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Integrating millennial and interdecadal shoreline changes: Morpho-sedimentary investigation of two prograded barriers in southeastern Australia

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Disciplines

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Integrating millennial and interdecadal shoreline changes: morpho-sedimentary investigation of two prograded barriers in southeastern Australia

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Abstract

Prograded barriers are distinctive coastal landforms preserving the position of past shorelines as low relief, shore-parallel ridges composed of beach sediments and commonly adorned with variable amounts of dune sand. Prograded barriers have been valued as coastal archives which contain palaeoenvironmental information, however integrating the millennial timescale geological history of barriers with observed inter-decadal modern beach processes has proved difficult. Technologies such as airborne LiDAR, ground penetrating radar (GPR) and optically stimulated luminescence dating (OSL) were utilised at Boydtown and Wonboyn, in southeastern Australia, and combined with previously reported radiocarbon dates and offshore seismic and sedimentological data to reconstruct the morpho-sedimentary history of prograded barrier systems. These technologies enabled reconstruction of geological timescale processes integrated with an inter-decadal model of ridge formation explaining the GPR-imaged subsurface character of the barriers. Both the Boydtown and Wonboyn barriers began prograding ~7500-8000 years ago when sea level attained at or near

present height along this coastline and continued prograding until the present-day with an initially slower rate of shoreline advancement. Sources of sediment for progradation appear to be the inner shelf and shoreface with a large shelf sand body likely contributing to progradation at Wonboyn. The Towamba River seems to have delivered sediment to Twofold Bay during flood events after transitioning to a mature estuarine system sometime after ~4000 cal. yr BP. Some of this material appears to have been reworked onto the Boydtown barrier, increasing the rate of progradation in the seaward 50% of the barrier deposited over the past ~1500 years. The GPR imaged beachfaces are shown to have similar geometry to beach profiles following recent storm events and a model of ridge formation involving cut and fill of the beachface, and dune building in the backshore, explains the character of the preserved beachface record and the morphology of the ridges. This model is applicable to future management of individual beaches where such beaches are subject to ongoing cut and fill, dune building processes and inherited sediment budget conditions.

Keywords

Prograded barrier; OSL dating; ground penetrating radar; airborne LiDAR

Introduction

Prograded barriers, also called regressive barriers (Otvos 2000) or strandplains, are coastal landforms which preserve past shoreline positions in the form of shore-parallel, low-relief ridges composed of relict beach sediments commonly with an aeolian capping (Tamura, 2012). Such barriers form along coastlines with positive sediment budgets (Roy et al., 1994), and whereas relative sea-level fall may promote seaward shoreline movement (Tamura et al., 2007), shoreline progradation can also occur independent of sea-level influence (e.g. Fruergaard et al., 2015a). Morphodynamic interactions between beach and dune are instrumental in determining the form of the preserved ridges, with larger ridge forms being generally related to more energetic beach states and smaller ridge forms related to less energetic beach states (Short & Hesp, 1982; Short, 1988). The

degree of aeolian capping atop each ridge is also closely related to beach state with more dissipative beach states having greater aeolian transport potential and thus larger dunes. This interplay between beach and dune morphodynamics has been considered responsible for different barrier forms (Psuty, 1992), but also exerts a more subtle influence on the morphology of particular prograded barriers. The processes of storm cut and recovery of the beachface have been considered important in the formation of relict foredune ridges on coastlines with positive sediment budgets (Davies, 1957; Bird, 1976; McLean & Shen, 2006; Dougherty, 2014). The rate of sediment supply has also been suggested as influencing ridge height with smaller ridges indicative of high sediment supply and larger ridges of lower sediment supply (Shepherd, 1987).

Recent reviews of prograded barrier deposits have emphasised the complexity of the morphodynamic processes which form these ridges, while also noting the potential of these geo-archives for reconstructing both millennial and even inter-decadal timescale changes using established technologies such as optical (OSL) dating of beach and dune sediments, ground penetrating radar (GPR) and advanced remote sensing datasets such as airborne LiDAR (Scheffers et al., 2011; Tamura, 2012; Oliver et al., 2016). These technologies have resulted in a greater understanding of the coastal processes forming prograded barriers and the timescales over which they occur on coastlines around the globe subject to differing climates and geological frameworks, including America (Rink & López, 2010; Timmons et al., 2010), Australia (Murray-Wallace et al., 2002; Nott, 2011; Forsyth et al., 2012; Jahnert et al., 2012; Nott & Forsyth, 2012; Gontz et al., 2014; Engel et al., 2015; Oliver et al., 2015; Kinsela et al., 2016; Oliver & Woodroffe, 2016), Brazil (Guedes et al., 2011; Hein et al., 2013; 2016), Canada (Rémillard et al., 2015), Denmark (Fruergaard et al., 2015a, b; Hede et al., 2015), Germany (Reimann et al., 2010), Thailand (Brill et al., 2015), New Zealand (Dougherty, 2014), Poland (Reimann et al., 2011) and Vietnam (Tamura et al., 2012). Despite this, few studies have integrated these technologies, which have the potential to produce a more comprehensive understanding of prograded barrier development over millennial to inter-decadal timescales. Furthermore, while many studies of prograded barriers in recent years have utilised GPR

to understand the subsurface architecture of the relict ridges, there has been no systematic assessment of GPR-imaged beachface geometry in comparison to modern-day beachface profiles during both storm and fair-weather conditions.

The coastline of southeastern Australia is an ideal field laboratory for integrating the established technologies available for investigating prograded barrier deposits, having a rich history of coastal research and a wide variety of prograded barrier systems infilling bedrock embayments. This study examines two of the four largest prograded barriers on the south coast of New South Wales (NSW) (see Fig. 4 in Oliver et al. 2016) and utilises a variety of datasets including airborne LiDAR elevation data, GPR, OSL dating and previously reported radiocarbon ages and offshore sediment and seismic data. By combining these datasets a new picture of barrier progradation emerges, spanning both the millennial timescale as well as informing inter-decadal timescale processes of ridge formation. Furthermore, this study also serves as an additional inter-comparison of reported barrier progradation derived from radiocarbon dating of shell material and OSL dating of quartz sediments (Murray-Wallace et al., 2002; Oliver et al., 2015).

Study sites

Regional setting

The Boydtown and Wonboyn prograded barrier systems are located in southeastern Australia 45 km and 25 km north respectively of the NSW/ VIC border at Cape Howe (Fig. 1). Sandy barrier deposits along this coastline have infilled the antecedent topography in the well-indurated Palaeozoic rocks. Successive glacial and interglacial cycles through both marine and fluvial processes have eroded and incised these rocks forming embayments which are now filled to varying degrees with Holocene sediments derived from shelf sands deposited during lower sea levels with ongoing supply from rivers being uncommon (Davies, 1974). There are no sub-aerial outcrops of sediments from previous Pleistocene sea-level high-stands in this southern region of the NSW coast, despite these

embayments likely having been filled with such deposits during previous interglacial periods. Twofold Bay and Disaster Bay, which contain the Boydtown and Wonboyn prograded barriers respectively, are large shallow bays in this region, which is otherwise dominated by rocky cliffs and small pocket beaches (Fig. 1A). Various sandy deposits have been described on the inner shelf based on seismic profiles and coring by Hudson (1991). These deposits are potential sand-sources for the Boydtown and Wonboyn prograded barriers over the Holocene. The Towamba River connects with the ocean via Kiah Inlet and has a catchment area of 1026 km² whereas the two other rivers entering Twofold Bay, the Nullica River and the Pallestine River, have catchments sizes of 53 km² and 28 km², respectively. The Wonboyn River flowing into Disaster Bay via Lake Wonboyn has a catchment area of 335 km². The wave climate of this region of southern NSW is dominated by southeast swells with average significant wave height ~1.5 m (McLean et al., 2010) and the tidal range is ~2 m (Thom, 1984). Moderate to strong south-westerly winds prevail in the winter months, whereas in the summer months moderate north-easterly winds are dominant. Severe storms occur periodically along this coastline and during recent east-coast low event in June 2016, a record wave height of 17.7 m was recorded by the Eden wave buoy (Mortlock et al., 2017). These storm events cause periodic beach erosion along much of the NSW east coast.

Previous studies

Previous studies of the Twofold Bay Holocene sediments show that there is strong sediment partitioning and variability in sediment thickness within Twofold Bay (Fig. 1B, C) (see also Hails, 1967; 1969). Of particular note is the large lobe of coarse grained river sands containing quartz, feldspars (especially K-feldspar), lithic grains and mica at the northern end of Whale Beach (Fig. 1B, C). River gauge and rainfall data for the Towamba River for the past ~40 years, combined with Landsat imagery, shows that the Towamba River breaches the low sandy barrier at the northern end of Whale Beach during severe flood events. These flood events appear responsible for depositing the lobe of sediment at the northern end of Whale Beach observed in the seismic and coring data by

Hudson (1991) (Fig. 1B, C) (see also Hudson & Ferland, 1987). Based on systematic analysis of the Boydtown barrier sediments, it was hypothesised that the Towamba River has been an important source of sediment during the formation of the seaward half of the Boydtown barrier, as a distinct change in sediment composition to a higher proportion of feldspar and heavy minerals was noted in sand samples collected from across the width of the ridge sequence (Hudson, 1991). Radiocarbon dating of shell material recovered from a series of cores through the Boydtown barrier (Table 1, Fig. 2) showed that more than 60% of the barrier had formed during the last 3000 years at a faster rate than the previous 40% (Fig. 2) (Hudson, 1991). This change to a faster progradation rate with a strong fluvial sand input was also correlated with a radiocarbon date of ~4000 cal. yr BP from estuarine shell (Table 1), sampled from a mud-basin facies outcropping upstream of the Kiah Inlet (see Fig. 1B for sample location), indicating that infilling of the Kiah Inlet estuary after ~4700 cal. yr BP, could have led to the delivery of fluvial sediment into Twofold Bay in the past ~3000 years, whereas prior to this fluvial sediments would have been infilling the shallow estuary (Hudson, 1991).

Previously reported radiocarbon dating for the Wonboyn prograded barrier demonstrated progradation occurred from 6500 cal. yr BP to 1000 cal. yr BP (Figs. 3, 4) (Thom et al., 1981). These radiocarbon dates indicated a possible slower phase of progradation between 6500 and 4000 cal. yr BP, followed by a steady progradation trend to 1000 cal. yr BP (Fig. 4) (Thom et al. 1981). Offshore seismic and core data reveals a large shelf sand body to the southeast of Wonboyn Beach (Hudson, 1991) (Fig. 1A) which may have been a source of sediment for the Wonboyn barrier augmenting the inner-shelf and bay floor sediment delivery regime (Kinsela et al., 2016). However, the timing of its potential influence on the barrier history and its relation to the increase in barrier progradation rate is unknown and requires an understanding of the depositional history of this sand body.

Methods

LiDAR processing and sub-aerial barrier volume calculation

LiDAR data was acquired from Land and Property Information (LPI) NSW as a series of DEM tiles in ASCII format with 1 m cell size covering the areas of interest. These files were viewed and processed in ArcGIS 10.2 and topographic profiles depicting ridge and swale morphology were extracted. Volumes of sediment contained in each barrier system above MSL were determined using the 'polygon volume' tool in order to compare the subaerial store of sediment at each site through time and relate this to the barrier morphology and ridge formation process. This tool calculates a volume between a defined reference plane (in this case 0 m AHD) and a DEM surface, for an area defined by a separate polygon. The value of 0 m Australian Height Datum (AHD) approximates MSL on this coastline.

OSL dating

Locations for OSL sampling were selected along access tracks and sample locations were intentionally spread across the barrier width and informed by the location of existing radiocarbon dating samples. Samples of sandy sediment were collected at depths of between 0.7 and 1.2 m from auger holes below the barrier surface. Light-safe plastic and metal tubes were capped and taped to preserve soil moisture content and sample locations were recorded with RTK GPS at Boydtown and with handheld GPS at Wonboyn. Sixteen samples in total were analysed at the University of Wollongong OSL dating laboratory.

Under dim red-light conditions, ~4 cm of material at each end of the sample tube was treated as light-exposed and was utilised as an indicator of sample moisture content and for determination of the environmental dose rate using ICP-MS and ICP-OES analysis (completed by Intertek Genalysis). Environmental dose rate was calculated using the concentrations of uranium, thorium, and potassium determined using the conversion values of Guérin et al. (2011). A water content of 5% $\pm$ 2.5% was used for all samples due to the uncertainty of time-varying hydrological conditions in free-

draining quartz sand soils. The cosmic dose for each sample was calculated taking into consideration geographic position, sediment density, altitude and depth of overburden following the methods of Prescott and Hutton (1994).

Sub-samples of light-safe 180-212 μm quartz grains were isolated and prepared for measurement following the procedure outlined by Oliver et al. (2015). Twenty-four 3 mm diameter aliquots of quartz were prepared on stainless steel discs and were loaded onto a Risø TL/OSL reader for stimulation, measurement and irradiation. Prior to measurement of equivalent dose (D_e) values, a preheat-plateau was used to assess the thermal stability of the quartz grains. Based on this pre-heat plateau experiment, a pre-heat cut-heat combination of 180°C and 160°C, respectively, was adopted for all D_e measurements. 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 multi-grain aliquot, standard tests were applied, including a recycling ratio test, recuperation test (Murray & Wintle, 2000) and OSL-IR depletion ratio test (Duller, 2003). Luminescence data for each aliquot was processed in 'Luminescence Analyst' version 3.24 © University of Wales, 2007 and dose response curves were fitted with an 'Exp+Linear Fit' function. The final D_e and overdispersion values for each sample were calculated using the central age model (CAM) (Galbraith et al., 1999).

GPR collection and processing and analysis

GPR data was collected using a Mala ProEx system with a 250 MHz antenna along transects indicated by lines in Fig. 2 and Fig. 3. Profiles were collected in common offset mode and sampling interval was set to 0.05 m. Distance for each transect was metred using the wheel integrated into Mala ProEx 'cart'. A two layer velocity structure was determined in the field by determining the depth of the water table with a hand auger. Velocity values of 0.14 m/ns above the water table and 0.07 m/ns below the water table were adopted based on these field measurements. This two-layer velocity structure for barrier sands above and below the water table is well-documented (e.g. Neal & Roberts, 2000; Bristow, 2009). GPR data was processed using RadExplorer 1.42 and standard

processing routines were applied including desaturation, first arrival time correction, amplitude correction, bandpass filtering and Stolt F-K migration. Topography correction was applied to each GPR profile, based on RTK GPS elevations every 2-5 m at Boydtown and from ground elevations extracted from the airborne LiDAR derived DEM shown in Fig. 3 at Wonboyn.

Lines that traced preserved beachfaces were extracted every ~5-10 m from each GPR profile at Boydtown and Wonboyn so as to systematically compare the geometry of the preserved reflectors with modern day profiles. Each traced line extracted from the GPR data was 'distance normalised' by treating the point of intersection with mean sea level (MSL) (or 0 m AHD) on each profile, as 0 m distance on the x-axis. Landward of the MSL intersection point, distance on the x-axis is denoted by negative numbers. Conversely, seawards of the MSL intersection point, positive numbers indicate distance seaward away from the MSL intersection point. When these 'distance normalised' profiles are plotted on an x and y graph with distance on the x-axis and elevation on the y-axis, an 'envelope' of profiles is achieved, similar to a beach-profile envelope from a fixed datum. In this instance each profile's intersection with MSL is treated as the fixed datum, allowing comparison of profile geometry. The envelope of relict GPR-imaged beachfaces was compared to modern profiles which were 'distance normalised' using the same method. One profile from each site was collected immediately following a severe storm event in June 2016, both measured with a tripod and staff. One beach profile during fair-weather conditions from each site (Boydtown and Wonboyn) was collected with RTK-GPS in 2015 and extracted from the LiDAR data flown in 2011, respectively. These four beach profiles, one storm and one fair-weather for each site, were located proximal to the GPR transects at each site (adjacent to transect A for Boydtown (Fig. 2), and adjacent to the GPR transect shown in Fig. 3 at Wonboyn).

Barrier sedimentological analysis

Sediments exhumed from shallow auger holes during collection of samples for OSL dating at both sites were considered in the field and compared with the detailed sedimentological analysis presented in Hudson (1991) (which is partially summarised in Fig. 1) and Thom et al. (1981). An additional auger hole to the water table at each site (which served to indicate velocity values for the GPR data) also provided an opportunity to examine barrier sediments. Sediment samples were also collected from the modern beachface at Boydtown in December 2015. These auger holes and sediment samples supplemented the auger holes spaced across the Boydtown barrier by Hudson (1991) and combined provide a baseline of sedimentological information. The cores spaced across the Wonboyn barrier by Thom et al. (1981) which enabled the collection of shell samples for radiocarbon dating also offered the opportunity for description of the sedimentological character of the barrier sands. The results of subaqueous sediment sampling and analysis as well as seismic data collection in this region by Hudson (1991) are summarised in Fig. 1 (see also Hudson and Ferland, 1987).

Results

Ridge morphology and sedimentology

The Boydtown barrier forms the westernmost shoreline of Twofold Bay and is approximately 2.1 km wide. The barrier contains approximately 50 shore-parallel, low-relief ridges with crest heights around 4 m above mean sea level (MSL) (Figs. 2, 5). The seaward margin of the barrier is dominated by a high foredune, which stands almost 2 m higher than all other ridge crests in the barrier sequence (Fig. 5). Between this higher foredune and the present-day beach (Boydtown Beach) an 'established foredune' is periodically cut back by severe storms and subsequently recovers. A small 'incipient foredune' seaward of this 'established foredune' is present during prevailing fair-weather beachface conditions.

The sediments of the Boydtown barrier are generally fawn-grey, well sorted, fine to medium grained quartzose sands with a high (20-30%) proportion of abraded shell fragments. The upper 1-2 m of barrier sediments are generally finer grained than those from 2-4 m deep which are coarser grained. This change appears to correspond to a change from dune to beach deposition and is consistent with changes in grain size observed on the modern beach in a sampling transect from the dune to the lower beachface. The compositional change in sediments that was noted by Hudson (1991) is defined by a higher proportion of feldspar (10-20 %) and heavy mineral grains (especially mica 1-2%) in the seaward half of the barrier compared to landward half of the barrier where sediments are composed of <10% feldspar and a variable heavy mineral assemblage <1%. Of the heavy mineral grains from the seaward half of the barrier, amphibole makes up 55-65% compared with the landward half of the barrier where a more variable array of heavy minerals was found.

The Wonboyn barrier is approximately 1.7 km wide and contains around 40 shore-parallel, low-relief ridges with crest heights between 6 and 7 m AHD (Figs. 3, 5). A high foredune is also present along the seaward margin of the Wonboyn barrier, which is approximately 2 m higher than other ridges in the barrier sequence (Fig. 5). An established foredune and incipient foredune are also present between the high foredune and the modern Wonboyn Beach which are cut by storms and subsequently recover in a similar manner to Boydtown Beach. However, due to the greater exposure to wave and wind processes, and thus a more energetic beach state, the established ridge and incipient ridge at Wonboyn form at a higher elevation than at Boydtown. The sediments of the Wonboyn barrier comprise fawn grey well-sorted, fine to medium quartzose sands which are well-rounded. Soil development increases landwards across the ridge plain in accordance with increasing age of the ridges landwards.

Depositional chronology and progradation rates

OSL dating indicates the burial time of quartz grains collected from depths of 0.7-1.2 m across each barrier with ages systematically younging in a seaward direction at both Boydtown and Wonboyn

(see Table 2, Figs. 2, 3, 4). The most landward ridge in the sequence for both sites was deposited when sea-level reached at or near present levels between 7700 and 7400 cal. years BP for this coastline according to Sloss et al. (2007) (Fig. 4) (see also Lewis et al., 2013). From this time until present, progradation of the shoreline at both sites appears to have steadily advanced, although with a slower rate of progradation at first, followed by a period of faster progradation to present (Fig. 4). At Wonboyn this change in progradation rate appears to take place around 4500 years ago (Fig 4) with an average rate of 0.08 m/yr from ~7770 to ~4500 followed by an average rate of 0.32 m/yr from ~4500 years ago to present. At Boydtown, the OSL ages indicate around 50% of the barrier appears to be less than 1500 years old, with a slower rate of progradation prior to 1500 years ago (0.16 m/yr), followed by more rapid progradation from 1500 years to present (0.65 m/yr) (Table 3). It is noteworthy that progradation rates at Boydtown are twice as fast that Wonboyn (Table 3). The reasonable agreement between the radiocarbon and OSL chronologies at each site gives greater confidence to these shoreline progradation rates although the OSL ages have been used to determine the each value as OSL ages indicate the sediment burial age.

The average ridge 'lifetimes' for Boydtown and Wonboyn are reflective of the changing progradation rate during the barrier history. At Boydtown an average ridge lifetime of 280 years per ridge between ~7940 and 1500 years ago, changes substantially to approximately 50 years per ridge from 1500 years until present (Table 3). At Wonboyn the average ridge lifetime between ~7770 and ~4480 years ago is 410 years, whereas average ridge lifetime between ~4480 years ago and present is 130 years (Table 3). Comparing the volumes of sediment stored above MSL in each barrier, Wonboyn, being a longer barrier system with higher ridges, contains far greater volumes of sub-aerial sediment compared to Boydtown (Table 3). However, it is significant that when sediment supply in m^3/yr is considered as a value per metre of beach ($\text{m}^3/\text{m}/\text{yr}$), in the more recent past, Boydtown has a higher value: $1.83 \text{ m}^3/\text{m}/\text{yr}$ compared to Wonboyn $1.34 \text{ m}^3/\text{m}/\text{yr}$ (Table 3).

The anomalously high foredune fronting both the Boydtown and Wonboyn barriers appears to be a recent feature of the depositional history of each site. At Boydtown a sample taken at 0.9 m depth beneath the foredune crest returned an OSL age of 90 ± 5 years ago (Fig. 2). At Wonboyn an age from the ridge immediately behind the high foredune at a depth of 0.8 m, returned an age of 450 ± 40 years ago. However, a sample from the northern section of the Wonboyn barrier on the crest of the high foredune which stands at 12 m AHD (ridge crest heights behind this foredune are ~ 6 m AHD) returned an age of 70 ± 5 years ago, which is in close accord with the Boydtown foredune.

The sub-aerial sediment volume was calculated for the area of the Boydtown barrier seaward of the high foredune dated to 90 ± 5 years ago, returning a value of $345,754 \text{ m}^3$, which equates to $1.80 \text{ m}^3/\text{m}/\text{yr}$ for the current beach length. This value is in close agreement with the average value calculated for the barrier over the last 1500 years of $1.83 \text{ m}^3/\text{m}/\text{yr}$ (see Table 3). In contrast, the volume of sediment accumulated at Wonboyn seaward of the ridge dated 450 ± 40 years ago (which includes the high foredune) is $1,124,959 \text{ m}^3$, which equates to $0.68 \text{ m}^3/\text{m}/\text{yr}$. This value is substantially lower than the longer-term average value over the past ~ 4500 years of $1.34 \text{ m}^3/\text{m}/\text{yr}$ (see Table 3).

GPR imaged structures

GPR data traversing almost the full width of the Boydtown barrier and the seaward portion of the Wonboyn barrier (Figs. 2, 3) successfully imaged dune, beach and shoreface subsurface structures within the barrier sediments (Fig. 6). Imaged dune structures are characterised by discontinuous reflectors, which are generally seaward-dipping and commonly convex-up (Fig. 6). At Boydtown these structures are observed above 2.5 m AHD and at Wonboyn above 3 m AHD (Fig. 6). Imaged beach structures are characterised by more continuous seaward-dipping reflectors, which are commonly flat or slightly concave-up in shape (Fig. 6). At Boydtown these beach structures were generally observed between -0.5 m AHD and 2.5 m AHD and at Wonboyn between -0.5 m AHD and 3 m AHD (Fig. 6). This change from dune to beach sedimentary structures is concordant with

sedimentological data from core and auger holes spaced across these two barriers. Upper shoreface structures are characterised by discontinuous hummocky reflectors overlapping one another, with landward-dipping reflectors commonly onlapping seaward-dipping reflectors (Fig. 6). Upper shoreface structures were observed between -3 m AHD and -0.5 m AHD at Boydtown and Wonboyn (Fig. 6).

The geometry of imaged beachface reflectors was systematically compared with modern fair-weather and storm profiles at each site using a 'distance normalised' method, where the intercept of each profile with 0 m AHD acts as a fixed datum (Figs. 7, 8). GPR imaged reflectors showed a tight grouping in terms of their geometry for both sites, allowing an envelope of beachface geometry to be delineated (Figs. 7, 8). During June 2016 a severe east-coast low storm event occurred and resulted in substantial cut of the beachface at both sites. A strong NE swell direction resulted in particularly severe erosion for Boydtown Beach and the southern portion of Wonboyn beach. At both sites a beach profile taken one week following this storm event was processed using this same 'distance normalised' method. These 'distance normalised' profiles from June 2016 fell within the envelope of GPR-imaged beachface reflectors. In contrast, a beach profile from fair-weather conditions processed with the 'distance normalised' method, had a substantially different geometry (Figs. 7, 8). This demonstrates that the structures preserved within the barrier sub-surface are erosional storm beachfaces. It is also noteworthy that beachface envelopes for Profiles A through to F at Boydtown (see Fig. 2 for locations) showed a close correlation in terms of geometry (Fig. 7) despite covering almost the full barrier width, and thus potentially capturing any changes in beach state as the shoreline moved closer to its present position and became more exposed to wave energy.

Modern beach conditions

Seaward of the high foredune fronting the Boydtown barrier is a smaller well-vegetated established foredune, which is laterally persistent alongshore and at an elevation of 3 m AHD (Fig. 9A). During

fair-weather conditions a low sparsely vegetated incipient foredune was observed in the backshore, seaward of this established foredune, as can be seen in the photo in December 2015 (Fig. 9A). A berm is also present during fair-weather beach conditions indicating the persistence of intermediate beach states. During the severe storm in early June 2016, this incipient ridge and berm at Boydtown was eroded and the storm scarp cut back into the established foredune (Fig. 9B).

At Wonboyn in March 2014 an incipient foredune was observed (Fig. 9C) seaward of a well-vegetated established foredune and a berm is also laterally persistent and indicative of a prevailing intermediate beach state. Airborne LiDAR from 2011 shows the established foredune with an elevation of ~4 m AHD behind the modern beach (Fig. 5). The incipient foredune seen in March 2014, just to the seaward of the established foredune, has formed between 2011, when the airborne LiDAR was flown, and 2014. The embryo form of this incipient foredune can be seen in Fig. 8 as the small backshore mound at -38 m on the August 2011 profile. The storm event in 2016 removed this small incipient foredune and cut back into the established foredune, forming the scarp seen in Fig. 9D. The heavy mineral lag deposit following the June 2016 storm event seen on the upper beachface in Fig. 9D, is at an elevation of between 2-2.5 m AHD. This elevation range of 2-2.5 m AHD in the GPR data for Wonboyn (Fig. 6) is characterised by seaward-dipping reflectors likely resulting from such heavy mineral lag deposits, deposited during past storm events. These reflectors commonly continue seawards into the lower beachface and upper shoreface zone.

Discussion

Comparison of OSL and radiocarbon-derived ridge chronologies

OSL and radiocarbon ages show similar patterns of progradation (Fig. 4) for the Boydtown and Wonboyn barriers considering the differences in sampling location (see Figs. 2, 3) and depth (radiocarbon samples were collected from around 2 m below the ground surface whereas OSL samples were collected from between 0.8-1.2 m deep). Other comparisons of barrier age structure

in southeastern Australia determined using radiocarbon dating of shell fragments and OSL dating of quartz dune sands have shown more disparate patterns of progradation (Murray-Wallace et al., 2002; Oliver et al., 2015). This was especially evident in the comparison drawn at Moruya between the OSL and radiocarbon dates (Oliver et al., 2015). At Moruya, OSL samples were collected from the upper metre of aeolian dune sands, whereas the shells for radiocarbon dating were collected from the 'nearshore shelly sand' between -5 m AHD and -25 m AHD. A model of shoreface response over the Holocene as shown in Kinsela et al. (2016) is needed at Moruya to reconcile these contrasting chronologies, as the radiocarbon age of shell detritus, collected from deeper within the barrier stratigraphy, has a less robust association with a surface position because each sample requires an interpretation of relict shoreface geometry in order to determine the shoreline position at the time the shell material was deposited. Better agreement between the two dating techniques is evident at both Boydtown and Wonboyn because shells for radiocarbon dating were collected from the beach facies rather than from the nearshore as at Moruya (Oliver et al. 2015).

Source of barrier sands and its influence on shoreline progradation

Hudson (1991) present detailed sedimentological analysis for both barrier and offshore sediments in this region and inferred a depositional history from this dataset and the observed geomorphology of the area. Hudson (1991) noted that the sands comprising the landward half of the Boydtown barrier, which had a slower rate of shoreline progradation up until ~3000 cal. yr BP according to the radiocarbon dating, contained a lower proportion of feldspars and heavy minerals compared to the seaward portion of the plain where such minerals were more prevalent. This change is also reflected in the total dose rate (Gy/ka) measured for OSL samples which values of 1.10-1.35 Gy/ka for samples in the landward 50% of the barrier and 1.75-2.00 Gy/ka for samples in the seaward 50% of the barrier (Fig. 2 and Table 2). This change in total dose rate is directly related to the percentage of potassium in each measured sample (Table 2). Hudson (1991) noted that K-feldspar was the

dominant feldspar mineral in the sediment composition of the Boydtown barrier and demonstrated a marked increase in K-feldspar in the seaward 50% of the barrier. Based on this lithological change and the outcrop of a shelly mud-basin facies radiocarbon dated to ~4700 cal. yr BP approximately 2 km upstream of the mouth of the Towamba River, Hudson (1991) proposed that the increase in progradation rate of the Boydtown Barrier resulted from infilling of Kia Inlet at the mouth of the Towamba River and the delivery of sandy sediments to Twofold Bay, which shallowed the shoreface profile seaward of the Boydtown barrier shoreline and were then worked westward to Boydtown Beach by the prevailing south-easterly swell as the shoreface adjusted to equilibrium (Kinsela et al., 2016). Further evidence for this sediment supply to Boydtown is seen in the sedimentological analysis of subaqueous sediments and seismic data for Twofold Bay from which Hudson (1991) demonstrated the presence of a large lobe of river sand at the northern end of Whale Beach and the distinct partitioning of sediment types within Twofold Bay (Figs. 1B, C). The finer material from this lobe of river sand appears to be reworked onto Boydtown Beach based on the sedimentological data of Hudson (1991) which demonstrated the similarity in sediment composition between Boydtown and Whale Beach while noting a distinct difference in grain size as summarised in Fig.1C. Other beaches to the north and east within Twofold Bay appear to be unaffected by this river influence, which is hypothesised as due to the presence of submerged rocky reefs, which are a physical barrier preventing sediment exchange and also the prevailing westerly movement of waves refracting into the bay (Fig. 1B).

OSL dating for the Boydtown barrier indicates that the change in rate of progradation occurred ~1500 years ago rather than ~3000 cal. yr BP, as was indicated by the radiocarbon dating. However, the hypothesised influence of sediment delivery from the Towamba River in the late Holocene is still plausible, given the lithological data and geomorphology. It is possible that sediment delivery to the Boydtown barrier from the Towamba River may have been limited to the past 1500 years, as the Kia estuary may still have been transitioning to a 'mature riverine estuary' (Roy et al., 2001) until 1500 years ago. Further dating of fluvial and marine deposits within the Towamba River would help to

constrain the timing of such changes to this system, however, it is clear that more than half of the Boydtown barrier is less than 1500 years old and appears to contain sediments sourced from the Towamba River. Progradation rates at Boydtown are twice as fast as at Wonboyn, which also suggests an additional input of sediment from the Towamba River.

It has been hypothesised that a larger dune fronting a prograded barrier is evidence for a cessation of progradation and transition to an erosion-dominated shoreline (Bird, 1976; Shepherd, 1987). This does not appear to be the case at Boydtown, where the volume of sand accumulated seaward of the foredune above MSL appears to be consistent with the longer-term average sediment delivery between 1500 years ago and present. However, at Wonboyn, much less sand has accumulated above MSL since ~450 years ago when compared with the longer-term average, and this volume calculation includes the high foredune, which is seawards of the ridge dated 450 ± 40 years ago. This evidence, and the broader geomorphology of these two barriers, suggests that the Boydtown barrier continues to maintain a progradational shoreline at a similar rate to the past 1500 years due to the influence of sediment supply from the Towamba River, whereas at Wonboyn progradation has slowed, possibly due to a diminishing shelf sand supply. Nevertheless, at both sites, sand has accumulated seaward of the high foredune (and this dune is thickly vegetated and no longer active), which implies that the processes leading to the formation of this feature may be a discrete event, rather than an ongoing trend i.e. it is not proximal to the current active shoreline. Systematic OSL dating and subsurface imaging of this high foredune at other prograded barriers in southeastern Australia would provide further insight into the timing and mode of its formation.

Ridge formation model based on barrier morpho-stratigraphy

Comparison of GPR imaged seaward-dipping reflectors and modern beach profiles during storm and fair-weather conditions demonstrates that these two prograded barrier systems have preserved

storm beachfaces. These storm beachfaces appear 'stacked' and any model of prograded barrier formation must explain this phenomena. The ridge formation model shown in Fig. 10 draws upon the imaged GPR data for these two sites, field observations of cut and recovery (Fig. 9), beach profiling, published models of ridge formation (Dougherty, 2014; Oliver et al., 2016) and the long-term beach monitoring data published for Moruya (Bengello beach) (Thom and Hall, 1991; McLean and Shen, 2006). The proposed model shows two 'cut and fill' cycles where ongoing sediment supply results in preservation of the storm beachfaces, whereas fair-weather beach states are not preserved, despite being critical for promoting dune formation in the backshore during beach recovery and in quiescent beach conditions, as was observed at both study sites (Fig. 9). This dune formation process in the backshore follows the model of Hesp (1984) where sand trapping by pioneer plants results in dune growth as a terrace forming an incipient foredune (Figs. 9A, C). This is at variance with the model proposed by Bird (1976) (which is a modification of the original Davies (1957) model) where dune formation occurs directly on top of a berm. Dune development on top of berms is also depicted in Figs. 15 and 16 of Dougherty (2014). Formation of incipient foredunes directly on top of berms is not supported by the observations at these sites (Fig. 9) or for other sites in NSW for example at Moruya (see McLean and Shen, 2006) and at Dark Point (see Hesp, 2013). The two models of Dougherty (2014) also emphasise the importance of a storm-deposited ridge of sand as a nucleus of further ridge building, which is supported by field observations at those sites examined by Dougherty (2014) in New Zealand. Such a storm deposit was not evident in field observations at Boydtown and Wonboyn.

The incipient foredune building activity evident at Boydtown and Wonboyn occurs in the backshore, immediately in front of an established foredune and well landward of the berm (Fig. 9) as proposed by Hesp (1984). The process of storm cut at these sites completely erodes the incipient ridge in the backshore during large storm events and cuts into the established ridge behind (Fig. 9). The beach system then rebuilds by swash zone accretion and backshore dune development. Where this rebuilding or beach recovery is of a greater volume than that which was removed from the beach

during the storm (under positive sediment budget conditions), the active beach zone, including the incipient foredune and berm, shifts seawards, and the established foredune may transition to a relict dune (see stage 8 in Fig. 10). This ridge formation model (Fig. 10) emphasises the process of cut and fill (Davies, 1957; Bird, 1976) as critical in producing a ridge topography with distinct ridge and swales (see also Dougherty, 2014) while also stressing the importance of dune building in the backshore following the observations of Hesp (1984).

The closely spaced storm-reflectors observed in the GPR data result from the successive cut and fill of the beachface at these sites, where a positive sediment budget means that each new storm event erodes the fair-weather profile, but does not erode the material landward of the previous storm's landward incursion. Hence the GPR profiles traversing the relict ridges contain no fair-weather profiles, despite such fair-weather conditions being critical in dune building between successive storm events.

In this model the progression of one ridge being succeeded by another, is not due to a unique process or series of events, rather it is caused by the decreasing proximity of the established ridge to the active beach and dune processes. The cut-and-fill and dune building observed annually to decadal on almost all beaches of the southern coastline of NSW, is also common on the shorelines of prograded barriers; it is the positive sediment supply and resultant seaward accretion of the shoreline which produces a succession of low-relief ridges. Thus, in this model (Fig. 10), *proximity* to processes, not *uniqueness* of processes is responsible for one ridge being succeeded by another.

Moore et al. (2016) explain multiple dune ridge development with an autocyclic model based on internal dune dynamics and emphasise the rate of progradation and lateral dune growth rate as key drivers of resultant ridge height and spacing (see also Durán & Moore, 2013). The datasets and model presented in this paper also suggests that the rate of shoreline progradation is critical in controlling the timescales at which ridges are formed and hence their morphology. Faster rates of shoreline progradation will more rapidly move the active beach/dune zone seaward, meaning there

is less time for vertical dune building. Conversely, a slower shoreline progradation rate will allow time for greater dune building.

It should be noted that this proposed model of ridge formation is seen as broadly applicable to coastal barriers with intermediate beach-states and small tidal ranges. On dissipative beaches which do not develop berms, reflective beaches, meso- or macrotidal beaches and very coarse grained or gravel beaches, other modes of ridge formation prevail (see Fig. 2 in Tamura 2012). However, intermediate beach states are common worldwide on microtidal sandy coastlines, and while incipient foredune and berm development may occur at different elevations (c.f. Boydtown and Wonboyn) due to relative wave energy exposure, the model presented here, involving cut and recovery of the beach and dune construction in the backshore, seems broadly applicable to these systems and thus relevant to management of such shorelines in the future. In fact, stage 1 to stage 4 of the model in Fig. 10 is a generalised cycle of events following a storm, for beaches with a balanced sediment budget, based on observations in southeastern Australia.

Published models of ridge formation do not specify the timescales over which they occur. The eight stage model in Fig. 10 involving two successive cut and fill events of the beachface under sediment surplus conditions is envisaged as a decadal to interdecadal process, on the basis of progradation rates at Boydtown and Wonboyn, and the observed cut and recovery of the beachface. The Boydtown prograded barrier system in particular has prograded rapidly from 1500 years to present (0.65 m/yr, average ridge lifetime of 50 years) in comparison to other published rates for Australian prograded barrier systems, which generally range between 0.19 and 0.41 m/yr (see Table 3 in Oliver et al., 2015). Based on observational evidence and the beach profiling record for Moruya in McLean and Shen (2006) it is hypothesised that at Boydtown, a series of moderate storm events of a magnitude similar to the June 2016 event over a period of ~50 years would likely result in the transition of an established ridge to a relict ridge (Fig. 10: stage 8). Severe storm events in the future of a magnitude similar to the 1974 event (McLean and Shen, 2006) would require a longer recovery

time and may temporarily interrupt shoreline progradation. Storms are viewed as important in creating the ridge and swale topography as storms create substantial beach scarps which become the low-point (swale) behind the newly forming ridge in the backshore during the recovery phase (Fig. 10, stage 6-8). However, storms are not viewed as necessary in promoting seaward accretion of the shoreline which (it is hypothesised) would still occur during quiescent periods (possible 100s of years) under the influence of 'constructive' swell waves transporting sediment available for beach accretion landwards onto the active beachface. Furthermore the largest storms which temporarily interrupt shoreline progradation do not necessarily cause a cessation of shoreline progradation, rather the recovery phase from such a large storm event is longer, as there is substantially more rebuilding of the active beach needed before the shoreline is back to its previous position, both in planform and profile.

In light of the model presented in Fig. 10, the presence of the higher foredune (see Fig. 5) at both Boydtown and Wonboyn represents a significant change in barrier morphology. This greater vertical dune building would, in the model presented, relate to a far slower progradation rate prevailing while dune accretion could occur. The GPR transect A at Boydtown (Fig. 2) which traverses the foredune shows some evidence of landward-dipping reflectors at 10 m distance (Fig. 6) consistent with cascading dune sediment moving landwards over previously established relict ridge topography. The higher foredune is no longer active at either site and progradation has occurred seawards, as shown in planform, profile and in calculations of sub-aerial barrier sand volumes. This (apparently) discrete episode of dune building is anomalous in the context of the barrier history and should be a focus of future investigations.

It is noteworthy that storm events which cut back the modern Boydtown beach, are often accompanied by substantial amounts of precipitation in the Towamba River catchment, which cause moderate to severe flooding and delivery of additional sediment into Twofold Bay near Whale Beach (Figs. 1B, C). This sediment may be worked westward to Boydtown Beach during post-storm

recovery, promoting seaward shoreline progradation. Further investigation of the geomorphology of the Towamba River system and the response of the Boydtown barrier shoreline has the potential to increase our understanding of possible future changes in sediment supply due to catchment land-use changes and climate dynamics as demonstrated in southeastern Queensland by Brooke et al. (2008).

Conclusions

OSL dating of prograded barrier sediments at Boydtown and Wonboyn on the NSW south coast shows that shoreline progradation has occurred from 8000-7500 years ago to present. Rates of progradation at both sites appear to be slightly slower in the early stages of progradation (0.16 m/yr for Boydtown and 0.08 m/yr for Wonboyn) and then faster until present (0.65 m/yr for Boydtown and 0.32 m/yr for Wonboyn). This pattern of progradation is similar to that inferred from radiocarbon dating of buried shell material from these barriers which is in contrast to the discordant patterns observed at Moruya, NSW ~140 km to the north when these dating techniques were compared (Oliver et al., 2015).

Sediment sources contributing to the Holocene progradation of these barriers appear to be from the inner shelf and shoreface, although at Wonboyn an additional source may be from the large shelf sand body to the southeast. At Boydtown multiple lines of evidence suggest that the Towamba River has been supplying additional sediment for shoreline progradation in the past ~1500 years and this is reflected in the more rapid progradation rates for this site.

GPR was used to image dune, beach and shoreface sub-surface structures at both barriers which enabled the development of a model of ridge formation which also utilised modern beach observations and insights from other published models. This model specifically explains the character of the barrier sub-surface structure which is dominated by erosional storm beachfaces and

565 emphasises the importance of cut-and-fill of the beachface and backshore dune development in
566 forming ridges at an interdecadal timescale.

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Figure Captions

Figure 1: A) The coastline of southern New South Wales showing Twofold Bay and Disaster Bay and offshore environments (after Hudson, 1991). B) Sediment thickness within Twofold Bay and location of rocky reefs (after Hudson, 1991). C) Sub-aqueous sediments in Twofold Bay (after Hudson, 1991).

Figure 2: Elevation of the Boydtown prograded barrier from airborne LiDAR showing radiocarbon and OSL ages and the location of GPR transects (data used under licence from Land and Property Information NSW).

Figure 3: Elevation of the Wonboyn prograded barrier from airborne LiDAR showing radiocarbon and OSL ages and the location of GPR transect (data used under licence from Land and Property Information NSW).

Figure 4: Plot of age versus barrier width as a percentage for radiocarbon and OSL ages for Boydtown and Wonboyn.

Figure 5: Topographic profiles for the Boydtown and Wonboyn prograded barriers derived from LiDAR (see Figures 2 and 3 for transect locations).

Figure 6: Full sections (Boydtown A and B) and part sections (Boydtown C – F and Wonboyn) of GPR data using a 250 MHz antenna (see Figure 2 and Figure 3 for transect locations). (Full sections without interpretation are available as supplementary data).

Figure 7: Comparison of GPR-imaged beachface geometries with two modern profiles at Boydtown Beach. The modern profiles were collected during fair-weather conditions in December 2015 and immediately following a severe storm in June 2016. Shaded envelopes, which demarcate the variability of GPR-imaged beachface profiles traced every 5-10 m alongshore are shown for transects 'A' through to 'F' (see Figure 2 for locations). All profiles have been 'distance normalised' with the intersection of each profile with 0 m AHD acting as a fixed datum. Note that progradation has not occurred between the modern beach profiles in December 2015 to June 2016 as the x-axis shows 'relative distance' from the 0 m intersection point. Each envelope from GPR profiles 'A' through to 'F' contains between 10 and 50 individual relict beach profiles traced from the GPR data.

Figure 8: Comparison of GPR-imaged beachface geometries with two modern profiles at Wonboyn Beach. The modern profiles were collected during fair-weather conditions in August 2011 and immediately following a severe storm in June 2016. The coloured envelope demarcates the variability of GPR-imaged beachface profiles traced every 5-10 m alongshore for the shore-normal GPR transect at Wonboyn (see Figure 3 for location). This envelope represents 34 individual relict GPR-imaged beachfaces. All profiles have been 'distance normalised' with the intersection of each profile with 0 m AHD acting as a fixed datum. Note that progradation has not occurred between the modern beach profiles in August 2011 to June 2016 as the x-axis shows 'relative distance' from the 0 m intersection point.

Figure 9: Photos of Boydtown and Wonboyn before and after a severe storm event in June 2016. Photos A and B are from Boydtown looking north. Photos C and D are from Wonboyn looking south (ed = established foredune, id = incipient foredune, b = berm).

Figure 10: Eight stage model of beach-ridge formation showing a process of cut and recovery (Davies, 1957; Oliver et al., 2016) where foredune building occurs in the backshore (Hesp, 1984) as berm formation widens the beach and increases aeolian transport potential (McLean and Shen, 2006) (stage 1). During a storm event the beach is cut back (stage 2) and post-storm recovery occurs,

788 building the beach back up to its previous volume (stages 3 and 4). Under positive sediment budget
789 conditions the beach may accumulate a greater volume of sediment (stage 5) so that when the next
790 storm occurs, the beach cut and resulting storm beachface is seaward of the previous beach scarp
791 (stage 6). During the post storm recovery from this event (stage 7 and 8) the beach may accumulate
792 sediment and prograded seawards such that the established dune transitions to a relict dune and is
793 no longer actively being cut and recovered by storms or receiving wind-blown sediments. The
794 resultant preserved sub-surface structures from this ridge formation process are characterised by a
795 series of 'stacked' storm beachfaces because fair-weather beach profiles are eroded by the next
796 storm.

A **B** **C** **D**

Table 1: Radiocarbon ages for Boydtown barrier, Kiah Inlet and Wonboyn barrier derived from various materials. Samples from each barrier are arranged landward to seaward. Radiocarbon age in years BP is corrected for isotopic fractionation only. The calibrated radiocarbon age is presented in cal. yr BP according the calibration of Stuiver and Reimer (1993) using CALIB REV 7.0.1. and incorporates the mean correction factor of 450 ± 35 years from Gillespie and Polach (1979). The Delta R of 11 ± 85 for the calibration is also taken from Gillespie and Polach (1979). Reported error margins are ± 1 sigma.

Laboratory Code	Dated Material ¹	Radiocarbon Age (yr BP)	Calibrated radiocarbon age (cal. yr BP)
<i>Boydtown barrier</i>			
SUA2321	W	5590 ± 140	6340 ± 150
SUA2322	W + C	5810 ± 150	6570 ± 170
SUA2323	WS ²	6520 ± 170	7010 ± 210
SUA2324	SF	5350 ± 110	5720 ± 140
SUA2356	SF	3520 ± 120	3390 ± 180
SUA2325	SF	3080 ± 100	2870 ± 150
SUA2320	SF	2510 ± 110	2150 ± 170
SUA2318	WS ³	2090 ± 110	1660 ± 160
SUA2326	SF + WS	2360 ± 100	1980 ± 160
SUA2327	SF	2120 ± 110	1690 ± 160
SUA2328	SF + WS	1740 ± 100	1280 ± 140
SUA2329	SF	2030 ± 110	1570 ± 160
<i>Kiah Inlet exposed mud basin facies</i>			
SUA2315	W + C	4250 ± 130	4700 ± 170
SUA2316	WS + SF	4510 ± 110	4670 ± 170
<i>Wonboyn barrier</i>			
GX3635	SH	9100 ± 150	9840 ± 230
SUA900	SH	5765 ± 75	6150 ± 130
ANU1585	SH	5930 ± 90	6340 ± 130
SUA899	SH	4140 ± 70	4210 ± 160
SUA898	SH	3750 ± 80	3680 ± 150
GX4461	SH	3760 ± 130	3680 ± 200
SUA897	SH	3230 ± 70	3070 ± 90
ANU1396	SH	3610 ± 130	3510 ± 190
SUA896	SH	2610 ± 65	2270 ± 140
ANU1584	SH	3050 ± 90	2840 ± 140
SUA895	SH	2210 ± 70	1800 ± 140
SUA894	SH	2145 ± 65	1720 ± 130
GX3634	SH	1850 ± 125	1400 ± 160
SUA893	SH	1525 ± 65	1060 ± 110
SUA892	SH	1445 ± 65	1000 ± 120

¹WS = whole shell, SF = shell fragments, SH = shell hash, W = wood fragments, C = charcoal fragments

²Estuarine and marine species

³*Bankivia* sp.

Table 2: OSL ages for samples collected from relict ridges across the Boydtown and Wonboyn barriers.

Sample Code	-----Radionuclide Concentrations-----			-----Dose Rates-----						
	U (ppm)	Th (ppm)	K (%)	Beta (Gy/ka)	Gamma (Gy/ka)	Cosmic (Gy/ka)	Total Dose Rate (Gy/ka) ^c	D _e (Gy)	Over-dispersion (%)	OSL Age (years)
Boyd2	0.52 ± 0.02	2.52 ± 0.10	1.34 ± 0.03	1.05 ± 0.04	0.49 ± 0.01	0.18 ± 0.02	1.75 ± 0.07	2.04 ± 0.04	8.4 ± 1.4	1170 ± 60
Boyd4	0.40 ± 0.01	1.84 ± 0.07	1.52 ± 0.03	1.15 ± 0.04	0.49 ± 0.01	0.18 ± 0.02	1.85 ± 0.07	0.93 ± 0.01	2.9 ± 1.2	500 ± 20
Boyd6	0.55 ± 0.02	2.53 ± 0.10	1.44 ± 0.03	1.13 ± 0.04	0.52 ± 0.01	0.18 ± 0.02	1.86 ± 0.07	0.16 ± 0.01	20 ± 5	90 ± 5
Boyd9	0.63 ± 0.02	3.81 ± 0.15	0.77 ± 0.02	0.69 ± 0.03	0.42 ± 0.01	0.18 ± 0.02	1.33 ± 0.05	7.80 ± 0.10	5.8 ± 1.1	5870 ± 270
Boyd11	0.57 ± 0.02	3.25 ± 0.13	0.74 ± 0.01	0.66 ± 0.02	0.39 ± 0.01	0.18 ± 0.02	1.25 ± 0.05	3.88 ± 0.04	3.3 ± 0.9	3100 ± 140
Boyd13	0.41 ± 0.01	2.06 ± 0.08	1.68 ± 0.03	1.26 ± 0.05	0.54 ± 0.01	0.18 ± 0.02	2.01 ± 0.08	3.02 ± 0.07	11.2 ± 1.8	1500 ± 80
Boyd14	0.48 ± 0.01	2.34 ± 0.09	0.71 ± 0.01	0.60 ± 0.02	0.33 ± 0.01	0.18 ± 0.02	1.14 ± 0.05	9.07 ± 0.14	6.7 ± 1.2	7940 ± 380
Won1	0.16 ± 0.01	0.76 ± 0.03	0.32 ± 0.01	0.26 ± 0.01	0.13 ± 0.002	0.19 ± 0.02	0.61 ± 0.03	1.82 ± 0.09	23 ± 3	3010 ± 200
Won2	0.16 ± 0.01	0.86 ± 0.03	0.26 ± 0.01	0.22 ± 0.01	0.12 ± 0.002	0.19 ± 0.02	0.56 ± 0.03	1.87 ± 0.06	16 ± 2	3350 ± 200
Won3	0.14 ± 0.01	0.66 ± 0.03	0.25 ± 0.01	0.21 ± 0.01	0.11 ± 0.002	0.19 ± 0.02	0.53 ± 0.03	2.08 ± 0.05	7 ± 2	3900 ± 210
Won4	0.14 ± 0.01	0.76 ± 0.03	0.19 ± 0.01	0.17 ± 0.01	0.10 ± 0.002	0.19 ± 0.02	0.48 ± 0.02	2.17 ± 0.04	7 ± 1.4	4480 ± 250
Won5	0.15 ± 0.01	0.77 ± 0.03	0.33 ± 0.01	0.26 ± 0.01	0.13 ± 0.002	0.19 ± 0.02	0.61 ± 0.03	5.14 ± 0.64	59 ± 9	-
Won6	0.13 ± 0.01	0.71 ± 0.03	0.3 ± 0.01	0.24 ± 0.01	0.12 ± 0.002	0.19 ± 0.02	0.58 ± 0.03	0.70 ± 0.02	13 ± 1.9	1200 ± 70
Won7	0.15 ± 0.01	0.94 ± 0.04	0.35 ± 0.01	0.28 ± 0.01	0.14 ± 0.002	0.19 ± 0.02	0.64 ± 0.03	0.29 ± 0.02	30 ± 5	450 ± 40
Won8	0.21 ± 0.01	1.02 ± 0.04	0.28 ± 0.01	0.24 ± 0.01	0.14 ± 0.002	0.19 ± 0.02	0.60 ± 0.03	4.63 ± 0.08	8 ± 1.3	7770 ± 400
WN-Fdune	0.21 ± 0.01	0.91 ± 0.04	0.54 ± 0.01	0.42 ± 0.02	0.19 ± 0.003	0.19 ± 0.02	0.83 ± 0.03	0.06 ± 0.01	28 ± 5	70 ± 5

*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).

** 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).

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

Table 3: Boydtown and Wonboyn barrier progradation metrics calculated from airborne LiDAR and the position and age of OSL samples. Two sets of values are given for each site as the plots of barrier width according to age for each site (Figure 4) indicate two phases of progradation at differing rates.

Site	Time period (yrs ago)	Progradation rate (m/yr)	Average ridge lifetime (yrs)	Volume (m ³)	Historical accumulation rate (m ³ /yr)	Accumulation rate for average historical beach length (m ³ /m/yr)
Boydtown	7940 to 1500	0.16	280	3 127 969	486	0.46
Boydtown	1500 to present	0.65	50	4 071 592	2714	1.83
Wonboyn	7770 to 4480	0.08	410	4 822 346	1466	0.56
Wonboyn	4480 to present	0.32	130	20 676 589	4615	1.34

Boydton A

Boydton B

Boydton C

Boydton D

Boydton E

Boydtown F

Wonboyn GPR