefore the topmost portions of ridge subsurface structure may have been altered or removed. Thus the full subsurface structure of ridge building may not be fully captured by this GPR data, nevertheless vertical accumulation and incipient ridge building is demonstrated.

Although incipient ridge building at Wonboyn appears to be occurring at a comparable elevation to Moruya (3-5 m), the elevation at which imaged reflectors change from concave-up to convex-up appears to be different. At Wonboyn this change appears to be at an elevation of ~2.5 m. At Moruya this change in geometry occurs at around ~3.5 m. The reason for such a difference is unknown but is possibly related to energy regime and modal beach state of the two barriers (Bengello; inner Transverse Bar and Rip,
outer Rhythmic Bar and Beach, Wonboyn; both Transverse Bar and Rip, outer Rhythmic Bar and Beach, Short 2007). However, there is no beach profiling work at Wonboyn to test this hypothesis. Bristow and Pucillo (2006) imaged a similar change in geometry at Guichen Bay at ~3 m (see their Figure 4).

The apparent change in water table level in profile B (Figure 4.8B) compared with profile A and C is puzzling. The environmental factors that control groundwater level in quartz-rich sands are not well understood. However, in general it is accepted that a mostly flat water table will prevail with possibly a slight downward slope towards sea level close to the coast (Donaldson 2010). Such a pattern of slowly falling water table seawards was clearly demonstrated at Moruya. The slight rise is water table in the order of 0.5-1 m for section B is anomalous.

The overall ridge building process as evidenced by the GPR reflectors appears to be similar to that of Moruya where there was some resemblance to the model of ridge development (see Figure 3.8) proposed by Bird (1976), which involves foredune cut and recovery where the volume of recovery exceeds that of the cut. There is some evidence for berm development and storm cut and recovery in the Wonboyn GPR sections especially in section A (Figure 3.8A).

In the ~750 year interval between the OSL samples marked on section C (Figure 4.8C) there was approximately 200 m of progradation. Given that 21 distinguishable concave-up beachface reflectors are evident in this ~750 year, this equates to a beachface being preserved every ~36 years. However, we should be cautious not to make too much of such a calculation, as it is well understood that not all beachface ‘events’ are preserved as subsurface structures. Further sedimentological work coring to a series of these reflectors is required to understand their nature and genesis.
4.5 Morphology of the barrier

4.4.1 Introduction

This section examines the morphology of the Wonboyn barrier including ridge height, amplitude and spacing as well as broader-scale features of the barriers Holocene deposition using LiDAR data covering this embayment. The Quaternary geological mapping by Troedson et al. (2004) and Lake Wonboyn bathymetry are also presented for additional context.

4.5.2 Ridge morphometrics

The ridge sequence at Wonboyn is separated into two sections by bedrock control known as Bay Cliff (Figure 4.1) where Lake Wonboyn connects to Disaster Bay. The southern ridge sequence was where the radiocarbon dating and topographic profile was completed by Thom et al. (1981b) and is the more extensive of the two portions (Figure 4.9). The southern sequence has 42 distinct ridges and the northern sequence has approximately 15 ridges. In the northern section, the ridges abut the bedrock margin which has a series of very small embayments created by small catchments draining to the ocean.
Figure 4.9: using A DEM derived from LiDAR data of the Wonboyn coastal plain. Black lines numbered 1 to 5 refer to topographic profiles across the barrier shown in Figure 4.10. The OSL ages are also shown for context.

Five example profiles across the ridges are shown in Figure 4.10. There was a general trend for ridge height to increase toward the north in the embayment. Figure 4.10 shows for the southern portion of the Wonboyn barrier a steady increase in the order of 0.5 m comparing profiles 5,4 and 3. For the northern portion of the barrier there is a similarly small increase in height also around 0.5 m (c.f. profile 2 and 1).
Figure 4.10: Five topographic profiles for the Wonboyn barrier extracted from a DEM from LiDAR. Profile numbers refer to Figure 4.9.
For the northern section, profile 2 has no foredune while profile 1 has the highest foredune of all the profiles (11 m). For the southern section of barrier, there is a steady increase in foredune height to the north, from 6.5 m in profile 5, to 7 m in profile 4, to 8 m in profile 3. The contrast from no foredune to an 11 m high foredune between profiles 2 and 1 is therefore more startling.

Trends in height in a shore normal direction were also observed from topographic profiles across the ridge sequence. Focusing on the southern ridge sequence first (profiles 3, 4 and 5), the ridge heights are generally similar along each profile (5-7 m) with respect to distance from the shore. However, the most landward ridge is significantly higher than all other ridges in the sequence, except the foredune fronting the barrier. This is evident in almost all profiles for the southern ridge sequence including the three examples seen in Figure 4.10, profile 3, 4 and 5. Larger ridges have been associated with a lower sediment supply to the barrier, hence a longer formation time (Shepherd 1987). The potentially slower initial rate of barrier progradation from ~7750 to ~4500 indicated by both the OSL and radiocarbon chronology would support a long-formation time hypothesis for this ridge. However, it should be noted that none of the seaward ridges in this supposed slower progradation phase of barrier development are of comparable height.

Another trend in shore-normal ridge height is the fall in height towards the ocean direction for seaward 300 to 400 m of most profiles. Linear regressions of ridge crest and inter-ridge swale height were examined using the method described by Davies (1961) for 17 shore normal profiles spaced 200 m apart across the entire width of southern ridge sequence. These profiles reveal a drop in height in the order of 0.5-1 m for the seaward 400 m of the barrier. For most profiles the first ~1400 m appears almost unanimously flat while the last 400 m shows a stronger declining trend (average $R^2$ values for crests = 0.44 and inter-ridge swales = 0.38) with a drop in height in the order of 1 m. This change from relatively flat height trend to a falling height trend occurs ~1200 years ago according to the OSL and radiocarbon ages. While my be enticing to attribute this drop in ridge crest and inter-ridge swale height to a late Holocene fall in sea-level as has been argued by some researchers for this region of Australia (see Sloss et al. 2007 for review), a significant caveat must be placed on such a hypothesis.
The drop in height at ~1200 years is most clearly seen in profiles toward the northern end of the southern ridge sequence and is not so obvious at the southern end (c.f. profile 5 with profiles 3 and 4 in Figure 4.10). If, as is likely, an increase in alongshore ridge height is due to an increase in aeolian cap thickness (Thom 1964), due to to greater aeolian activity resulting from flatter beach profiles, then it follows logically that at the southern end, where there is less aeolian capping, the drop in ridge height would be most obvious. For, at this southern end, the ridge height would be most related to swash facies height over time. Davies (1961) proposed that in embayments with less aeolian activity, a drop in sea-level, if it occurred, would be most effectively captured in ridge height, as the height of each ridge would less influenced by the thickness of aeolian sands draping swash-formed deposits.

A series of cores along select ridges is needed to establish if significant variations in the thickness of the aeolian capping occurs alongshore. The GPR data covering the last 400 m of the barrier shown above does not support a fall in the elevation of swash built facies. This is evidenced by the consistent height at 2.5 m AHD for the change in reflector geometry from concave-up below 2.5 m AHD to convex-up above 2.5 m AHD indicating the transition of swash dominated process to aeolian dominated, what Bristow and Pucillo (2006) called the upper-shoreface dune-interface at Guichen Bay, SA.

Ridge heights in the northern portion of the barrier are comparable to the heights across the southern ridge sequence with crests heights around 5 – 6 m. Ridge amplitudes of 0.5-1.5 m also appears to be similar between the north and the south ridge sequences. However, profile 1 and 2 (Figure 4.10) differ significantly from the 3 profiles for the southern ridge sequence in terms of ridge spacing. The two northern profiles appear to have much more closely spaced ridges. It is significant that this spacing trend is not accompanied by a difference in height or amplitude as might be expected considering the models of Shepherd (1987) and the obvious difference in embayment size between the north and the south ridge sequences. Closely spaced ridges might be expected to have lower crest elevations and have formed quickly in this comparatively small embayment, yet there is no substantial difference in height. There is as yet no chronological data, apart from the one date on the foredune, to constrain the timing of the formation of these northern ridges.
The other feature of note for the northern two topographic profiles is the ~11 m high foredune for profile 1 (Figure 4.10). This foredune, and the foredune fronting the southern ridge sequence is discussed further below. However, it is noted here, that seawards of this foredune in profile 1 (Figure 4.10) are two incipient ridges, which from field inspection, are well vegetated with significant shrubbery. These two incipient ridges are also at a similar elevation to the ridges behind the foredune. At Moruya, the two small incipient ridges which have developed after the 1970’s storms are only covered in Spinifex grasses. Therefore these two ridges in front of the northern foredune at Wonboyn, are not really *incipient* in the same way that the Moruya ridges are *incipient*. Morphologically the two ridges seaward of the northern foredune at Wonboyn are better described as established ridges.

### 4.5.3 Boarder scale morphology of the barrier

Considering the morphology of the barrier with LiDAR data, in the context of the chronological data, reveals the timing of broader morphological changes in the embayment as well as the reconstruction of the emplacement of the ridge sequence. For instance, it is clear from the radiocarbon and OSL ages, that around 3000 years ago, the southern ridge sequence would have aligned with the small bedrock outcrop seen in Figure 4.9. This outcrop would have acted as a structural control for the entrance of Lake Wonboyn. To the north, this bedrock outcrop was connected to the main bedrock valley by a small sand ridge and a tombolo would likely have existed projecting out to Bay Cliff (Figure 4.9).

The LiDAR DEM indicates significant variation in the position of the Lake Wonboyn entrance over the late Holocene as it is clearly seen that both the southern and northern ridge sequences show erosional features along their margins of the current estuarine channel. Constructional recurved spits are also seen along the margins of small streams which cut through the barrier especially in the northern ridge sequence. These recurved spits are curving low ridges which bend away from the ocean and back in towards the older channel sequence. Good examples of these features can also be seen at Moruya along the margins of the two small streams which cut across the barrier. However, these small streams are not tidal and it is likely that such constructional forms are not possible along the margins of an active tidal channel like Lake Wonboyn where ebb and flood tide flow strength is far greater than any flows possible in the smaller streams.
At Wonboyn, four small streams can be seen cutting across the northern ridge sequence, two of which have created channels which terminate at the current beach. On the southern ridge sequence one stream channel meanders across the barrier near to the southern margin of the ridges and connects to Disaster Bay at a place named ‘Greenglades’. All of these streams are likely only to be active during periods of high rainfall and only isolated pools of water in their channels are evident from aerial photography. However, the discharge from their catchments must be of a sufficient amount over the Holocene to maintain them during barrier progradation.

4.6 Aeolian barrier volumes and accumulation rates

Calculation of subaerial barrier volumes and accumulation rates for the Wonboyn barrier over the Holocene using LiDAR are reported and discussed in the context of the equivalent calculations at Moruya and that of other sites. Barrier volumes were calculated above 3 m AHD as at Moruya.

Volumes of sediment accumulated on the Wonboyn prograded barrier have a similar pattern compared to barrier width vs time (Figure 4.6) when plotted as cumulative aeolian volume (Figure 4.11). Taking the strong linear relationship seen in Figure 4.11 as trend, there was an average aeolian sediment accumulation rate of ~1760 m$^3$/yr for the southern section of the barrier over the past ~4500 years. This equates to ~0.5 m$^3$/m/yr of sediment above 3 m AHD at the current embayment length. While some variation from the linear trend in barrier volume is apparent (Figure 4.11), the error bars, for example between the two ages 3350 ± 200 and 3010 ± 200, overlap and thus an apparent sudden increase in barrier volume may be a product of age uncertainties.
Examine the ‘volume slices’ in Figure 4.12 reveals a steady increase in embayment length through time. The alignment of the ridges in this southern section of the barrier is particularly strong making the delineation of such volume ‘slices’ more robust. Note that the small portion of the barrier south of the steam which outflows near the southern end of the embayment was not included in the volume calculations due to uncertainty involved in delineating the volume slices.

As was noted when barrier width was plotted against time in section 4.3.3 above, an initially slower rate of progradation could be supported by the chronology at this site. Calculating a volumetric progradation for this initial ‘phase’ of progradation gives a value of ~0.2 m³/m/yr, which is much lower than the average of ~0.5 m³/m/yr for the barrier sequence from ~4500 years to present.

The average aeolian sedimentation rate of ~0.5 m³/m/yr at Wonboyn is in close accord with the values for these same calculations at Moruya (0.6 m³/m/yr). Yet, when sand accumulation volumes are expressed as m³/yr, the average for Wonboyn of ~1760 m³/yr is much smaller than the average for Moruya of ~3600 m³/yr. However, the larger volume at Moruya is spread over a longer length of beach; hence reasonable agreement in the m³/m/yr values.
These aeolian volumes and accumulation rates reported for the Wonboyn barrier show a steady increase in accordance with the pattern of the OSL ages. It is noteworthy that the ridge topography is formed of aeolian sediments and hence the rates of aeolian accumulation reported above 3 m AHD indicate a more or less continuous trend of ridge building throughout the Holocene.

4.7 Foredune analysis

4.7.1 Introduction

This section will examine the morphology, timing and mode of emplacement of the foredune on the frontal portion of the Wonboyn barrier using LiDAR data, OSL dating and an examination of the most seaward portion of the GPR data. A discussion of the significance of this feature with respect to the Holocene deposition of this barrier and in the context of a similar feature at Moruya will provide insight into current conditions in this embayment.
4.7.2 The southern foredune

The foredune is 1-3 m higher than other ridge crests in the barrier sequence as was seen in profiles in Figure 4.10. Like all other ridges in the sequence (see Figure 4.9) there is a general tendency of this foredune feature to increase in volume (Figure 4.13A) and height (Figure 4.13B) towards the north. In this respect then, its morphology is characteristic of the older ridges in the sequence.

Figure 4.13: (A) Wonboyn foredune volume for the southern end of the barrier from south to north. (B) Wonboyn foredune height for the southern end of the barrier from south to north. A linear fit with associated $R^2$ value has been applied for (A) and (B). (C) Four 1000 m sections, showing the morphology of the foredune at Wonboyn in relation to the previous ridges. (D) Smaller scale view of the Wonboyn barrier showing the location of the 1000 m sections. The shore perpendicular lines are the locations of the 5 transects in Figure 4.10 which serve as a further comparison of the foredune in relation to other ridges in the sequence.
At some locations along the foredune the LiDAR has been prevented from recording a ground return due to thick vegetation. The lack of ground points in these areas has resulted in a very sparse TIN model for these sections. This is the case in the region near the OSL age estimate of ~450 years ago, where there is a section of foredune somewhat lower for a distance of 150 m (Figure 4.13C). Field inspection in this area revealed the presence of tall trees with a dense canopy, which explains the difficulty of the LiDAR pulse to reach the ground surface. Another example of this may be seen on the foredune in the centre of frame 3 in Figure 4.13C. The reduction in height in this 100 m long section is particularly evident in Figure 4.13B at ~2500 m on the x axis. An RTK GPS survey along its crest of the foredune would be beneficial to further delineate foredune height in these areas, although the thick vegetation would also hamper such work.

It is noted that at the southern end of the barrier sequence, until frame 2 of Figure 4.13C, no foredune is apparent. A foredune only begins to appear as a distinct feature standing taller than the other ridges, near the position of the OSL age collected closest to the shoreline in this study (Figure 4.13C, frame 2). The increase in height northward (Figure 4.13B) explains to some degree the increase in volume northward (Figure 4.13A). However, the increasing trend of volumes seen in Figure 4.13C is also due to the increasing width of the foredune. This increase in width is particularly evident at the very northern end near Bay Cliff (Figure 4.13C frame 4).

This increase in foredune width is accompanied by the development of a lobed and curved landward margin of the foredune in frame 3 and 4 of Figure 4.13C. Like the foredune feature at Moruya, it appears that some cascading of aeolian sands has occurred, which have moved into the intervening inter-ridge swale and modified its topographic expression in an alongshore direction.

Considering the most seaward portion of the GPR data collected next to the OSL age in frame 2 of Figure 4.13C in detail (see Figure 4.8C), there is no evidence of landward dipping reflectors as seen in the GPR over the foredune at Moruya. However, this may be due to the GPR being collected on a well-worn beach access track which was also slightly lowered with respect to the true ridge topography. It should be noted that at Moruya, the landward dipping reflectors were imaged over an undisturbed section of the foredune, which was possible because there was little impedance from thick vegetation. The most distinctive feature of the GPR data in this seaward portion of the barrier is a
scarp feature discernible just to the seaward of the foredune. This is not to say that the foredune is necessarily a result of such an erosional event and its subsequent recovery. Rather it may be that this scarp feature is the imprint of the 1974/1978 storm events seen in the recent topography of the Moruya barrier.

In considering the timing of the development of this foredune the OSL age of 450 ±40 just on the landward of the foredune constrains its age to post ~500 years ago. Taking the aeolian volume of this feature as between 70-100 m³ (Figure 4.13A) for the northern portion of this southern ridge sequence and the average long-term aeolian accumulation rate determined from the OSL and LiDAR as ~0.5 m³/m/yr this feature is likely to have formed over a 140-200 year period. This seems a reasonable estimate considering the average ridge formation time for the barrier is 130 years for the last ~4500 years and this foredune is a larger feature and would be expected to have a somewhat longer formation time. It is likely then that this foredune ceased forming around ~250-300 years ago, taking into consideration the error on the OSL age estimate, the range in foredune volume and long-term aeolian accumulation rate estimate.

4.7.3 The northern foredune

The foredune in the northern section of the barrier has a distinctive morphology and its presence and the timing of its development warrants consideration. The volume of this foredune increases to the north like the southern portion, although there are two distinct volume ranges, rather than a gradual increase in volume (Figure 4.14A). Its height follows this same distinctive change from south to north (Figure 4.14B). This sudden increase occurs in both volume and height at around 800 m in Figure 4.14A, B. In Figure 4.14C it is noted that this abrupt change in volume and height occurs just northeast of the small stream which cuts through the middle of the barrier sequence. The foredune volume and height reduces substantially in the northern corner of the barrier Figure 4.14A, B, C and it curves seaward, presumably in response to the jutting bedrock promontory. This bedrock promontory shows signs of marine erosion as do many of the promontory bedrock features bounding the ridge sequence in this northern portion of the embayment. Marine erosion, around 7000-8000 years ago, and also during the last interglacial (MIS 5e), would cause these eroded cliff features seen in the DEM.

The curving of the foredune at the southern end of this section of the barrier, near to the current entrance of Lake Wonboyn, shows that this foredune likely formed when the
Lake Wonboyn entrance was further north. The two distinct ridges, which may be named incipient ridges, (although they are of a similar height to others in the sequence) have formed as the estuary entrance moved southward.

Figure 4.14: (A) Wonboyn foredune volume for the northern end of the barrier from south to north. (B) Wonboyn foredune height for the northern end of the barrier from south to north. (C) Large scale map showing the morphology of the foredune in the northern portion of the Wonboyn barrier.

The volume and height of this foredune is significantly greater than the foredune in the southern portion of the barrier as the transects attain a volume of ~400 m$^3$ and a height of ~12 m compared with the southern end where the maximum volume and height is 100 m$^3$ and 8 m respectively. Unfortunately there is no chronological record across the ridges for this northern portion of the barrier to estimate the formation time of this northern foredune using an average accumulation rate. However, it is likely that a greater rate of sediment accumulation has occurred for this sequence of ridges; as this northern portion of the Wonboyn embayment enclosed by Green Cape is clearly acting as a substantial sediment trap and northward moving sediment would be concentrated in
this northward corner of the barrier. The southward orientation of the small creeks in Figure 4.14C suggest that wave refraction patterns into the bay under modal wave climate actively deposit sediment in the most northern corner and have gradually shifted the creek entrances southward (see also Figure 1.7 in the Thesis Introduction).

One OSL age was collected on the crest of this foredune within 1 m of the surface towards its northern end which has an age of 70 ± 5 years. Therefore this age should be treated as the termination age for the formation of this foredune. This age of 70 ± 5 in in close accord for the age of the large foredune feature at Keppel Bay, Queensland stated as <100 years old (Brooke et al. 2008b). It is startling that this age is far younger than the estimate for the formation of the foredune at the southern end, which is likely between 240 and 420 years ago. It is not known whether the overall age of this whole portion of the barrier is younger and hence the foredune has a much younger age. A series of OSL ages covering this northern ridge sequence would constrain the timing of its deposition and provide a comparison with the southern ridge sequence.

The general morphology of the foredune at the northern end of this north section of the Wonboyn embayment closely resembles that of the north end of Moruya, although at Wonboyn the foredune is a 1-2 m higher. The lobed margin on the landward side and crest position which moves slightly seaward and landward in planform view bears a significant resemblance to the foredune at Moruya. Also the two incipient ridges on the seaward side of the foredune at Wonboyn and Moruya, are of an elevation close to the older ridges in the sequence.

4.8 A summary of Holocene barrier deposition

The Wonboyn barrier has progradated at a linear rate over the late from ~4500 at 0.3 m/yr. An initially slow rate of progradation from ~7750 to ~4500 years ago at ~0.1 m/yr is suggested by both the OSL and radiocarbon chronology. The average ridge lifetime from ~4500 years to present is 130 years. The GPR data for the coastal sand ridge plain at Wonboyn has a series of beachface reflectors preserving the cumulative deposition of sediment wave and aeolian deposited sediment. The LiDAR data has enabled a general morphology of the barrier sequence and ridge heights and dimensions to be determined. By combining this LiDAR data with the OSL ages, volumes of sediment accumulated on the barrier over the Holocene have been calculated. For the time period from ~4500
to present, a linear rate of aeolian sediment accumulation is evident for the barrier equating to an average of ~0.5 m³/m/yr. Integrating the LiDAR and GPR with the OSL dating for the high foredune reveals that this feature is less than 450 years old in the southern portion of the barrier. The OSL age of ~70 years for the top of the foredune in the northern portion of the barrier is considerably younger than the estimated age of the foredune in the southern portion of the barrier. One explanation for this difference would be that if a core was taken at an elevation within this larger northern foredune comparable to the elevation of the southern foredune the age would be similar. That is the northern foredune has continued to accumulate sediment until ~70 years ago and was a comparable height to the southern foredune around ~400 years ago. This difference illustrates the complexity of this system and demonstrates that the northern and southern sections of this barrier have differing Holocene depositional histories. LiDAR data has enabled the characterisation of the morphology of these two foredunes and GPR across the frontal portion of the barrier at the southern end shows that this foredune feature is not accompanied by a noticeable change in the subsurface structures. However, a transect across an undisturbed section of the foredune would likely further constrain the formative processes responsible for this feature. Unfortunately such an exercise is significantly impeded by dense vegetation.

Considering the embayment characteristics, it is noted that the promontory of Green Cape which encloses Disaster Bay, is a significant sediment trap. However, it seems that unlike Moruya, progradation began at a relatively slow rate. One hypothesis for this initially slow rate of progradation would be the depth of the antecedent bedrock valley in which the Wonboyn barrier has developed. Judging from the slope of the bedrock margin, this once fluvial valley (during the Last Glacial Maximum (LGM)) would be far deeper than that of Moruya. Therefore, while the embayment is a large sediment trap, the available sediment may have been filling in the much deeper embayment. After this period lasting some 3000 years, the embayment and offshore was likely sufficiently filled for progradation rate to effectively triple. Testing of this hypothesis would require seismic studies to determine the depth and character of the bedrock substrate in this embayment which is beyond the scope of this thesis.
CHAPTER 5: CALLALA BEACH
5.1 Introduction

This chapter sets out the findings relating to the coastal sand ridge plain at Callala Beach. This site has little or no chronological, stratigraphical or morphological information pertaining to it; therefore the results presented below are a foundational investigation of the Holocene evolution of this region of Jervis Bay. A brief description of the general physiographic setting and a synthesis of past research is followed by results of OSL dating of the distinct sand ridges evident at the southern end of the barrier.

GPR collected for this site characterises the subsurface structure of the barrier sand. An examination of the ridge and broader barrier morphology and volumes of sediment prograded over the Holocene as defined by the sequence of OSL ages was completed using LiDAR. An analysis and discussion of the morphology of the high foredune fronting this barrier is followed by a concluding section synthesising the Holocene deposition of the barrier based on the presented datasets.

5.2 Site characteristics

5.2.1 Physiographic setting

Callala Beach is situated to the west of the large body of water named Jervis Bay. This is a moderately shallow bay with a maximum depth of around 30 m. Callala Beach is one of the few beaches inside Jervis Bay, which at times may receive unrefracted ocean swells. This Bay formed as the rising sea following the LGM flooded what would have been a spectacular landscape of cliffs surrounding a river valley. The present day sea cliffs around the northern headland (Beecroft Peninsula) at Point Perpendicular have 135 metre vertical faces above present sea level. The Bherwerre Peninsular forming the southern headland of the Bay has similarly spectacular sea cliff topography. These headlands are primarily of Permian sandstones such as the Snapper Point Formation and the Conjola Formation. The softer Wandrawandian Siltstone dominates the western side of the Bay (Figure 5.1) and has produced lower relief topography.
On the northern side of Jervis Bay there is a high stationary barrier which connects Beecroft Peninsula with the southern headland of Culburra Beach to the north via a series of small bedrock outcrops. Carama Inlet which is boarded by extensive mangrove and saltmarsh deposits cuts through a backbarrier flat on the lee side of this stationary barrier. The Bherwerre barrier forming the southern side of Jervis Bay and separating St Georges Basin from the sea is an extensive long-walled transgressive dune field reaching up to 60 metres above MSL which had an active mobile dune sheet before being stabilised with marram grass in the 1970’s. The dune morphology of this barrier suggests there have been three distinct phases of dune activity and preliminary drilling of the barrier supports lengthy periods of dune mobilisation (Thom 1987). A core taken from Lake Windermere (a freshwater lake in the barrier complex) indicates a similar pattern of aeolian activity (Thom 1987). Numerous Pleistocene dunes occur on the southern headland and to a lesser degree on the northern headland (Figure 5.1). The southern headland is very exposed to the prevailing south easterly swells and acts as a
large sediment trap for the Bherwerre barrier as well as collecting sediment itself (Figure 5.1).

Behind Callala Beach itself is an extensive back barrier swamp named “Black Swamp” (Thom 1987) (Figure 5.2). At the southern end of Callala Beach is Currambene Creek, which is the largest of the estuaries connected to Jervis Bay having a catchment size of 160 km². This estuary also has extensive coastal wetlands bordering a well-defined channel, and there are numerous palea channels and a series of well-developed point bars in the lower reaches (Figure 5.2).

Figure 5.2: Callala Beach and surrounding area from 2004 air photo showing the location of OSL sample sites. Map data from Google Earth.

5.2.2 Past studies

There have been a number of studies which have examined various aspects of the geomorphology of Jervis Bay including sedimentary characteristics of the seafloor (Taylor 1971), sea bed lowering in the recent past (Bowyer 1992), Tsunami records (Bryant et al. 1997) and more general geomorphic characteristics of the coastal landforms surrounding the Bay (Thom 1987). The subaqueous sediments are well sorted medium-fine to fine sands of 80 – 90 % quartz (Taylor 1971). Sediment thickness in Jervis Bay reaches a maximum of approximately 30 m in the centre of the Bay, while
thicknesses within 1 – 2 km of the shoreline margin reach a maximum of around 15 m (Taylor 1971). Seabed lowering was observed between the years 1894 and 1988, comparing two hydrographic surveys, and was demonstrated to be on average -0.41 m, with the greatest lowering of around -1.24 m was in the central portion of the Bay close to the entrance to the ocean (Bowyer 1992). Thom 1987 stated that the Callala Beach ridge sequence was greater that 3 m above MSL and that a core through the barrier encountered nearshore shelly sand overlying bedrock at -5 m below MSL with the shell assemblage composed of a mixture of estuarine and open ocean species.

**5.3 OSL dating**

### 5.3.1 Introduction

OSL dating was completed for 8 samples from the upper 1 m of aeolian dune sands of selected ridges at Callala Beach. Below are the dating results and discussion of their significance in relation to the broader coastal evolution of Jervis Bay. These results are the first chronological determinations for this site and are a basis for further chronological examination of the surrounding coastal deposits.

### 5.3.2 OSL dating results

Samples for OSL dating were collected from the crests of 8 ridges in the sequence along two slightly offset profiles (Figure 5.2). The quartz samples for OSL dating were found to have generally excellent luminescence characteristics, as was demonstrated for Moruya and Wonboyn. The same preheat and cutheat combinations (180/ 160) were used for these Callala samples, as the decay curve results were satisfactory indicating minimal thermally transferred charge component in the D$_e$ signal. Dose response curves were typically linear for all aliquots as was also the case at Moruya and Wonboyn; as is common for young marine quartz.
Unlike Moruya and Wonboyn, there was a weak trend of increasing total dose rate from landwards to seawards across the barrier (Figure 5.3). In addition, all dose rates were below 1 Gy/ka (similar to Wonboyn) in comparison to Moruya where the average dose rate was 0.96 Gy/ka with 5 samples with values above 1 Gy/ka. This does rate trend is reflected in the measured concentrations of Potassium (K) and Uranium (U), which also gradually increase in a seawards direction. The very low dose rates, especially for the most landward ridges may be a result of a low percentage of heavy mineral material in this embayment and more broadly within Jervis Bay. In general the sands of Jervis Bay beaches are world renowned as being extremely white. Overdispersion values for all samples except Cal6 were 12% or less with the most seaward four samples having values between 2 – 7% (Table 5.1). Sample Cal6 (Table 5.1) had a higher overdispersion value (23 ± 12) and thus the error margin for this date is considerably greater than other samples. However it does not alter the progradation trend and its error overlaps the sample immediately landward (Cal7: Table 5.1). In general, the OSL dating and analysis for samples from Callala Beach emphasise the homogeneity of the sands in this barrier and likely in Jervis Bay.
Table 5.1. OSL ages for sand ridges across the Callala Beach barrier. The samples are ordered according to sample position with respect to the ocean, so that the first sample listed in the table corresponds to the sample closest to the shore. All samples include an internal dose rate contribution of 0.03 ± 0.01 Gy/ka assumed based on measurements made on Australian quartz (Bowler et al. 2003).

*All sample dose rates were measured with ICP-MS (U and Th) and ICP-OES (K) and calculated using the conversion values of Guérin et al. (2011).

**A water content of 5 ± 2.5 % was assumed for all samples.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Beta (Gy/ka)</th>
<th>Gamma (Gy/ka)</th>
<th>Cosmic (Gy/ka)</th>
<th>Total Dose Rate (Gy/ka)</th>
<th>D, (Gy)</th>
<th>Over-dispersion (%)</th>
<th>OSL Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cal1</td>
<td>0.23 ± 0.01</td>
<td>0.65 ± 0.03</td>
<td>0.58 ± 0.01</td>
<td>0.45 ± 0.02</td>
<td>0.19 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.86 ± 0.03</td>
<td>0.45 ± 0.01</td>
<td>2 ± 2</td>
<td>530 ± 20</td>
</tr>
<tr>
<td>Cal2</td>
<td>0.26 ± 0.01</td>
<td>0.60 ± 0.02</td>
<td>0.39 ± 0.01</td>
<td>0.32 ± 0.01</td>
<td>0.15 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.69 ± 0.03</td>
<td>0.90 ± 0.01</td>
<td>7 ± 1</td>
<td>1320 ± 60</td>
</tr>
<tr>
<td>Cal3</td>
<td>0.15 ± 0.004</td>
<td>0.58 ± 0.02</td>
<td>0.40 ± 0.01</td>
<td>0.31 ± 0.01</td>
<td>0.14 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.67 ± 0.03</td>
<td>1.98 ± 0.03</td>
<td>7 ± 1</td>
<td>2950 ± 140</td>
</tr>
<tr>
<td>Cal4A</td>
<td>0.19 ± 0.01</td>
<td>0.69 ± 0.03</td>
<td>0.58 ± 0.01</td>
<td>0.44 ± 0.02</td>
<td>0.19 ± 0.003</td>
<td>0.19 ± 0.02</td>
<td>0.86 ± 0.03</td>
<td>2.94 ± 0.04</td>
<td>6 ± 1</td>
<td>3440 ± 150</td>
</tr>
<tr>
<td>Cal4B</td>
<td>0.14 ± 0.004</td>
<td>0.56 ± 0.02</td>
<td>0.25 ± 0.01</td>
<td>0.21 ± 0.01</td>
<td>0.10 ± 0.002</td>
<td>0.19 ± 0.02</td>
<td>0.53 ± 0.03</td>
<td>2.05 ± 0.05</td>
<td>12 ± 2</td>
<td>3890 ± 210</td>
</tr>
<tr>
<td>Cal5</td>
<td>0.11 ± 0.004</td>
<td>0.58 ± 0.02</td>
<td>0.17 ± 0.004</td>
<td>0.15 ± 0.01</td>
<td>0.08 ± 0.001</td>
<td>0.19 ± 0.02</td>
<td>0.44 ± 0.02</td>
<td>2.22 ± 0.05</td>
<td>12 ± 2</td>
<td>5000 ± 310</td>
</tr>
<tr>
<td>Cal6</td>
<td>0.13 ± 0.004</td>
<td>0.56 ± 0.02</td>
<td>0.06 ± 0.004</td>
<td>0.07 ± 0.003</td>
<td>0.06 ± 0.001</td>
<td>0.19 ± 0.02</td>
<td>0.35 ± 0.02</td>
<td>2.56 ± 0.41</td>
<td>23 ± 12</td>
<td>7370 ± 1290</td>
</tr>
<tr>
<td>Cal7</td>
<td>0.17 ± 0.01</td>
<td>0.72 ± 0.03</td>
<td>0.19 ± 0.01</td>
<td>0.14 ± 0.01</td>
<td>0.10 ± 0.001</td>
<td>0.19 ± 0.02</td>
<td>0.49 ± 0.02</td>
<td>3.64 ± 0.08</td>
<td>11 ± 2</td>
<td>7460 ± 430</td>
</tr>
</tbody>
</table>

All sample dose rates were measured with ICP-MS (U and Th) and ICP-OES (K) and calculated using the conversion values of Guérin et al. (2011). A water content of 5 ± 2.5 % was assumed for all samples.
5.3.3 A chronology of Holocene progradation

The pattern of progradation observed for the Callala Beach barrier is from ~7500 to ~500 years ago (Figure 5.4). These ages, from the most landward ridge and the ridge immediately behind the large foredune fronting the barrier closely align with the ages for these same locations at Moruya and Wonboyn. However, the rate of progradation over this time period is ~0.1 m/yr, which is far slower than Moruya or Wonboyn. This slower rate of progradation is reflected in a longer ridge ‘lifetime’ of 390 years for this barrier.

Figure 5.4: OSL age estimates for 8 samples collected the sequence of sand ridges across the Callala Beach barrier. The sample numbers associated with each age correspond to the numbers after the letters ‘Cal’ in Table 5.1. The DEM is a TIN derived from LiDAR. The black lines represent the position of a topographic profile interpolated from this DEM seen in Figure 5.5.
The age of 7460 ± 430 for the most landward ridge at Callala is very close to the reported age for the stabilisation of Post-glacial sea-level at or near its present height. Noteably, the landward most two ages of 7460 ± 430 and 7370 ± 1290 (which are not statistically different) are for ridges which do not persist along shore past the jutting bedrock promontory seen at the top of Figure 5.4. The age of around 5000 ± 310 is for the fourth ridge in the sequence and this is also the most landward ridge in the rest of the barrier north of this bedrock control (Figure 5.4). One can therefore envisage a situation where at around 7000 years ago, to the south of this bedrock promontory there was series of three ridges and to the north possibly a low ridge later built higher or reworked cutting off “The Black Swamp”, then a marine dominated tidal estuary with extensive open sand flats.

As can be seen from Figure 5.5, the ridge with the age of ~5000 years is the highest in the entire sequence. It is here suggested that an older and once lower ridge existed in this location cutting off Black Swamp between ~7500 and ~5000 years. Its height, as well as its multi-crest morphology, suggest that it was active for a longer period of time than other ridges in the sequence. A series of OSL ages down through this ridge, as well as subsurface stratigraphic information (there is no GPR over this ridge as the GPR profile collected in this study begins at the profile offset in Figure 5.4) would be insightful in understanding the deposition of this ridge. An alternative hypothesis to a longer formation time for this higher ridge dated ~5000 years is a higher sea level during its formation. While many of the profiles across the barrier do show a drop in height (see section 5.4 below), this issue of a higher sea level during this ridge’s formation is not fully resolved by height data alone and requires determination of the
CHAPTER 5: CALLALA BEACH

Elevation of wave deposited sediments within each ridge to be determined. As no cores deeper than 1 m (for OSL sampling) were taken in this location, the height of the wave zone facies with respect to current sea level is not known as no wave deposited material was encountered in the OSL sampling cores. This issue is discussed further in the section below which presents the GPR data.

With the exception of the most seaward age, which lies on the ridge directly behind the foredune, samples were taken from topographically strong ridges, which had laterally persistent higher crests. Interestingly the two ridges, or possibly one multi-crest ridge, just seaward of the profile offset position (Figure 5.5), are close in age but statistically separable at 1 sigma error level. This can be explained when we consider the average ridge ‘lifetime’ which is ~390 years.

![Image](image.png)

**Figure 5.6**: OSL age estimates for coastal sand ridges on the Callala Beach barrier plotted against barrier width as a percentage of total width. A linear trend line has been fitted through these points with an associated $R^2$ value. Dotted red line represents the possible shorter-term trends of progradation rate (the older two ages are not connected by this dotted red line due to the magnitude of the error bars).

Plotting the OSL age estimates according to barrier width indicates a linear trend of barrier accumulation over the late Holocene (Figure 5.6). A polynomial fit is also possible with this data ($R^2 = 0.97$) where the curve has a slight upward bend, which would indicate a slightly increasing rate of progradation over time. Such a trend is possible but the similarity of the two line ‘fits’ means that either line could be defended.
as the most logical fit. Interestingly, as the error bars, especially for the ages less than ~4000 years, are quite small it is possible that the different rates of accumulation (i.e. the trajectory of the line joining two ages) between age estimates could be actual variations over time (Figure 5.6, red dotted line). Such variations would deviate somewhat from the long-term trend. Two increases in rate are evident, from 3440 ± 150 to 2950 ± 140 and from 1320 ± 60 to present (assuming a 0%, 0 years mark). These two intervals of slightly increased progradation rate are also seen when calculating an average ridge lifetime for these shorter intervals of progradation. Between the 3440 age ridge and 2950 age ridge are three slightly lower ridges (Figure 5.5), where the average ridge lifetime is ~100 years; therefore an increased rate demonstrated. A similar change is observed between ~1320 and 0 where the ridge lifetime age is calculated as 220 years. Determination of potentially differing shorter-term progradation rates was not attempted at Moruya and Wonboyn due to greater error margins on the OSL ages.

5.4 GPR

5.4.1 Introduction

This section presents the GPR results for Callala Beach followed by a discussion of the insights from this data for characterising coastal progradation at this site. The results presented span approximately two thirds of the barrier (~400 m) beginning at the profile offset seen in Figure 5.4 and Figure 5.5 and continuing to the present shoreline. This transect was collected using a 250 MHz antenna, however some additional GPR data using a 500 MHz antenna has been collected and processed for a short transect at the northern end of the barrier. The southern transect with the 250 MHz antenna, while not covering the entire barrier width, nevertheless provides important insight into the subsurface stratigraphy of the Callala ridge plain and spans the past ~4000 years of the barriers history. The 250 MHz antenna results are presented in two sections of approximately 200 m. The discussion that follows these results will focus on characterising the shallow subsurface structures and comparing and contrasting these results with the Moruya and Wonboyn GPR record as well as other published GPR data for prograded sand barriers.
5.4.2 Characterising the subsurface structures

The GPR data presented below was collected along a beach access foot track between Myloa and the modern beach. This foot track is almost 400 m long but contains some minor curving so that for small sections of the transect, data collection is slightly offset from perpendicular to ridge crest strike (Figure 5.7). While not ideal, these changes are very localised along the transect. It should be noted that the topographic expression of the ridges and inter-ridge swales in the GPR profile is somewhat diminished as the path along which the GPR data was collected is slightly incised through some ridge crests (in the order a few tens of centimetres) and there is a small degree of infill within some of the inter-ridge swales. Furthermore, some compaction due to human traffic is to be expected in the upper portions (0-0.5 m) of the GPR data.

Figure 5.7: Locations of the GPR sections presented below in relation to the OSL dates and LiDAR data. Note: elevation colour scheme and height divisions are the same as those in Figure 5.4.
Some ridges have not been captured topographically by the GPR profile, for instance, the ‘narrow’ ridge immediately behind the foredune (see Figure 5.7) has no topographical expression in profile B of the GPR (Figure 5.8). However, it was generally noted that there was little signal noise at this site.

Part A of the GPR for this site (Figure 5.8) shows a series of closely spaced seaward dipping reflectors, the tops of which are mostly between 3 and 4 metres AHD. These reflectors reach down to around 0-1 m AHD. Most of these reflectors are convex-up in their upper portions and then flat or sometimes very slightly concave-up in their lower portions. This change from convex-up to flat or slightly concave-up occurs at around 2 m AHD. There are some almost horizontal reflectors present in profile A (Figure 5.8) between 0 and 1 metres AHD which contrast with the normal dip of other reflectors in the sequence (e.g. beneath the 3890 ± 220 age). Some of these seem to be concordant with, or extensions of, some of the regular dipping reflectors, while others appear to lie discordantly with other surrounding reflectors. Two excellent examples of seaward migration of convex-up reflectors exist in profile A at an elevation of 3-4 m. One set either side of the 50 m mark, and another set between 150 and 175 m near to the 2950 ± 140 OSL age (Figure 5.8).

Part B of the GPR profile is the most clear and well-imaged section of GPR examined in this entire study. An series of regular seaward dipping reflectors are consistently imaged throughout the entire profile. The tops of these reflectors are consistently between an elevation of 3-3.5 m and reach down to an elevation between 0 and 1 m AHD. These regular reflectors have remarkably similar geometries with convex-up upper portions and concave-up lower portions. The change from convex-up to concave-up occurs at around 2.5 m elevation. At 280 m along the transect at an elevation of around 1 m AHD are two anomalous reflectors with respect to the other reflectors in the profile. The regular seaward migration of convex-up reflectors around 3 m AHD is remarkably clear in profile B stretching for the full 150 m of the profile.
The lack of signal noise and ‘ringing’ in the GPR sections for Callala Beach is likely due to the pristine character of the sand found at this site, as seen in the low does rates of the OSL samples across the barrier. The lack of impurities such as heavy minerals, feldspars and carbonate material as well as the absence of iron leaching has resulted in the clear reflectors being imaged at this site. Despite the well-imaged GPR reflectors, the inherent depth limitations of the 250 MHz antenna means that the character of the structures below 0 m AHD is uncertain.
One of the most characteristic features of the GPR for Callala Beach is the geometric regularity of the reflectors across each transect. These reflectors demonstrate the sequential deposition of sediment on the barrier over time and the preservation of such a regular geometry suggests a morphodynamic stability over the last ~4000 years (Figure 5.8). This regular geometry allows the identification of the transition of each reflector from a convex-up geometry to a concave-up geometry at an elevation of ~2.5 m AHD. This is interpreted as the interface of the beachface (dominantly swash deposited) facies, and the dune (dominantly aeolian deposited). A similar interface was identified by a change in reflector geometry at Guichen Bay, South Australia (Bristow & Pucillo 2006), and inspection of the modern beach profile in this region of the Callala Beach barrier indicated that the elevation of ~2.5 m AHD for this change was reasonable.

It is insightful to overlay the OSL age estimates on the GPR profiles in order to constrain the timing of deposition of reflectors imaged by the GPR equipment. Two examples of prodgrading reflectors, likely to be marking the position of incipient ridges, may be seen in profile A. One set is bounded by two of the ages 3890 ± 220 and 3440 ± 150 either side of the 50 m distance mark in profile A (Figure 5.8). As mentioned in section 5.3.3 above, these two ages are statistically separable at the 1 sigma error level, and yet taking the differential as the minimum 80 years and maximum of 820 years, an appreciation for the uncertainty of the timing of these prodgrading reflectors is apparent.

This is not the case for profile B, where the time interval between the two ages is far more precise (maximum of 870 years and a minimum of 710 years). A series of 18 reflectors between 0-3 m AHD are evident over this ~800 year time period. Thus we have barrier progradation of ~100 m over ~800 years equating to a rate of 0.125 m/yr. Over this time period a reflector has been preserved every 5-6 m or every 45 years. Thus on average between ~1300 and ~500 years ago, every ~50 years the barrier built seawards 5-6 m. Following 530 ± 20 to present only 5 of these reflectors with consistent geometry are evident over a distance of just 45 m. This equates to a progradation rate of just 0.08 m/yr. Over this time period of ~530 years a reflector was preserved every 106 years. For the purposes of comparison with the rates stated above, over the past 530 years progradation seawards has been proceeding at just 3-4 m every ~50 years, rather than 5-6 m.
Such a calculation while no doubt, containing some quantifiable and unknown errors, is nevertheless very informative for coastal managers. Plans are currently underway to nourish Callala Beach with sand, due to problems of coastal erosion over the past few decades. While there is apparently a slight slowing of progradation rate comparing ~1300-500 years ago with ~500 to present, there has still been a net accumulation of sediment occurring in the system; and hence overall progradation of the barrier. Combining the GPR profiles with the OSL ages demonstrates that one would expect progradation to be continuing today, albeit at a slower rate. Therefore the question remains as to whether the coastal erosion observed is in fact a reversal of previous progradation trends over the barriers history, or are the erosional events merely perturbations expected within the cycle of cut and recovery occurring while coastal progradation continues. An assembled account from residents, air photos, and more recent beach profiling could possibly detect a 3-4 m advancement of the beachface over the last ~50 years, although it is possible that the error or subjective nature of such data would leave this question unresolved. Thus here again the uniqueness of the beach profiling record at Bengello Beach (Moruya) is reinforced.

5.5 Morphology of the barrier

5.5.1 Introduction

This section will discuss the morphology of the barrier including ridge height, amplitude and spacing as well as broader scale aspects of the barriers Holocene deposition. This was completed using LiDAR in the context of the Quaternary geological mapping completed as part of the Comprehensive Coastal Assessment (Troedson et al. 2004). At a smaller scale, these two datasets will be put in the context of the bathymetry of Jervis Bay from Geoscience Australia.

5.5.2 Ridge morphometrics

The ridge crests at Callala align closely with the present beach curvature except at the northern end where there is a distinct eastward bend towards Jervis Bay (Figure 5.9). A very slight bend in the ridge alignment is also evident in the area around the jutting bedrock promontory in the southern third of the barrier. Ridge topography in the central and much of the northern third of the barrier has been flattened during the construction of the township of Callala Beach; however, many distinct ridges are still visible in the LiDAR (Figure 5.9).
There are two height trends to note for this ridge system. The first is a very obvious increase in height from south to north from ~5 m in profile five to up to ~8 m in profile three (Figure 5.10). No such dramatic increase in height (~ 3 m) over such a distance (~600 m) was observed for either Moruya or Wonboyn. The maximum ridge height is obtained in profile three (Figure 5.10) and further northward of this location, there is a significant decrease in height in the order of 2 – 3 metres (Figure 5.10). This trend can be clearly seen in the schematic profile in the bottom right corner of Figure 5.10 where the overall ridge height increases through profiles 5 to 4 to 3 and then decreases again from 3 to 2 to 1.
Figure 5.10: A series of five shore normal topographic profiles extracted from a DEM derived from LiDAR. Profile locations refer to Figure 5.9. All y axes are in Elevation (m AHD) and x axes are Distance in (m) as shown in the bottom right schematic profile. All profiles are in proportion to one another including the schematic.

The second significant height trend is a decrease in height from landward to seaward across the barrier. This fall in height is evident for all profiles across the barrier to some degree but is most pronounced at the northern end of the barrier (Figure 5.10). Here the decrease in ridge height is around 3 metres over a distance of ~300 m. In other parts of the barrier the decrease is ~0.5 -1 m.

The decrease in height is apparent in both the crest and the inter-ridge swale heights, i.e. it is not simply a change in the ridge – inter-ridge swale amplitude of any given profile (Figure 5.10). While there may appear to be a significant change in ridge amplitude for profiles 1 and 5, close inspection of the LiDAR DEM reveals that the construction of infrastructure e.g. roads, has modified the original topography for these profiles (first 250 m in profile 1 and first 200 m in profile 5 are modified, see Figure 5.9 and 5.10).

The case of the significant shore-normal fall in height at the northern end of Callala Beach is not yet known and further work is required to understand this trend. The GPR for this site discussed above was taken from the southern end of the barrier, not the northern end. A GPR transect across this northern end of the Callala Beach barrier was
completed using a 500 MHz antenna during testing of various antenna frequencies at this site. Unfortunately the data from this transect does not resolve the issue of whether the decrease in ridge height is accompanied by a decrease in the elevation of swash zone facies, as this antenna frequency did not provide sufficient data quality to characterise the subsurface facies. However, a hand auger core to water table in an inter-ridge swale (~380 m in profile 1, Figure 5.10) for topographic correction of this 500 MHz GPR data encountered coarse beach sands in the first metre of coring suggesting that there is minimal aeolian material at this end of the Callala Beach barrier. Further GPR collection using the 250 MHz antenna, accompanied by hand auger ground truthing at this site, would likely determine the elevation of the swash zone facies.

Examining the undisturbed southern end of the barrier it is apparent that particularly high ridges in the sequence are often separated by a series of lower ridges on either side (see Figure 5.10, profile 4). These lower ridges are generally ~0.5 m lower than the higher ridges. However, while there appears to be this variation in ridge height across the barrier, unlike the central topographic profile at Moruya, there is no obvious increasing or decreasing trend in amplitude change across the barrier width in any of the profiles (c.f. Figure 3.10).

A foredune higher than previous ridges can be seen in some profiles in the centre of the barrier, but its elevation is not a great deal higher (in some instances lower) than the most landward ridge. At the northern end of the barrier, there is no foredune. At the southern end, a foredune does exist, however understanding its exact height and morphology is impeded due to the LiDAR data for this small area of the barrier not penetrating through thick vegetation to the ground surface. It seems however, that it’s elevation is quite similar to the previous landward ridges.

5.5.3 Broader scale morphology

The Callala Beach barrier cuts off an extensive back barrier swamp named “The Black Swamp” which has a small catchment. This swamp would have been formed behind a sandy ridge ~7500 years ago when sea level reached its present height. The ridge cutting of the The Black Swamp, is preserved and is now the most landward ridge of the barrier.
At the southern end of the barrier, Currambene creek flows into Jervis bay. The ridge sequence along the northern channel margin of the creek is truncated as may be seen for the Wonboyn ridge sequence bordering the Lake Wonboyn estuarine channel. The Currambene Creek estuarine channel has a distinct southward bend cut off by the likely spit-like growth of the Callala Beach barrier which is here a single high dune.

This long single dune now cutting off Currambene Creek and forcing the entrance southward requires further discussion. This feature has formed over the past ~500 years according to the OSL ages. While it may have appeared to have migrated southwards with the channel entrance, a more detailed examination of its morphology from LiDAR demonstrates that it does not contain any of the classic spit-like constructional forms, such as concentric curving ridges or a slowly diminishing elevation trend towards its active margin. In fact in morphology, it appears to be a single high foredune, which actually increases in height southwards.

A small rocky island approximately 500 m NE from the mouth of Currambene Creek (Figure 5.9) is important in understanding the formation of this dune. The maximum height of the dune is attained at the swash confluence zone caused by this island and aerial imagery indicates a subaqueous tombolo like projection of sediment concentrated by the island (Figure 5.2). Therefore the formation of the dune would appear to coincide with the time at which the barrier had built out to such a degree as to have its active swash zone influenced by the presence of this island. The concentration of sediment in this vicinity would likely have forced the southward migration of the Currambene Creek channel and the single dune structure would have gradually built higher and consolidated its connection with the rest of the barrier. A series of OSL ages along this dune feature would further help resolve the timing and mode of its emplacement.

5.6 Aeolian barrier volumes and sediment accumulation rates

This section presents the results of the calculation of volumes of aeolian sediment forming the Callala Beach ridge topography over the Holocene. Using LiDAR the barrier has been divided into a series of time ‘slices according to the OSL ages. A plot of cumulative aeolian volume versus time for Callala Beach has a strong linear relationship (Figure 5.11). The average aeolian accumulation rate calculated using this cumulative barrier volume plot is ~650 m$^3$/yr. Taking an average embayment length of
5 km and calculating an average accumulation rate based on the cumulative volume trend gives a value of ~0.13 m$^3$/m/yr.

Despite the fact that the large dune, which cuts off Currambene Creek, was included in the volume calculation for the most recent time period of the barrier, only a small increase in may been the cumulative aeolian volume plot (Figure 5.11). It should also be noted that the age of 7370 ± 1290 in Figure 5.6 and Table 5.1 was not included in the volume slice analysis as its errors overlapped that of the age on the most landward ridge and was not statistically different.

![Figure 5.11: Cumulative aeolian volume (above 3 m AHD) over time delineated using the OSL age estimates. Horizontal error bars reflect stated error for each OSL age. Vertical error bars are plotted but not seen due to smaller error margins as overall volumes are significantly smaller than Moruya or Wonboyn.](image)

It should be noted, that urban development through the centre of the barrier has resulted in the destruction of the natural topography of the ridges. Thus delineating the boundaries of the volume ‘slices’ involved some uncertainty. There is also significant constriction of the width of the ‘slices’ at the northern end of the barrier. Comparing the Callala Beach cumulative volume and accumulation rate with the rates reported for Moruya and Wonboyn the average rate of 0.13 m$^3$/m/yr for Callala Beach is far smaller than Moruya and Wonboyn. This is unsurprising given the average ridge lifetime for Callala Beach is 390 years compared with Moruya and Wonboyn which have ridge lifetimes of 110 and 130 years respectively. This data demonstrates that Callala, while a
prograded barrier system, has a substantially lower ridge formation rate and associated aeolian accumulation volume rate over the Holocene.

As Callala Beach has experienced significant erosional problems in recent years, information about the long-term sediment budget of this system is critical for coastal managers in planning for the impact of future coastal pressures such as sea-level rise. The Holocene depositional history presented here informs coastal managers of measured rates of progradation and hence puts the observed shorter-term erosion in its proper context. Also the nature of the subsurface stratigraphy, showing a cumulative succession of beachface reflectors, informs coastal managers and community groups that the way in which this system erodes during storms and subsequently recovers has not prevented overall progradation over the Holocene, albeit at a slow rate. Such knowledge is critical for informed coastal management of Callala Beach.

5.7 Foredune analysis

5.7.1 Introduction

This section examines the morphology, timing and mode emplacement of the foredune on the frontal portion of the Callala barrier using LiDAR data and an examination of the most seaward portion of the GPR data. A discussion of the significance of this feature with respect to the Holocene deposition of this barrier and in the context of similar features at Moruya and Wonboyn may provide insight into current conditions in this embayment.

5.7.2 Foredune morphology

The morphology of the Callala foredune may be understood with the aid of LiDAR data for this region. Unfortunately, some of the true topography of this feature of the barrier has been lost due to dense undergrowth. In addition, some significant portions of the foredune have been modified by human activity during the development of the Callala Beach Township. Nevertheless, analysis of foredune volume (Figure 5.12A) and height (Figure 5.12B) from south to north is still informative in determining the morphology of this feature.
Figure 5.12: (A) Callala foredune volume from south to north along the barrier. (B) Callala foredune height from south to north along the barrier. The error bars for each point in (A) and (B) incorporate the stated LiDAR vertical error of ± 0.3 m. (C) Four ~1200 m sections showing the morphology of the foredune at Callala Beach. (D) Smaller scale view of the Callala Beach barrier showing the location of frames 1-4 in part C.

Foredune volume appears to fall slightly from between 0 and 2000 m along the barrier from south to north (Figure 5.12A). However, this is most likely due to the lack of LiDAR ground points in this region, which has attenuated the topography of the foredune (see the dashed red oval in Figure 5.12C frame 1). The height value of the DEM on the foredune in such areas where there are few ground points is the height of the nearest ground returns on either side of the foredune (Figure 5.13).
The human modified and unmodified sections of the foredune (Figure 5.12A, B) show an increasing and then falling trend in volume and height. While it is apparent that in the human modified section there have been changes to the true topography, the magnitude and direction (higher or lower elevation) is uncertain. However, as this rising and then falling height and volume trend is seen in the foredune heights and volumes for both Moruya and Wonboyn it is unlikely that such a pattern at Callala Beach is a product of human modification.

The other feature of note which is most apparent in the volume calculation is seen at around 1800 m. The distinct jump in volume at this distance is due to an apparent switch in the position of the foredune. Up to this point, the main dune which cuts off Currambene Creek is the foredune. However, after this point, the low narrow dune on which the OSL age with the age of 450 ± 20 was taken, assumes the position of the foredune with respect to the beach morphology and older ridge sequence. This may be seen in Figure 5.12C frame 2 and a more detailed view of this small ridge can be seen in Figure 5.7. It is here hypothesised that the overall narrowing of the barrier in planform from the southern end to this point is the likely reason for this small ridge ‘becoming’ the foredune.

At the peak of the trend in height of ~7 m at 4500 m along the barrier in Figure 5.12B the foredune is unmodified. This area may be seen near the base of frame 4 in Figure 5.12C as the light brown/grey areas just behind the beach. This peak in the height trend in this location is not the location of a corresponding peak in volume. The location of the largest foredune volume is 1000 m south at 3500 m along the barrier. This spatial offset of the maximum height and the maximum volumes is due to the human

![Figure 5.13: Schematic of topography attenuated due to lack of LiDAR ground points.](image)
modification of the foredune for road building at 3500 m, which while flattening the foredune somewhat, has also widened it in planform.

The decrease in foredune volume and height toward the north after ~4000 m is very distinctive pattern in the graphs in Figure 5.12A, B. While such a trend has been observed in the foredune morphology of Moruya and Wonbyon, the data for Callala shows that the decrease in volumes and height is far greater in magnitude. This phenomenon may be seen in the LiDAR in Figure 5.12C frame 4 where colours of yellow and green represent heights of just 2-4 m. A proposed mechanism for such a drop is related to the sudden change in barrier alignment seen near the top of frame 4 in Figure 5.12C. This distinct ‘kink’ in the barrier is most likely due to the bedrock structural control of the headland separating the town of Callala Bay to the north and Callala Beach to the south. In addition, this northern end of the barrier would experience a significantly differing wave climate to the rest of the barrier, which, with a certain swell direction, can receive unrefracted ocean waves. This influence of unrefracted waves is diminished to a much smaller window of swell direction in this northern corner of the barrier. Also, the partially submerged rock platform in the northern corner of the barrier (see Figure 5.12D) significantly attenuates and refracts wave energy in this portion of the barrier.

5.7.3 Foredune stratigraphy and age

A close examination of the GPR data collected on the frontal portion of the Callala barrier reveals some interesting detail about the foredune stratigraphy. As at Wonboyn, the full topographic expression of the foredune has not been captured by the GPR survey due to restrictions with dense vegetation. The survey line follows a beach access foot track, which has also modified the topography to some degree so that the small ridge with the OSL age of 530 ± 20 is not present in the survey (Figure 5.14). It should also be noticed that in this area, the true height and topography of the foredune has not been captured by the LiDAR data due to the thick vegetation. Thus while it appears as the though the elevation of the GPR profile is comparable to the elevation of the foredune, the foot track along which the GPR was collected is in fact ‘cut’ into the foredune to some degree and the DEM is not showing the true foredune elevation. This is important to remember when interpreting the GPR profile shown below in Figure 5.15.
The GPR data in Figure 5.15 shows a complex series of seaward dipping reflectors. The OSL age of 530 ± 20, while collected on a small ridge just landward of the foredune in this part of the barrier (Figure 5.14), has been shown on the GPR profile in its approximate position. From 0-30 m in the profile a series of seaward dipping reflectors are evident with a convex-up geometry between 1-3 m AHD and a concave-up geometry below 1 m. These are interpreted as storm beach faces as their geometry does not resemble a fairweather profile for this site which in this region of the beach has a clear berm feature at 1.5 m AHD.
In the GPR profile shown in Figure 5.15, there are some reflectors in the upper portion of the foredune between 10 and 25 m, which show the vertical accumulation of the foredune over time. This accumulation appears to be in a series of mounded layers with a strongly convex-up geometry. Cutting through these mounded reflectors near the front of the ridge is the reflector seen between 20 and 30 m at an elevation of 2.5-3.5 m AHD. This concave-up reflector appears to truncate the sequence of vertical accumulation and is interpreted as a storm event. The recovery from this truncation has contributed to subsequent building the foredune. Again it should be noted that perhaps 1-2 m of stratigraphic detail from the top of the foredune is not captured by this profile due to it being along a beach foot track which has been levelled and cut down into the existing foredune topography.
The timing of these foredune accumulation processes is not directly constrained by dating. A series of samples from varying depths within the foredune stratigraphy would likely reveal an informative sequence of erosional and depositional events relevant to understanding this barriers’ recent history. However, the OSL dating of the entire ridge sequence presented above demonstrates that the foredune formation on Callala Beach occurred at, or later than ~500 years ago. In fact, this OSL age on the small ridge behind the foredune in Figure 5.14 may be treated as an age for the foredune further north along the barrier as it appears that this small ridge ‘becomes’ the high foredune feature in the middle and northern end of the barrier. In that case it would seem that this middle and northern portion of the barrier has prograded only a small amount over the past 500 years. However, as this age is taken behind a foredune feature in the southern end, it is here proposed, that this southern portion of the barrier has had a somewhat different depositional history compared with the northern part of the barrier in recent times. In fact, if the OSL age of 530 ± 20 is on the small ridge behind the foredune in this location, then the larger frontal foredune must younger than ~500 years old. This is significant as this foredune extends southward and forms the constraint on the entrance of Currambene Creek, which must therefore have shifted southward during this 500 year period.

5.8 A summary of Holocene barrier deposition

This chapter has considered aspects of the morphology, subsurface structure and chronology of the Callala Beach prograded barrier system. This section is a synthesis of the major findings of this chapter bringing together these three data sets to form a cohesive and insightful picture of the Holocene deposition of the Callala Beach barrier.

The Callala Beach barrier has prograded at a relatively constant rate over the late Holocene from ~7500 years ago to present. This pattern of progradation equates to a rate of shoreline seaward movement of 0.1 m/yr and the ridges in the sequence have an average lifetime of 390 years. Combining the OSL ages for this barrier with the LiDAR data the general morphology of the barrier sequence and ridge heights and dimensions have been characterised through time. In addition the calculation of volumes of aeolian sediment accumulated on the barrier over the Holocene was calculated by dividing the barrier into a series of segments corresponding to the OSL age estimates. This reveals a linear trend of aeolian sediment accumulation at an average rate of 0.13 m³/m/yr. Such a
value is informative for current management of the barrier, which has undergone some significant erosion in recent times.

The GPR data has accurately characterised the subsurface stratigraphy of the Callala Beach barrier and shed light on the mode of progradation over the Holocene. The barrier has prograded over time with a complex series of cut and recovery events where an overall positive sediment budget results in the preservation of some storm beachfaces in the sedimentary record. The large foredune at this site is seen to be a feature that formed in the last 500 years, and the large complex dune system which forms the southward turn of the Currambene Creek estuary system has also developed in the last 500 years.

In broader terms this prograded barrier presents an interesting conundrum in terms of understanding the dominant drivers of progradation in coastal system in Australia. An offshore profile taken from Callala Beach out between the headlands to the continental shelf, is shallower than any others measured by (Thom et al. 1981b). However, while it is known that a shallowing of offshore profile would encourage progradation (Davies 1957), there is no evidence of rapid progradation at a rate exceeding the other sites in this study. Further comparison of progradation rates between sites examined in this study is found in Chapter 6: Discussion below.
6.1 Introduction

This chapter will bring together results from each study site and address issues relating to the Holocene deposition of prograded barriers on the southeast Australian coastline. A series of site comparisons demonstrate that progradation over the Holocene is primarily a function of local factors as no single variable or boundary condition appears to drive progradation. Consideration has been given to a possible ridge formation mechanism common to all sites, the anomalous presence of a high foredune fronting each of these barriers, and the potential of the GPR collected at each site to provide insight into Holocene sea-level change. A discussion of the applicability of OSL dating, GPR and LiDAR data for examining Holocene barrier deposition, and the potential expansion of these methods is given.

6.2 Site comparisons

6.2.1 Introduction

The purpose of this section is to provide some insight and raise further questions about what may be driving progradation in these embayments. Prograded barriers have only formed on the NSW coast in antecedent bedrock compartments of sufficient dimensions to capture sediment available on the inner shelf. However, the primary driver of sand being worked onshore and actively incorporated in ridge building is not well understood. Is a shallow offshore profile important, as had been suggested by Davies (1957) and considered in shoreface behaviour models (Cowell et al. 2003b)? How critical are embayment characteristics such as orientation and degree of enclosure? How is sediment availability related to progradation and how might this be reflected in barrier morphology? Some comments on these questions are given below based on an examination of the evidence presented in this study.

6.2.2 Commencement ages

Examining the OSL ages taken from the most landward ridge in the sequence at Moruya, Wonboyn and Callala Beach, a close alignment is evident (Figure 6.1A, B). Each of these ages overlap at the 1 sigma error level with the most recent determination of the Holocene sea-level curve for this coastline, where sea level reached its present height between 7500 and 8000 cal. yr BP (Lewis et al. 2013) (Figure 6.1B). As well as coinciding with this 500 year time period reported by Lewis et al. (2013), the ages with
their associated errors also all overlap with one another. As the ages seen in Figure 6.1B are from the most landward at each site, these OSL ages constrain the commencement age for seaward ridge building at these sites.

Figure 6.1: (A) Comparison of the oldest and youngest OSL ages from the relict ridges at each site. (B) Comparison of the oldest OSL age for each site with a grey shaded band corresponding to the time period at which sea-level attained its present height according to Lewis et al. (2013). (C) Comparison of the youngest OSL age from the relict ridges for each site, with a grey shaded band which corresponds to the total time period covered by the three ages and their associated errors.

6.2.3 Ages behind the foredune

At each site a sample was taken immediately behind the larger foredune evident in the LiDAR and in field reconnaissance. This serves as an additional point for cross-site comparison. The samples from just landward of the foredune form a 220 year ‘zone’, when compared with one another and considering their respective error margins (Figure 6.1C). This zone spans from 550 – 330 years ago. The Moruya and Wonboyn ages overlap at the 1 sigma error and there is a 10 year difference between the error bars of the Wonboyn and Callala Beach ages (Figure 6.1C). The significance of such a zone is apparent considering the obvious differences in general embayment characteristics and demonstrates that progradation at all three sites has continued until this time. It is also a constraint on the timing of the formation of the larger frontal foredune on these barriers and raises the problem of why these foredunes exist and how they formed. It is tentatively suggested here that some boundary condition change is the most logical explanation, for otherwise it is a startling coincidence that all three of these barriers,
covering a wide stretch of coastline, and having formed in very different embayments, and with very different barrier morphologies, should produce large foredunes in the last ~300 years. This point is elaborated on in section 6.4 below.

6.2.4 Progradation rates

The significance of progradation rates and ways of expressing progradation is considered in order to better understand the similarities and differences between Moruya, Wonboyn and Callala Beach. Progradation rate has often been plotted in terms of age versus barrier width with rate expressed in metres per year (Brooke et al. 2008 a,b; Goodwin et al. 2006: Murray-Wallace et al. 2002). In Thom et al. (1981a), between-site comparisons were presented using a dimensionless barrier width; with values 0 through to 1 where 0.4 refers to 40% of the barrier prograded (distance to age divided by total barrier width multiplied by 100). Such a measure of progradation rate is a convenient way of illustrating variation in pattern of progradation between sites and has been completed for the three sites in this study (Figure 6.2).

From Figure 6.3 it can be seen that Callala Beach has the slowest progradation rate as the ridge sequence builds seawards just over 600 m over ~7500 years compared with Wonboyn and Moruya which have prograded a distance of ~1600 and ~1900 metres respectively. The linear regression functions for each site have high $R^2$ values. Apart from the Wonboyn data set, which has two different rates, single linear regression lines are fitted for each site.

Figure 6.2: Age according to the OSL dates in years plotted against standardised (dimensionless) barrier width for Moruya, Wonboyn and Callala Beach.
However, the issue with expressing progradation rate as time versus dimensionless width is that it does not show the difference in barrier width between sites, which is critical when discussing a m/yr progradation rate or expressing an average ridge formation time. Figure 6.3 plots the OSL ages for each site against distance from the shore in metres. This better illustrates the individual site characteristics.

Figure 6.3: Age according to the OSL dates in years plotted against distance of each sample from the shoreline in metres for Moruya, Wonboyn and Callala Beach.

A contrast between progradation rate plotted using barrier width and cumulative aeolian volume shows different patterns of Holocene deposition. It appears from the barrier-width method, that Wonboyn has a faster overall rate of progradation, but aeolian sedimentation rates are calculated, Moruya in fact has a greater average aeolian sediment accumulation rate in m$^3$/yr due to its longer and wider embayment. Figure 6.4 shows that three different trajectories of aeolian sediment accumulation on each of the barriers commences around 5000 years ago. Before this time there may be a period of slower accumulation for Moruya and Wonboyn. Callala Beach appears to maintain a consistent rate for its entire depositional history. An initially slower rate for Wonboyn was noted as a possibility in chapter 4.
The aeolian volumes reported in this study, as they do not account for sediment accumulation below 3 m AHD, are not indicative of total barrier volume. Only at Moruya, where more detailed stratigraphic and shoreface data was available, were barrier volumes for the central portion of the barrier determined from a series of isochrones with interpreted palaeobeachface geometry. This exercise indicated a linear pattern of sedimentation over the Holocene with better agreement between the OSL ages from the upper portion of the ridges and radiocarbon ages from the shoreface facies. However, as this exercise only considered a two dimensional slice of the barrier, this result cannot be applied with certainty alongshore to the north and south where Thom et al. (1981b) show substantial variation both stratigraphic relationships and radiocarbon chronology. Modelling after Kinsela et al. (2016) would be of great benefit for the central profile and would likely further constrain the volumes of Holocene progradation.

The calculation of aeolian sediment volumes throughout the Holocene includes the assumption that MSL has not changed throughout the progradation history of each
barrier. A higher late Holocene sea level along the southeast Australian coast is still a matter of debate (Lewis et al. 2013). An allowance for a late Holocene sea-level high stand and fall to present was not incorporated into the volume calculations in this study, as the timing of the fall and nature of such a sea-level curve is one of the things about which there is disagreement (Sloss et al. 2007). An allowance for sea-level change would have added uncertainty to the volume calculations.

6.2.5 Progradation rate comparisons with other studies

A comparison of progradation rates reported in this study with those reported for other studies shows that Moruya, Wonboyn and Callala Beach are somewhat slower than other sites (Table 6.1).

Table 6.1: A list of other coastal sand ridge plains with OSL chronologies and their respective reported progradation rates.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Age Range (yr BP) (oldest – youngest)</th>
<th>Progradation rate (m/yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beachmere</td>
<td>1700 ± 130 – 140 ± 50</td>
<td>0.32</td>
<td>(Brooke et al., 2008a)</td>
</tr>
<tr>
<td>Keppel Bay</td>
<td>1575 ± 130 - &lt;60</td>
<td>1.20</td>
<td>(Brooke et al., 2008b)</td>
</tr>
<tr>
<td>Cowley Beach</td>
<td>5760 ± 400 – 200 ± 10</td>
<td>0.40</td>
<td>(Nott et al., 2009)</td>
</tr>
<tr>
<td>Guichen Bay</td>
<td>5400 ± 230 – 51 ± 5</td>
<td>0.41</td>
<td>(Murray-Wallace et al., 2002)</td>
</tr>
<tr>
<td>Rockingham Bay</td>
<td>5010 ± 240 – 10 ± 20</td>
<td>0.33</td>
<td>(Forsyth et al., 2010)</td>
</tr>
<tr>
<td>Woody Bay</td>
<td>1690 ± 200 – 230 ± 50</td>
<td>0.28</td>
<td>(Goodwin et al., 2006)</td>
</tr>
<tr>
<td>Wonga Beach (North)</td>
<td>4550 ± 250 – 40 ± 10</td>
<td>0.23</td>
<td>(Forsyth et al., 2012)</td>
</tr>
<tr>
<td>Wonga Beach (South)</td>
<td>2110 ± 120 – 80 ± 10</td>
<td>0.19</td>
<td>(Forsyth et al., 2012)</td>
</tr>
</tbody>
</table>

At Guichen Bay, Bristow and Pucillo (2006) used GPR to determine the thickness of the beachface and dunes over 3 distinct ridge sets, and using aerial photography to determine area, calculated sediment accumulation of the barrier in m$^3$/yr for these ridge sets using the OSL chronology of Murray-Wallace et al. (2002). Since the lower limit of the shoreface imaged by Bristow and Pucillo (2006) was within 1 m of MSL, and the approach taken here using LiDAR combined with the OSL age estimates gives volumes above MSL, a comparison may be undertaken.

For three of the Guichen Bay ridge sets, sediment accumulation was between 40,000 and 50,000 m$^3$/yr. These volumes are significantly greater than those of Moruya, Wonboyn and Callala Beach (see Table 6.2) and reveal a substantial difference in overall sediment supply regime. Carbonate production in this environment is likely to
be a cause of such larger volumes of sediment accumulation on this coastline. There is little or no carbonate production on the continental shelf off the NSW coast (Short 2000). Although Bristow and Pucillo (2006) do not report a volume in m$^3$/m/yr, a calculation reveals values of 3.5, 6.3 and 3.7 m$^3$/m/yr for their ridge sets 3, 4 and 5 respectively; see Table 2 in Bristow and Pucillo (2006). Thus the length of the Guichen Bay embayment, which is up to 12 km long, moderates the larger volumes to a degree by spreading them over a longer beach.

Table 6.2: A selection of comparative data for Moruya, Wonboyn and Callala Beach. The potentially slower ‘phase’ of progradation at Wonboyn has not been included in this summary as it requires further dating.

<table>
<thead>
<tr>
<th>Site</th>
<th>Progradation rate in (m/yr)</th>
<th>Aeolian accumulation (m$^3$/yr)</th>
<th>Average ridge lifetime (yrs)</th>
<th>Offshore depth at 1 km (m)</th>
<th>Degree of embaymentisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moruya</td>
<td>0.3</td>
<td>3600</td>
<td>110</td>
<td>-24</td>
<td>Not embayed</td>
</tr>
<tr>
<td>Wonboyn</td>
<td>0.3</td>
<td>1760</td>
<td>130</td>
<td>-15</td>
<td>Semi-embayed</td>
</tr>
<tr>
<td>Callala Beach</td>
<td>0.1</td>
<td>650</td>
<td>390</td>
<td>-12</td>
<td>Deeply embayed</td>
</tr>
</tbody>
</table>

6.2.6 Offshore profiles

There is a substantial difference in the nature of the offshore profiles for each of the three sites Moruya, Wonboyn and Callala Beach (Figure 6.5). The difference in offshore depth between sites is apparent after just 1 km seawards of the shoreline position.
Figure 6.5: (top) Shore normal offshore profiles for Moruya, Wonboyn and Callala Beach. Moruya and Wonboyn are taken from Thom et al. (1981b). Callala Beach offshore profile is extracted from bathymetry of Jervis Bay courtesy of Geoscience Australia. (bottom) Air photos of Callala Beach, Wonboyn and Moruya showing the degree of embaymentisation for each coastal sand ridge plain.

The difference in these offshore profiles is related to the degree of embaymentisation (Short 1996) of each site and this in turn results in variation in wave exposure and nearshore wave propagation. Callala Beach, which is deeply embayed, being inside
Jervis Bay, has the shallowest offshore profile, Wonboyn, which is semi-embayed, has the next shallowest offshore profile and Moruya, which is not embayed, has the least shallow offshore profile (Figure 6.5). It is noteworthy that Moruya and Wonboyn, which have only a moderately shallow offshore profiles, have the fastest progradation rates, and Callala Beach, which has the slowest progradation rate has the shallowest offshore profile. It appears from this summary data that progradation rate is not directly related to offshore depth or degree of embaymentisation.

6.2.7 Drivers of progradation

The summary data presented in Table 6.2 illustrates the apparent conundrum when comparing these data sets. Moruya, with the deepest offshore profile and the least degree of embaymentisation, has the fastest progradation rate in m/yr, the shortest ridge lifetime and the highest rate of sediment accumulation. Callala Beach which has a very shallow offshore profile, and thus would be expected to have a rapid progradation rate, in fact has the slowest progradation rate and the longest ridge lifetime.

It is noteworthy that in Figure 6.3, despite Callala Beach only being around 600 m in width compared to Wonboyn at 1600 m and Moruya at 1900 m, the progradation commencement age, and the age behind the foredune, are remarkably similar (see also Figure 6.1). This comparison poses the question: why, if Callala Beach barrier is less than half the width of Wonboyn and Moruya, did progradation continue until around the same time as the other two barriers? Why was its rate so much slower? This comparison requires either a sediment supply difference or a difference in accommodation space. If there is a sediment supply difference, it is significant that the offshore profile at Callala Beach is the shallowest of all three sites in Figure 6.5. A shallow offshore profile recently referred to as an ‘overfit’ shelf has been invoked as a key driver of progradation over the Holocene through the adjustment of the shoreface to mean wave climate (Cowell et al. 2003; Davies 1957).

It appears that Callala Beach and Jervis Bay more generally, despite having an extremely shallow offshore profile in comparison to Moruya and Wonboyn, still has a low sediment supply. Callala Beach is deeply embayed inside Jervis Bay and this bay appears not to have trapped sediment moving northward on the shelf over the late Holocene (Roy 1999). The white sands of Jervis Bay suggest this large Bay is a distinct sediment province. The major sediment trap in this region is Bherwerre Barrier to the
south. Taylor (1971), while noting that sediment thickness in Jervis Bay is up to 30 m, also stated that “no sediment is entering the bay from the shelf under present conditions” (Taylor 1971 p.304).

Another interesting site comparison of note is the initially slow rate of progradation at Wonboyn from ~7500 years to ~4500 years implied by both the radiocarbon and OSL chronologies. Over this ~3000 year period progradation rate was at a rate of ~0.1 m/yr and average ridge lifetime was 410 years. This is similar to the average rate of the entire Callala barrier sequence. Such a slow initial rate contrasts with Moruya where progradation beginning at the same time (~7500 years ago) proceeded at 0.3 m/yr with an average ridge lifetime of 110 years. Both embayments are substantial traps for sediment moving along the shelf during this early phase of progradation. An untested explanation proposed here is that, judging by the topography of the surrounding bedrock at Wonboyn, the embayment is much deeper, and thus in the early phase of progradation vertical rather horizontal filling of the embayment was taking place. Then, once the embayment had filled to a certain degree, progradation increased and continued at a faster rate comparable to Moruya for the remainder of the Holocene. Such an explanation requires additional deeper cores from the Wonboyn barrier.

Moruya has the largest aeolian volumetric accumulation rate of all sites, which is significant considering it is the least embayed and hence the least likely to trap northward moving sediment from the shelf. However, a relative abundance of sediment available for barrier progradation, compared to Wonboyn and Callala Beach, may have existed locally on the shelf in this region. Roy et al. (1994) proposed that material deposited in the Holocene barrier is derived from the reworking of offshore sand reserves on the continental shelf. Therefore, comparing the sediment accumulation rates of Moruya, Wonboyn and Callala Beach would suggest that greater sediment reserves were present on the continental shelf near the Moruya barrier. An assessment of the current volume of shelf sediment in this region would likely inform whether the Moruya barrier will continue to prograde in the future. In conjunction with shelf sediment bodies, assessments of wave climate changes (Mortlock & Goodwin 2015) and the prevalence of onshore or alongshore sediment transport would help to understand how material available on the shelf may be incorporated in the barrier stratigraphy (Daley 2012).
The subaerial component of barrier deposition has not been considered by recent studies of Holocene barrier evolution in NSW (Daley 2012; Kinsela 2014). It has been proposed that progradation of Holocene barriers has been driven by disequilibrium shoreface profiles which have adjusted over the mid-late Holocene to the variable wave climate (Mortlock & Goodwin 2015) which actively drives nearshore sand supply. However, these studies have not examined the shoreline response and volumes of sediment trapped in the shore-parallel ridges of these coastal plains. The radiocarbon ages from shoreface sediments below MSL in the barrier stratigraphy are of great value in modelling shoreface response through the late Holocene, yet understanding rate of shoreline seaward movement requires a chronology from the upper portion of the barrier stratigraphy. Therefore OSL ages which help to constrain this shoreline movement enable testing of shoreline sensitivity to shoreface response through the mid-late Holocene.

This point is reinforced in recent work by Kinsela et al. (2016) where they demonstrate that modelled shoreface response to a disequilibrium profile may produce a situation where, despite a decreasing rate of overall volumetric progradation, shoreline progradation rate remains uniform due to shoreface steepening causing a reduction in upper shoreface accommodation space. Thus a uniform subaerial rate of progradation (both according to shoreline position and subaerial barrier volume) at Moruya deduced from the OSL dating of this study is an important insight into Holocene barrier evolution and may be reconcilable with the radiocarbon dating from the shoreface. Therefore Moruya is the ideal location for testing of shoreface modelling similar to Kinsela et al. (2016) because both the shoreface and shoreline progradation is chronologically constrained.

Bishop and Cowell (1997) noted that the degree to which Cainozoic drainage networks are ‘filled’ when the sea rose to present height, determines embayment size and the accommodation space available for sediment deposition and shoreline progradation. Embayments formed in areas of high stream order, that is where multiple streams join, generally create larger embayments which capture more sediment (Bishop & Cowell 1997). The sea level in the Moruya embayment has infilled to a degree whereby a higher order Last Glacial Maximum (LGM) stream network exists at the present coastline unlike Wonboyn or Callala Beach where there seems to be lower order LGM stream networks at the present coastline. Evidence from the coring at Moruya by Thom
et al. (1981b), which reaches bedrock topography, also suggests that the Moruya barrier is emplaced over a confluence of LGM river networks where the current Moruya River was joined by a stream flowing north to south. As well as providing sufficient accommodation space for progradation, it is possible that the region of the continental shelf near to Moruya would have inherited a substantial amount of sediment from an extensive LGM drainage system.

The difference in ridge lifetime between these three sites is inferred as also related to differences in accommodation space and sediment supply. Despite a similarity of commencement ages and ages immediately behind the foredune, Moruya has a slightly shorter average ridge lifetime than Wonboyn and these two sites have in turn much shorter ridge lifetimes than Callala Beach. The average ridge lifetimes are reinforced by examining specific intervals between individual OSL ages. At Moruya, two OSL ages separated by one distinct ridge are not statistically separable (ridge lifetime 110 years), while at Wonboyn, two OSL ages separated by one distinct ridge are statistically separable (lifetime 130 years). Furthermore at Callala, two OSL ages on successive ridges are statistically separable (ridge lifetime 390 years). Thus the difference in whether two ages located geographically proximal on a ridge sequence are statistically separable, is reflected in average ridge lifetime.

As the most landward and most seaward OSL ages for these three prograded barriers are very similar, an explanation is required to explain why, having such similar bounding ages, these sites should be so different in terms of progradation speed and volume. It appears that eustatic sea level rising to present levels has dictated the position of the coastline with respect to the antecedent topography of the eastern Australian continental margin. The character of the antecedent topography itself resulting in embayments of varying dimensions, the magnitude of offshore sand reserves and modal Holocene wave climate has dictated the speed and degree of coastal progradation.
6.3 Ridge formation mechanism

The subsurface structures imaged by the GPR system at the three prograded barrier deposits examined in this study are insightful as regards the mode and process of ridge creation. The general character of these subsurface structures corresponds well with the model of ridge formation proposed by Bird (1976) (see Figure 1.6). In general, each GPR profile collected in this study has a series of seaward dipping reflectors which typify the geometry of a storm beach profile at each of the sites. In some instances reflectors indicating the recovery from a storm event are apparent which are coincident with a storm beachface reflector. The process of storm cut and recovery in building an incipient ridge was presented by McLean and Shen (2006) and further discussed in Tamura (2012). In the profile time series in Figure 8B of Tamura (2012) following the 1974 storm event a large berm is built, which subsequently forms a small incipient ridge. This ridge stabilises and accumulates shifting landwards by about 10 m and continues to develop (McLean & Shen 2006). More recent profile data has been collected at Moruya, capturing the 2007 storm event (McLean et al. 2010), however there is no published profile data to investigate the impact of this event on the present day beach. Despite this, it is proposed here that the primary mode of ridge formation at Moruya follows the observed succession of changes in the profile data of Moruya (McLean & Shen 2006) which broadly reflects the Bird (1976) model. While the whole 110 year ‘lifetime’ of a ridge has not been observed, the process of the incipient ridge formation observed on the current beach at Moruya becoming a relict ridge feature and a permanent part of the barrier is one of continuing vertical accretion and stabilisation. Wonboyn and Callala Beach appear to have similar subsurface characteristics in the GPR data, and while there is no published profile data available for verification, a similar process of ridge formation is envisaged.

While the processes of cut and recovery seemingly result in an incipient ridge morphology, it is only a positive sediment budget which results in a sequence of coastal sand ridges. Cut and recovery processes have been documented on many other beaches e.g. Narabeen Beach, NSW (Karunarathna et al. 2014; Short and Trembanis 2004), where only a few ridges are evident. The key factor required for a prograded system is an ongoing supply of sediment available to be worked onshore. Only then will successive storm cut and recovery form a series of low relief, shore parallel sand ridges.
6.4 The foredune conundrum

This section seeks to integrate the findings from Moruya, Wonboyn and Callala regarding the higher foredune present in the frontal portions of each of these barriers. This foredune, present on all three barriers examined by this study, poses a conundrum in understanding the recent changes to the dominant morphology of each of these barriers. An OSL age estimate immediately behind the foredune at each site constrains their formation to within the last ~300-500 years. At Moruya an OSL age of 180 ± 15 came from with 1 m of the foredune surface near the northern edge of the Moruya airport. It is worth noting in relation to the OSL ages in general that the depth of overburden significantly changes the cosmic radiation dose for a given sample. While all samples collected in this study were from a depth of between 70-100 cm, for a certain period of time, perhaps up to ~100 years considering the average ridge lifetime, the depth of overburden may have been significantly less than 70 cm. In this case a marginally higher dose of cosmic radiation would have been given to these samples over this 100 year period in the order or 0.001-0.005 Gy/ka. In the case of the youngest OSL samples dated in this study, the effect even of increasing the cosmic radiation contribution by this amount for the entire depositional period only lowers the age by around 5 years. For the older samples, a similar allowance lowers the age by 50-100 years and well within the error margins of the original age. Thus burial history is an important consideration for very young samples (less than 200 years old) as the contribution of cosmic radiation to the total dose rate is significant and its potential variability during burial history should be carefully considered in determining an age.

The morphology of the foredune at each site follows that of the older ridges with an increase in height northward to a maximum at around three quarters of the length of the beach after which a drop in height to the north end occurs. However, the morphology of the foredune at each site is different to the older ridges as it is substantially higher, wider and commonly has a lobed landward margin indicative of cascading of material burying existing ridge topography. In the GPR imaged subsurface structure of the Moruya foredune, the only GPR transect covering an undisturbed portion of these foredunes, the cascading of material downslope in successive events may be clearly identified. It is likely that a similar subsurface structure pattern would be evident in a GPR transect over an undisturbed section of the foredunes at Wonboyn and Callala.
Beach. Additional collection of GPR data at such locations should be a priority for future research at these sites.

Models explaining the formation of such foredunes fronting prograded barriers, which are found at many other sites in southeastern Australia, have been proposed, which involve the burying of pre-existing ridges with aeolian material (Bird 1976; Davies 1957; Shepherd 1987) (see Figure 3.23). The most significant problem in applying these models to the foredune evident at Moruya and Wonboyn is that an erosional trend is not currently evident at these sites. Callala Beach is an exception to this as ongoing erosional problems have led to beach nourishment in this embayment by the local council. However, at Moruya and Wonboyn, and especially in the northern half of these two barriers, where incidentally the foredune is highest, significant vegetated and seemingly stable ridges have formed. While they may still be called incipient ridges, the LiDAR data suggests that the elevation of such features is not far below the elevation of older ridges in the sequence. As Tamura (2012) demonstrates from the beach profiling data at Bengello Beach (Moruya), a storm event of equivalent magnitude to that in 1974 (McLean & Shen 2006), would not erode the beach to the same position as that original storm indicating a net positive sediment budget. Therefore the presence of the high foredune at both Moruya and Wonboyn is significant as the evidence at present suggests that neither of these barriers is in an erosional phase. The most plausible explanation for the foredune considering all the evidence involves a discrete change in storminess and wave climate as suggested by Goodwin et al. (2015) Further characterisation of the morphology and stratigraphy of this foredune, as well as OSL dating, would be beneficial in understanding the significance of its emplacement in these embayments.
6.5 Sea level change detection

Using swash zone facies as indicators of late Holocene sea level change has been attempted in several papers in recent years (Searle & Woods 1986; Semeniuk 1985, 1996). GPR images of subsurface structure which capture such swash zone facies allowed Holocene sea-level reconstruction in New Zealand (Dougherty 2009). In a recent thesis focused on the Moruya prograded barrier, some attempt was made to describe and correlate swash zone facies and heavy mineral layers to present sea level with GPR and hand auger ground truthing, which indicated a high stand of ~1.5 m during the late Holocene (Rae 2011). However, this work was only concerned with the seaward half of the barrier east of George Bass Drive (see Figure 3.1) (Rae 2011).

At Moruya, the GPR data presented in this study, which covers the entire barrier width, does not appear to show a distinct change in the elevation of the beachface reflectors which may indicate a late Holocene high stand and subsequent fall to present. A similarly continuous pattern of elevation for the beachface reflectors is evident from Wonboyn and Callala, however it is noted that at these locations, the GPR data only covers around half to two thirds of the total barrier width.

It is here proposed that while using swash zone facies as sea-level indicators has potential (Searle & Woods 1986; Semeniuk 1985, 1996), there are a number of issues which have not been satisfactorily addressed in our understanding of the relationship of swash zone facies, and especially GPR imaged swash zone reflectors to sea-level. The primary reason for such concerns, as regards this study, is the complexity of the modern day beach profiling record (McLean & Shen 2006) and its relationship to the GPR data. As illustrated by Tamura (2012), even a selection of the profiles from a series of years presents a complex pattern of beachface geometries and swash zone elevations. How a given profile relates to sea level, that is, where the profile intersects with sea level changes both laterally and vertically over time. The top of storm beach faces, which has been used as the most clearly identifiable marker for sea level (Dougherty 2009), is variable alongshore (McLean & Shen 2006) and its elevation is also likely to change in relation to storm run-up and hence storm intensity. These factors would imply the need for a cautious approach to interpreting sea-level changes from GPR imaged beachfaces.
6.6 The relevance of ridge morphometrics

The differences in height for ridge crests and inter-ridge swales observed at all sites is here primarily attributed to corresponding changes in the thickness of the aeolian decoration/ capping. However, there may also be a change in the height of swash built facies alongshore due to differences in beach state, and hence run-up, within an embayment. Further GPR and hand auguring of ridges at each site is required to determine the exact proportion of aeolian material on given ridge and how this may change alongshore, as well as to what degree changes in ridge height in a shore normal direction are a function of changing aeolian capping on successive ridges.

Wright et al. (1979) observed that beach states 2 to 5 were common at any given time along Bengello Beach (Moruya), with a general tendency for the northern end of the beach to be more dissipative in character compared to the southern end. It is here hypothesised that this generally flatter and more dissipative beach profile in the northern portion of Moruya beach is likely to result in higher aeolian transport potential (Short & Hesp 1982) and hence in greater aeolian capping on each ridge, which is in turn reflected in the ridge height trends alongshore.

Where this same trend in ridge height occurs alongshore at Wonboyn and Callala Beach, a similar mechanism is here proposed, whereby the change toward a flatter beach profile in the north of embayments promotes increased dune activity. This author observed, during data collection at Wonboyn, that a similar pattern of beach state change from north to south exists. At Callala Beach, the fall in height from the maximum around three quarters of the way along the barrier from south to north is far more substantial than at Wonboyn or Moruya. Preliminary hand auguring associated with GPR antenna testing at this northern end of Callala Beach suggests that there is minimal aeolian material at this northern end of the Callala Beach barrier. This author observed that at this northern corner of Callala Beach the beach state was at the reflective end of the beach state classification scheme (Wright & Short 1983).

Changes in ridge height, swale height and ridge-inter-ridge amplitude for shore normal transects were also observed at Moruya, Wonboyn and Callala Beach. Such changes are not well understood, in terms of whether they also reflect changes in the thickness of aeolian material capping each ridge. Understanding the cause of such elevation changes in a barrier sequence is highly relevant to current coastal management issues. It is
commonly seen that erosion occurring on beaches on the southeastern coast of Australia is localised to one section of the embayment. Understanding the processes underpinning distribution of aeolian and also swash deposited material within an embayment would directly inform management solutions to current problems of erosion. Prograded barrier deposits are therefore a repository of historical sediment movements, and especially dune activity, within an embayment. LiDAR elevation data along with GPR and sedimentological analysis provides the unique opportunity to further investigate these barrier deposits.

6.7 Future research

6.7.1 OSL dating

The dating results from this study demonstrate the applicability of the OSL technique for coastal environments in southeastern Australia and especially for deposits less than ~2000 years old as OSL error margins are smaller. It is noted that there is only one transect of OSL ages at each site to constrain the emplacement of the ridge sequences over the Holocene. These transects have been positioned on each of the barriers in this study at their widest point in order to capture the most complete record of coastal progradation. However, additional OSL dating of ridges at other locations, both north and south of these central dating transects, would further constrain the deposition of the ridges and increase the validity of progradation rate (both width and volume) estimates. At Callala Beach, dating of the foredune and other recent processes on the barrier should be considered a priority for future work at this site, as determination of the timing of recent morphologic changes is relevant to coastal managers concerned about future erosion at this site.

At Wonboyn, OSL ages for the ridges in the northern portion of the barrier would provide a comparative chronological dataset for this embayment and likely help to understand the influence of differing accommodation space as a control on Holocene progradation. Additional OSL dating alongshore at Moruya, would provide an insightful comparative dataset for the radiocarbon ages collected along the northern and southern dating transects by Thom et al. (1981b) as there was substantial variation in the pattern of progradation in the radiocarbon dataset alongshore (Roy et al. 1994).
No samples for OSL dating from depths of greater than 1 m were collected in this study. This approach of shallow sampling of the ridges has been proven successful on many other prograded barrier deposits in Australia (Brooke et al. 2008a,b; Forsyth et al. 2010; Goodwin et al. 2006; Murray-Wallace et al. 2002; Nott et al. 2009). Nevertheless samples from deeper within each ridge would provide an indication of vertical accumulation rates of individual ridges. In addition, OSL ages from depths equivalent to the radiocarbon ages at Moruya, would aid in determining whether the radiocarbon ages accurately constrain the emplacement of lower shoreface sand, distinct from the sequence of ridge development defined by the OSL ages.

Only two samples (both from Wonboyn) from all 28 samples dated in this study required additional measurement and analysis. One of these was from the northern foredune at Wonboyn which had a higher overdispersion than was acceptable which was resolved with additional equivalent dose measurements. The other sample also from Wonboyn in the southern OSL dating transect, which was also re-measured, was unable to be resolved and no age was able to be given for this sample. While this means a significant ‘gap’ in the chronological record exists at Wonboyn, it should be noted that, as the radiocarbon and OSL ages are similar across this barrier, the overall confidence in the Holocene chronology is not compromised.

Water contents for all OSL samples analysed in this study were assumed to be 5% ± 2.5%. While field water contents were measured for each sample, an assumed water content value was adopted due to the uncertainty of whether the measured water content for each sample is representative of its water content for the duration of its burial history. This decision was taken due to the variability of rainfall at each site during sample collection and also because, over longer time scales, each samples proximity to the ocean has changed as the barrier has prograded. The changes resulting from using this assumed water content value of 5% ± 2.5%, rather than measured water contents, did not alter the linear trends of barrier growth over the Holocene.

6.7.2 GPR collection

The GPR equipment used in this study successfully characterised the subsurface structures of each of the prograded barriers examined in this study. The penetration of the 250 MHz antenna used at all sites is of a range expected for this frequency. Subsurface structures were commonly imaged to depths of around 6 m. As the general
elevation of the prograded barriers examined in this study is around 6-7 m AHD the GPR data collected relates to processes occurring above ~0 AHD. While additional shore normal transects north and south at each barrier would be beneficial, further collection of GPR data is somewhat impeded by the lack of appropriate transect locations.

Other antenna frequencies such as a 100 MHz were tested during reconnaissance fieldwork at Seven Mile Beach and little success was had in characterising deeper facies units and subsurface structures. Further testing of this antenna and alternative data processing would likely resolve some of these ringing issues. Collection of data with this antenna would be beneficial for future investigations at each site as imaging beachfaces to depths of 10-12 m could advance our understanding of possible changes in offshore profile geometry which has implications for sediment availability in the offshore due to varying closure depth. Long-term coastal behavior modeling for Moruya (Daley & Cowell 2012; Kinsela 2014) would benefit from a Holocene shoreface data set, which could be used for model training and validation.

6.7.3 LiDAR

LiDAR data for each site examined in this study characterised the morphology of the barrier capturing the height and dimension of the ridges in the sequence as well as larger scale geomorphic information. This is a significant advancement of our understanding of these systems, considering that these barriers are consistently well vegetated meaning that ridge alignment is not easily determined form aerial photography. In addition, shore normal profiles of ridge heights are easily generated at any given point along the barrier, whereas prior to such data being available, information regarding ridge height, spacing and amplitude was only possible with field surveys.

The vertical and horizontal resolution of the raw LiDAR point data is ± 0.3 m and ± 0.8 m respectively, which is far less precise than that of an RTK GPS system. However, it is here regarded as of sufficient precision to successfully describe and measure aspects of the barrier morphology as well as being a powerful visualisation tool. LiDAR data enabled the calculation of volumes of progradation as well as the volume and height of the foredune at each site. The vertical and horizontal LiDAR point data uncertainty stated above was incorporated into error margins on the volume and height calculations at each site.
CHAPTER 7: CONCLUSIONS
The conclusions arising from this study of the Holocene depositional history of Moruya, Wonboyn and Callala Beach coastal sand ridge plains are presented below.

- Researchers investigating coastal barrier deposits around Australia have made a substantial contribution to this field of coastal research globally. Discussions in the late 1950’s and 1960’s concerning the formative processes of coastal sand ridge building have provided an important foundation for continued discussion of these issues in recent decades. The contribution has also included a systematic morphostratigraphic classification scheme of coastal barrier types applicable to a wide variety of settings around the world accompanied by the establishment of a general framework of Holocene coastal evolution. In addition, Guichen Bay, South Australia, was the first site at which the radiocarbon and OSL dating techniques for a prograded barrier were compared. Such a comparison, and the comparisons presented in this study, have implications for the interpretation of other sites with radiocarbon chronologies. This study sought to build on the foundation of research into Australian prograded barriers, and make a contribution to this current body of knowledge, through the use of OSL dating, GPR and LiDAR.

- The quartz grain samples for OSL dating had good luminescence qualities characteristic of Australian quartz. The OSL methodology dating the aeolian sands capping a series of ridges at each site enabled the construction of a chronology of ridge deposition over the Holocene. The suitability of OSL dating for younger coastal deposits is demonstrated. Overdispersion values for samples analysed were generally less than 20% and commonly less than 10%. The overall 1 sigma errors varied from ~300 years on samples 6000-7000 years old and between 20-100 years for samples between 500-2000 years ago.

- GPR data along shore normal transects characterised the subsurface structures for each of the barriers investigated in this study. The 250 MHz antenna proved to be the best frequency of antenna as it balanced penetration depth and data detail and imaged a successive series of seaward dipping beachface reflectors with penetration down to MSL. The GPR data collected has also captured more recent processes, such as foredune development, occurring on these barriers.

- LiDAR data for each site was used to create a DEM of the barrier ground surface enabling visualisation and measurement of various aspects of the
morphology of each site. The LiDAR was able to capture the ground surface in areas where tall vegetation impeded description of the ridge plain with aerial imagery. A range of ridge morphometrics such as ridge height, inter-ridge swale height, ridge amplitude and ridge spacing were measured with the DEM’s produced for each site and these datasets additionally functioned as powerful visualisation tools. Other elements of each embayment were also described using a DEM of ground surface including the character of the antecedent bedrock topography as well as the location of small freshwater swamp outflows which have persisted during Holocene progradation.

- The ridge sequence of the Moruya barrier, according to the OSL ages for the aeolian sediments on 11 of the ~60 ridges along a central shore normal transect, was deposited from ~7000 years to present with a linear pattern of seaward build-out when plotted according to barrier width (ridge lifetime 110 years). The large foredune proximal to the present day beach is shown to be around 180 years old and OSL age of ~40 years came from seaward of the 1978 storm scarp. This sequence of Holocene deposition contrasts with an existing radiocarbon chronology at this site which, for this same central portion of the barrier, showed initially rapid progradation followed by a slower phase of seaward build-out until ~2500 years ago after which time seaward growth was minimal. The difference in these datasets is hypothesised as primarily due to a complex interplay of shoreface and shoreline adjustment over the Holocene.

- There is no evidence for an ‘adjustment phase’ in the pattern of shoreline progradation at Moruya. While the radiocarbon ages at Moruya from the shoreface sands indicate an initially rapid progradation of the shoreface, the OSL ages indicate a consistent pattern of shoreline progradation. Modelling of the shoreface over the Holocene after Kinsela et al. (2016) at Moruya would be of great benefit in understanding the relationship between shoreface and shoreline progradation at Moruya.

- The GPR data along this same central transect at Moruya contains a series of preserved beachfaces at a consistent height range between ~4 m AHD and ~0 m AHD which is a similar elevation to that of storm beachfaces evident on the present day beach according to the beach profiling data (see McLean and Shen 2006). The GPR data supports previous conclusions that each ridge in the sequence at Moruya is a compound feature comprising swash built facies
overlain by aeolian deposited material. GPR data across the modern foredune at Moruya contains a series of landward dipping reflectors dated at 180 ± 15 (not seen anywhere else in the GPR data for this site), which are interpreted as preserving the cascading of aeolian material landwards during the formation of this modern feature of the barrier.

- LiDAR data for the Moruya barrier enabled the description of detailed ridge morphometrics including ridge and inter-ridge swale heights, ridge amplitude and ridge spacing. In general for a series of profiles along the barrier, ridge amplitude increased and ridge spacing narrowed with increasing proximity to the ocean. All ridges in the sequence, including the larger frontal foredune increased in height from south to north to a maximum just north of the outflow of Waldrons Swamp after which there was a decline in height. Such variables preserved in the relict ridges are here considered important in understanding general patterns of sediment movement and localised dune development within an embayment, especially considering the fact that current erosional problems on beaches on the east coast of Australia are often localised to, or more pronounced in, certain areas of a given beach.

- OSL ages for a selection of ridges across the Wonboyn prograded barrier demonstrated that the ridge sequence developed from ~7750 to present. A linear trend of progradation was evident between ~4500 to present when the OSL ages were plotted against barrier width (ridge lifetime 130 years) with a possible slower phase of progradation from ~7750 to ~4500. This OSL chronology is in agreement with the radiocarbon dating previously completed for this barrier, which also implied two phases of progradation at differing rates. However further dating in this landward portion of the barrier is required to confirm that such a pattern is not due to sampling location. The agreement between the radiocarbon and OSL chronology at Wonboyn, in contrast to the significant difference between these two techniques at Moruya, is attributed to sampling depth, as the radiocarbon shell hash samples from Wonboyn were taken almost exclusively from between 0-3 m AHD compared to Moruya where radiocarbon shell hash samples were from between 0m and -20 m AHD.

- GPR data across a shore normal profile covering the seaward half of the ridge sequence at Wonboyn contained a series of seaward dipping reflectors of regular geometry. The geometry of these features suggests they are storm deposits as
they do not represent the fair-weather conditions observed for the beach in this region of the embayment. Stacked convex-up reflectors between 3-4 m AHD were interpreted as showing the accumulation of aeolian material forming incipient foredunes.

- LiDAR data for the Wonboyn barrier captured the ground surface penetrating the tall vegetation covering this barrier. Ridge morphometrics as well as the broader embayment characteristics were also described. A fall in elevation of ridge and inter-ridge swale heights was evident for the seaward 200 m of the southern ridge sequence (~1200 years ago according to the OSL chronology) although there was no discernable change in the elevation of beachface reflectors in the GPR data. A higher foredune near the modern shoreline was evident in almost all profiles (less developed in the southern corner) of the southern portion of the barrier which increased in height and volume northwards. In the northern portion of the barrier a higher foredune is a dominant feature of the morphology and an OSL sample from the crest near the northern end of this foredune gave an age of 70 ± 5 years ago.

- The OSL ages across a selection of the 19 distinct ridges at Callala Beach showed that progradation of this barrier proceeded from ~7400 years ago to present with a linear trend of seaward accumulation. However, with only 19 ridges in the sequence, the rate of seaward accumulation was much slower than at Moruya or Wonboyn and the average ridge ‘lifetime’ was 390 years.

- GPR data collected along a shore normal transect covering most of the barrier width shows a sequence of successive beachface reflectors with strikingly similar geometry. Each profile has a convex-up top at an elevation of 3 m AHD. A change to concave-up geometry occurs at an elevation of 2-2.5 m AHD. This change is interpreted as the interface between aeolian dominated and swash dominated deposition.

- LiDAR data for the Callala Beach barrier captured the ridge sequence in great detail, although urban development of the Callala Beach township has modified the topography of the ridges in the central and northern portion of the barrier. A significant fall in elevation of the ridge crests and inter-ridge swales was evident in all shore-normal topographic profiles across the barrier. However, the fall is far more significant in the northern end of the barrier where the difference in
elevation between the landward portion of the barrier and the seaward portion is around 1.5 m. Further investigation with coring a GPR data collection is required to determine whether this fall in ridge height is a result of a decrease in the height of swash built facies.

- Aeolian barrier volume above (3 m AHD) which forms the ridge topography was calculated for each site with the aid of a DEM derived from LiDAR data. Aeolian volume was shown to increase at a steady rate at an average of ~3600 m$^3$/yr for Moruya, 1760 m$^3$/yr for Wonboyn and 650 m$^3$/yr for Callala Beach.

- The higher foredune evident at each site raises questions regarding recent depositional processes on these three barriers. An OSL age for each site was taken just landwards of the higher foredune in each dating transect and demonstrates that these foredunes have developed in the last 300-400 years. The foredune at Moruya is shown to have developed around 180 years ago as aeolian material has been moved landwards covering existing ridges in the barrier sequence. The morphology of the Wonboyn, and to some degree the Callala Beach foredune, suggests a similar mode of emplacement. Published models of foredune formation on prograded barriers imply that this feature is an erosional morphology where sediment has been deposited landwards in a way not observed for any other ridges in each barrier. However, considering the present beach morphology it does not seem as though the barrier is in a continual erosional state. It appears that a discrete phase of increased aeolian activity has occurred at these three sites possibly linked with changing wave climate and storminess. Understanding the emplacement of this modern foredune requires additional research.

- The oldest ages at each of the three sites in this study are all located on the most landward ridge and correspond to the time at which sea level reached at or close to its present height in southeastern Australia; between 7500 and 8000 years ago. This demonstrates that ridge building began at this time in each embayment and proceeded until present.

- Comparisons of the general embayment characteristics between sites appeared to emphasise the importance of local supplies of sediment as a control on barrier seaward growth rates. There was no particular characteristic of each embayment,
such as offshore depth or degree of embaymentisation, which appeared to correlate with measurements of progradation rate.

- The GPR data appeared to support of a model of ridge formation involving incipient ridge development following storm cut and recovery of the beachface. At Moruya the geometry of a time series of measured beach profiles from the beach monitoring program appears to correspond well with the observed range of reflectors seen in the GPR data and hence a continuity of process is envisaged over the Holocene depositional history of this barrier.

- There did not appear to be any discernable changes in the elevation of the swash built reflectors imaged by the GPR data at any of the sites. The complexity of profile geometry variation evident from the beach profiling at Moruya implies a cautious approach to using GPR imaged beachfaces for sea-level reconstruction where it is not accompanied by detailed ground truthing and sedimentological analysis.
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Appendix A: GPR processing details

DC removal

This processing routine is essentially a filter which corrects for over-saturation of the data and removes the initial DC component and subsequent slowly decaying low-frequency signal noise (Cassidy 2009), which is due to the large “transmit pulse” of the GPR equipment during collection (Neal & Roberts 2000 p.147). One form or another of this processing routine is applied to almost all GPR data collected with a variety of systems and configurations (Neal & Roberts 2000; Neal 2004). For the 250 MHz antenna data, the system default settings, which removes a down-trace averaged signal component within a 65-75 ns window, produced consistently good results. This processing routine was applied to all GPR data collected at all three sites.

Time Zero Adjustment

Time zero adjustment is an important second basic step which involves setting the 0 or ‘first arrival time’ on the y axis (two-way travel time in ns) to the correct position in line with the first reflector which is the ground surface. This process essentially removes the offset created by the air-surface interface. Variations in the arrival time of the transmitted signal reaching the ground surface can produce ‘jitters’ attributed to a range of factors such as thermal drift, electronic instability and variation with respect to the antennas position in relation to the ground (Cassidy 2009). Such ‘jitters’ were not evident in the GPR data collected in for the three sites in this study. However, an overall time zero adjustment of differing degrees was required for all data collected at each site to adjust for antenna air gap (Cassidy 2009).

Trace Edit

The trace edit process allows the selection and removal of traces from any section of GPR profile. This routine was used for dividing up each GPR transect into a series of
200 m sections. This process also allowed the removal of short sections of the GPR transect just the north of the Moruya airport where some right angled zig zag manoeuvres where required to continue in an unobstructed path.

Spatial Interpolation

Spatial interpolation is a processing routine which recalculate the distance between traces based on a specified interval. This process is most useful when a time-triggering data collection method has been applied. As the equipment setup used in this study involved the specification of a trace sampling interval based on distance measured by a wheel, this step was unnecessary.

Background Removal

Background removal is a processing routine that attempts to remove the background instrument noise resulting from components of the GPR system creating their own electromagnetic signal. This noise is essentially a ‘direct wave’: a signal that is received directly from the transmitting antenna. The visual result of this direct wave is a distinct horizontal banding throughout the profile. To remedy this horizontal banding the ‘Background Removal’ process applies a subtraction of the mean trace determined in a horizontal window of a fixed size running along the profile. RadExplorer has the option of running this process with various sized horizontal windows. The smaller the horizontal window specified, the more intense the reduction in horizontal banding. This may be controlled by a slider ranging from ‘strong’ (narrow window), ‘normal’ (medium sized window) and weak (wide window). The danger or drawback of applying this process to GPR data is that some actual horizontal reflectors representing real artefacts in the subsurface may be removed. Therefore a reasonable understanding of the likely character of the subsurface will help in determining a window size. The larger (weak) window size is more likely to preserve actual horizontal reflectors as only reflectors extending beyond the range of the range of the horizontal window are removed.

A ‘normal’ or medium sized horizontal window was used for all GPR profiles from each site in this study. This window size effectively reduced the visible horizontal banding in each profile with no noticeable change in the character of other reflectors. Few, if any, extensive horizontal reflectors were evident in any of the profiles, therefore
the danger of this processing routine removing actual data rather than instrument noise was minimal. The only true horizontal reflector was the ground surface, which was flat as topographic correction had not yet been applied, and this was removed by this processing routine. However, as the ground surface has little interpretation significance this ‘problem’ was not considered substantial enough to warrant not applying this routine. The other true horizontal reflector which may have been removed by the background removal processing routine was the water table. However, as the GPR data is not topographically corrected at stage, the water table is an undulating reflector and hence was not removed.

2D Spatial Filtering

Various types of 2D spatial filtering are available for use in the RadExplorer program including 2D mean, 2D median and Alpha-trimmed mean with options for filter size (specifying the number of traces or samples) and filter mode, normal (replacement) or subtraction. Spatial filters (unlike time based filters which act vertically on individual traces) act with respect to horizontal position and calculate values using adjacent traces. The ‘Background Removal’ process above is essentially a spatial filter operating in a subtraction mode where mean values are calculated along a window of a defined length. This 2D spatial filtering offers further scope to run similar processes with greater flexibility in terms of the type of 2D filter, its width and mode.

After testing a range of parameters and filter types, no additional filtering (other than the Background Removal above) was applied to any of the data processed in this study. This decision was taken in order to preserve the character of any reflectors present as the various filtering processes tested appeared to distort rather than enhance the existing data. The purpose of applying filters should always be to enhance rather than distort existing features and given that such filters are recalculating data values using various mathematical functions, they are also, to some degree, reducing the resolution of the raw data (Neal 2004).

Amplitude Correction

The amplitude correction processing routine allows the user to apply various gain functions which essentially boost signal strength. Such signal strength corrections are necessary as radar signal strength generally decreases with increasing travel time as the
signal progressively attenuates (Neal 2004). Each of the various gain functions enhances signal strength along a trace in a different way. Four specific gain functions are available for use in RadExplorer: ‘Spherical divergence correction’, ‘Automatic gain control’, ‘Trace equalisation’, ‘Time variant scaling’. ‘Spherical divergence correction’ applies a linear gain function which increases in strength (i.e. the amount of gain applied) according to two-way travel time. ‘Automatic gain control’ equalises gains down an individual trace by a series of mathematical functions with adjustable parameters. ‘Trace equalisation’ is a version of automatic gain control which applies a down trace correction function based on mean values but then applies this along a profile to adjacent traces within a specified window. This function is useful when there are significant variations in amplitude from trace to trace along a profile. ‘Time variant scaling’ allows the manual input of a gain function which is applied down each trace and may be used to emphasise specific regions of the two-way travel time profile.

These different methods for applying gain were tested for a selection of GPR data from each site. The most successful mode, which best aided the interpretation of the GPR data was the automatic gain control function. An operator length of 82 ns was selected as the down-trace window length with the mean value within this window being applied to the first ‘sample’ within this running window.

One disadvantage with this form of gain application is that because it equalizes (to a certain extent) the amplitudes down each trace, the relative strength of particular reflectors in the trace is diminished. When the strength of particular reflectors is an important consideration to the interpretation purposes of the user, automatic gain control is best avoided and display gain called ‘additional scalar’ in RadExplorer is best used, as it applies a single scaling factor which is applied to all trace sample values. Hence overall gain of the displayed data is increases, while the relative strength of amplitudes down each trace is retained. For the purposes of this study, the relative strength of certain reflectors was considered subordinate to understanding what subsurface structures actually exist; therefore automatic gain control was applied.

**Predictive Deconvolution**

Predictive deconvolution is a processing routine which is designed to increase the resolution of wavelets passing through layered substrate which narrow or constrict as the signal propagates (Neal 2004). This processing routine is commonly applied to
seismic data but has had little success for radar data processing routine and is likely to create various data artefacts and lead to no improvement in resolution (Annan 1999). This process is liable to create extra noise in the GPR data and is usually followed by bandpass filtering if applied. Predictive Deconvolution has not been applied to any of the GPR data collected in this study.

**Bandpass Filtering**

Bandpass filtering is used to reduce noise in the GPR data. In RadExplorer a series of moveable sliders are available so the user can adjust the ‘low cut’, ‘low pass’, ‘high pass’ and ‘high cut’ (Figure A1.1). Frequencies below the ‘low cut’ are removed from the data. Frequencies between ‘low cut’ and ‘low pass’ progressively retained. Between the ‘low pass’ and ‘high pass’ cut off values all frequencies are retained. Between the ‘high pass’ and ‘high cut’ frequencies are progressively attenuated. Frequencies above ‘high cut’ are removed. This ‘curve’ defining which frequencies of the GPR data are removed, attenuated or retained is illustrated in Figure A1.1.

![Bandpass Filter Parameters](image)

**Figure A1.1: Bandpass Filter parameters ‘low cut’, ‘low pass’, ‘high pass’ and ‘high cut’ may be adjusted to suite specific requirements.**

The results of a bandpass filter being applied may be seen in Figure A1.2. Part A and B of Figure A1.2 show two portions of GPR data from Callala beach. The top pane, part A has no bandpass filter applied, whereas the bottom frame, part B, does have a bandpass filter applied. There is a significant reduction in noise comparing B with A in Figure A1.2. Two frequency spectrums for this same portion of GPR data from Callala are seen in Figure A1.2 parts C and D. An attenuated and smoothed frequency spectrum in part D compared to C further demonstrates the effect of the bandpass filter in reducing noise and eliminating unwanted frequencies.
Appendix A: GPR processing details

Figure A1.2: A) A portion of GPR data from Callala beach before a bandpass filter has been applied. B) This same portion of GPR from Callala after a bandpass filter has been applied. C) Frequency Spectrum for the data displayed in part A. D) Frequency Spectrum for the data displayed in part B.

For all GPR data processes in this study a bandpass filter was applied to reduce noise. After testing of different ‘low cut’, ‘low pass’, ‘high pass’ and ‘high cut’ frequency combinations, it was found that the default settings (seen in Figure A1.1) satisfactorily ‘cleaned’ the GPR data. For the purposes of site comparisons, these default settings were adopted for all sites.

Stolt F-K Migration

Many forms of migration processing routines have been used for GPR data over the years. The purpose of these migration processes is to correct the location and shape of subsurface reflectors which may be displaced due to the inherent mode in which the GPR data is recorded. When a reflection is returned from a subsurface stratigraphic feature it is recorded as a 1D change in the trace and is located at the midpoint between the transmitter and receiver (Figure A1.3). This results in the underestimation of the reflector depth and a lower dip angle. A migration processing routine corrects for this error and ‘migrates’ the reflectors to their proper position and geometry (Annan 1999) by way of various mathematical functions which determine the curves seen in Figure A1.3.
Appendix A: GPR processing details

Figure A1.3: The necessity of migration processing for GPR data according to Kearey et al. (1991). Due to the inherent method of GPR data collection using a transmitter and receiver antenna, which places a reflector perpendicular to the ground surface at the midpoint between the antennas, the record surface is displaced laterally and has a different geometry to the actual reflector surface ($\alpha_t > \alpha_s$).

This migration process is particularly important for producing the most accurate reconstruction of subsurface stratigraphy (Neal 2004). Unfortunately, only one type of migration process was available for use in the RadExplorer software: Stolt F-K migration. This is considered an economical method of migration (Neal 2004) however, its major drawback is that a single migration velocity must be assumed as constant for each section of data processed. However F-K migration has been applied with good results to other coastal sand ridge environments (Bristow & Pucillo 2006) and the mixed sand gravel ridges of south eastern England (Neal et al. 2002). A standard migration velocity of 12 cm/ns was used for all migration processing at Callala and Wonboyn, while 11 cm/ns was selected for Moruya.

There is no consensus in the literature on whether it is best to migrate first and then correct for topography (Bristow 2009; Neal 2004) or whether to first correct for topography and then perform migration (Cassidy 2009). Here the decision was taken to first migrate and then topographically correct which is the order in which the processing routines are set out in the RadExplorer software.
Appendix A: GPR processing details

Reflection Strength

The reflection strength processing routine is used for converting each radar trace into ‘instantaneous amplitude’ which is done using a Hilbert transform and the resultant trace may be considered an envelope of the original trace (RadExplorer manual). This process is useful when a user wishes to consider amplitude variations along a particular reflector in a GPR data profile. This processing routine was considered unnecessary for the purposes of the processing in this study and hence was omitted from all GPR processing for all sites.

Topography

Topographic processing of the GPR data at all sites was completed by flattening the water table. In the un-topographically processed GPR data, the water table is a strong reflector which undulates as the GPR transect traverses over ridge crests and inter-ridge swales. An inter-ridge swale can be identified by a rise in water table level and a ridge crest by a drop in water table. Flattening this undulating water table reveals the relative topography of each transect. This process in RadExplorer involves digitising the water table which may be then exported as a text file and manipulated so as to have a syntax: trace number, depth; trace number, depth; etc. One major drawback of the RadExplorer software, which necessitated the dividing up of each full transect into a series of smaller 200 m sections, was that only a series of 34 trace number-depth combinations at a time were allowed to be input into the manual topography processing routine. The other parameter required during the topography correction is a velocity in cm/ns. This was set as 12 cm/ns for all sites. A multi part velocity model to account for the water table may be applied at a later stage.

Display parameters

The vertical scale of all profiles, which displays the two-way travel time values, was set from 0 to 250 ns, which captured all meaningful data for all GPR profiles. For the purposes of consistency and cross site comparison, the traces per screen value was set to 450 for all data sets, which displayed roughly 70-80 metres of the profile. This value was chosen as it allowed the best visualisation of the subsurface structures. An additional gain control, adjusted with the ‘additional scalar’ slider, which allows all
trace amplitudes to be multiplied by a single factor, was set to unity, thus overall amplitude strength was neither boost nor cut.

*Convert to depth*

Conversion of the ‘two-way travel time’ (in ns) to depth in metres may be completed after the topographic correction has been applied. This step involved digitizing a polygon covering the reflections below the water table which was assigned a unique velocity of 0.6 cm/ns, or half that of the above water table value. However, the results of this step in RadExplorer were not visually satisfactory, as the reflectors below the water table were compressed vertically so as to satisfy the velocity profile. To avoid this visual distortion, which makes reflector interpretation problematic, a two-scale depth axis has been applied as advocated by (Neal & Roberts 2000). Above the water table the value of 1 m is represented by an interval half the length of the interval for the value of 1 m below the water table. This two-scale depth axis has been used for presenting GPR for other coastal sand ridge plains in Australia (Bristow & Pucillo 2006, Donaldson 2010).

Elevation data for each GPR profile was extracted from LiDAR data displayed as a DEM using the TIN methodology. Thus the elevations for each profile have an error inherited from the LiDAR source data of ± 0.3 m. In addition, while auger holes to water table at Callala and Wonboyn provided some cross checking for depth conversion, some error is to be expected when characterising the velocity throughout any given profile. However, the general homogeneity of the substrate (as evidenced in the field by the auger holes down to water table: usually around 3 m), at least in the upper portion of the barrier stratigraphy, would minimize such error.

Despite some quantifiable and unknown errors in the depth correction phase of the processing routine above, the best estimation has been achieved. It is also important to consider that the primary purpose of the GPR data for this study is to characterise the subsurface stratigraphy. Thus the most critical elements are thus the presence of reflectors, their relation to one another and there general geometry. Their precise depth is of secondary consideration for this purpose, however it is here stated that (according to a cross-check of the known depth of the water table with the depth indicated in the GPR profile data) the depth error is not greater than the ± 0.3 m vertical error stated for the LiDAR data.