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Transition from marine to fluvial-dominated sediment supply at Shoalhaven prograded barrier, southeastern Australia

Abstract

Prograded barriers are depositional coastal landforms which have the potential to reveal changes in the primary drivers of coastal evolution within their varied morphology. Beach ridges and intervening swales preserve paleoenvironmental records of coastal processes, relative sea level and storm events. Optically stimulated luminescence (OSL) dating of quartz grains, airborne LiDAR-derived morphology, and sediment texture and mineralogy reveal four different periods of morpho-sedimentary progradation history in the Shoalhaven barrier system in southeastern Australia. The barrier is composed of approximately 40 ridges that occupy an area of 15.2 km², comprising an estimated sand volume of approximately 88,000,000 m³ above mean sea level. OSL dating of ten samples taken from a 940-m long transect across the Holocene system indicated that the barrier prograded at a slow rate of approximately 0.12 m/yr from 6130 ± 330 to 2400 ± 130 years ago and subsequently at a higher rate of 0.22 m/yr until 600 ± 130 years ago. More recently, an increase in historical accumulation and progradation rates has favoured development of an anomalously high foredune fronting the system with the formation of lower ridges in the past two centuries. Increasing angularity and feldspar content observed via Scanning Electron Microscope (SEM) and determined using X-ray Diffraction (XRD) analysis, respectively, imply a transition in sediment supply. Progradation has been sustained through delivery and reworking of marine sediments from offshore following the marine transgression, subsequently augmented by fluvial sands discharged to the coast by the Shoalhaven River. The adjustment in progradational rates and sediment provenance influenced the morphology and spacing of individual ridges and the regressive system as a whole. Average progradation rates for the Shoalhaven barrier, revised from those previously reported using radiocarbon dating, are considered lower than most of barriers studied in similar coastal environments around Australia, indicating the different ways that similar progradation systems have evolved.

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Transition from marine to fluvial-dominated sediment supply at Shoalhaven prograded barrier, southeastern Australia

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ABSTRACT

Prograded barriers, are depositional coastal landforms which have the potential to reveal changes in the primary drivers of coastal evolution within their varied morphology. Beach ridges and intervening swales preserve paleoenvironmental records of coastal processes, relative sea level and storm events. Optically stimulated luminescence (OSL) dating of quartz grains, airborne LiDAR-derived morphology, and sediment texture and mineralogy reveal four different periods of morpho-sedimentary progradation history in the Shoalhaven barrier system in southeastern Australia. The barrier is composed of approximately 40 ridges that occupy an area of 15.2 km², comprising an estimated sand volume of approximately 88,000,000 m³ above mean sea level.

OSL dating of ten samples taken from a 940-m long transect across the Holocene system indicated that the barrier prograded at a slow rate of approximately 0.12 m/yr from 6130 $\pm$ 330 to 2400 $\pm$ 130 years ago and subsequently at a higher rate of 0.22 m/yr until 600 $\pm$ 130 years ago. More recently, an increase in historical accumulation and progradation rates has favoured development of an anomalously high foredune fronting the system with the formation of lower ridges in the past two centuries. Increasing angularity and feldspar content observed via Scanning Electron Microscope (SEM) and determined using X-ray Diffraction (XRD) analysis, respectively, imply a transition in sediment supply. Progradation has been sustained through delivery and reworking of marine sediments from offshore following the marine transgression, subsequently augmented by fluvial sands discharged to the coast by the Shoalhaven River. The adjustment in progradational rates and sediment provenance influenced the morphology and spacing of individual ridges and the regressive system as a whole. Average progradation rates for the Shoalhaven barrier, revised from those previously reported using radiocarbon dating, are considered lower than most of barriers studied in similar coastal environments around Australia, indicating the different ways that similar progradation systems have evolved.

Keywords:

Strandplains; OSL dating; Relict foredune ridges; Sediment provenance

1. Introduction

Many contemporary beaches are the seawardmost active part of a more extensive regressive or transgressive sedimentary coastal deposit which has accumulated over a longer time scale. Progradational barriers are depositional sequences that build seaward along coastlines with positive sediment budgets (Roy et al., 1994).

These prograded barriers, also known as strandplains, beach-ridge plains or beach-ridge systems, are ubiquitous landforms that provide a palaeoenvironmental record within the sequence of successive beach ridges and intervening swales (Tamura, 2012; Tanner, 1988), that have a potential for understanding sea-level variations, sediment supply and paleo-storm activity during the postglacial coastal evolution (Scheffers et al., 2012).

Prograded barriers are distributed worldwide (Scheffers et al., 2012; Tamura, 2012) and have been studied in several locations, including Mexico (Curry et al., 1969), South Carolina (Moslow and Heron, 1979), Brazil (Dominguez, 1996), Northern Ireland (Carter, 1986), Spain (Goy et al., 2003), Malaysia (Nossin, 1965), Russia (Møller et al., 2002), Sierra Leone (Anthony, 1991) and Australia (Thom et al., 1981b).

Discussion on the origin of barriers dates back to the mid-19th century (De Beaumont, 1845), when the concept of beach ridges was first introduced

(Redman, 1852; 1864). Since then, divergences in coastal processes involved in the formation of beach ridges, which can vary from system to system or within the same system (Anthony, 2008; Goslin and Clemmensen, 2017; Nott et al., 2015), have caused confusion in the adopted terminology (Anthony, 2008; Hesp, 2006; Otvos, 2000; Tanner, 1995; Taylor and Stone, 1996) and in the proposition of models of formation (Goslin and Clemmensen, 2017; Sanderson et al., 1998; Tamura, 2012). A well-accepted model for sandy beach ridge formation involves beachface progradation under fairweather wave conditions following storm erosion (Tamura, 2012). This model, which attributes the contrast between the ridge and swale to aeolian sand accumulation, requires no sea-level oscillations and evolved from Davies' (1957) idea of a berm forming the nucleus for beach ridge development. Variations of this model have been adopted by several researchers including Bird (1960), Thom (1964), Hails (1969), Bird and Jones (1988) and Dougherty (2014), despite different views on the initiation of ridges by McKenzie (1958) and Hesp (1984).

Early investigations to determine the chronology of beach-ridge plains in Australia started with inferences based on the degree of soil development (Burges and Drover, 1953). Later investigations in the mid-late 1970's employed radiocarbon dating of organic materials (Thom, 1978). The first studies in southeastern Australia used uncased solid flight power augers to core to depths of up to 40 m into various ridge plain sequences (Thom et al., 1981b), and the majority of sediments collected for radiocarbon dating using this

technique was ‘shell hash’ (skeletal carbonate fragments derived from a variety of marine invertebrates), with occasional samples of organic mud, peat, charcoal and wood (Thom et al., 1981b).

The radiocarbon dating program on the east coast of NSW resulted in a conceptual model of prograded barrier morphology and chronology (Roy and Thom, 1981; Roy et al., 1980), whereby progradation was thought to have initiated during the final stages of the postglacial marine transgression in the mid- to late Holocene (Hesp and Short, 1999; Roy et al., 1980), when large volumes of sediment were supplied to the coast from the continental shelf (Roy and Thom, 1981; Thom et al., 1981a; 1981b; 1978), and progressed with varying degrees of continuity to around 2500-1000 cal. yr BP (Thom 1978; Thom et al. 1978; 1981b). Most prograded barriers in the region, blocking off drowned river valleys and estuarine lagoons, were formed over transgressive sediments of early Holocene age, which lie below sea level and are buried beneath regressive sands (Thom, 1983). Radiocarbon chronologies have also been particularly useful in modelling shoreface sand delivery (Cowell et al., 2001) and improving forecasts of future shoreline change (Kinsela et al., 2016).

Two main sediment populations are recognized along the NSW coast and named in relation to their immediate provenances. Marine sediments are generally rounded, well sorted quartz sands with usually less than 10 % lithic and feldspar grains, and include shell fragments and a mature heavy mineral assemblage. Marine sands are thought to be the result of marine/aeolian

reworking on the continental shelf during more than one eustatic cycle. By contrast, fluvial sediments are mainly trapped in estuaries (rarely reaching the open coast) and comprise more angular sands, richer in lithic fragments and feldspars than marine sediments. (Jones and Davies, 1979; Roy and Crawford, 1977).

It was shown in the late 1970's and early 1980's that thermoluminescence (TL) dating could be used to date the deposition of sediments in a number of locations around Australia (Huntley et al., 1993; 1994). This not only allowed the dating of coastal deposits where radiocarbon material was lacking (Bryant et al., 1994), but also supported the idea that sea level had been higher than the present along the NSW coast (Jones et al., 1979;) Young et al., 1993).

More recently, advances in remote sensing technology such as airborne light detection and ranging (LiDAR) and optically stimulated luminescence (OSL) dating of sand grains (Huntley et al., 1985; Jacobs, 2008) have enabled a more comprehensive understanding of formative processes and development of prograded barriers, including their detailed paleoenvironmental reconstruction (Costas et al., 2016; Murray-Wallace et al., 2002; Oliver et al., 2017a; Tamura, 2012). Topographical advances are driven by the ability of LiDAR to determine detailed elevation underneath thick canopy of forests that cover some prograded barriers around the globe. OSL dating of quartz grains reveals the time elapsed since deposition of sediment, in contrast to radiocarbon dating which records death and the cessation of radiocarbon uptake by biological material.

The chronological datasets for prograded barriers in southeastern Australia demonstrate substantial variability attributable to local variations in sediment supply, inherited geology and wave conditions. Application of OSL dating has provided an important reassessment at several key sites, demonstrating that progradation did not cease around 2500-1000 years ago but rather continued to near present-day (Oliver et al., 2017a; Oliver et al., 2015).

This study reconstructs the Holocene history of the Shoalhaven prograded barrier system on the south coast of NSW, Australia, using LiDAR elevation data, OSL dating and sediment analysis. The prograded barrier was formed along Seven Mile Beach to the immediate north of the Shoalhaven River which has contributed sand to the coast for the past few millennia (Short and Woodroffe, 2009; Wright, 1970). The study site and region as a whole, are ideal field laboratories, with a relatively undisturbed landscape, two distinct sediment populations based on their respective provenances (Jones and Davies, 1979; Roy et al., 1980) with excellent luminescence characteristics (Oliver et al., 2015). Besides the palaeo reconstruction, we hope the chronological interpretation can contribute to better understanding of sediment budgets and future shoreline change for the area.

2. Study site

The Shoalhaven prograded barrier is located approximately 100 km south of Sydney on the high-energy (Fig. 1), wave-dominated southeastern coast of Australia (Roy, 1997; Wright, 1977). The coast is subjected to a generally moderate south to southeasterly wave climate, and it is periodically affected by large coastal storms generated from a range of synoptic weather systems (Shand et al., 2011). Littoral drift is from south to north, due to the oblique coastal orientation in respect to the dominant swell direction. Tides are semidiurnal (spring range of 1.5 m at Crookhaven Heads) with significant diurnal inequalities (Wright, 1970).

Despite its name, the long Seven Mile Beach sweeps in a gentle arc for 17 km from Crookhaven Heads in the south to Gerroa in the north. The northern end comprises a wide flat beach with waves spilling over a wide shallow attached bar cut by rip currents every 300 m, whereas at Shoalhaven Heads and Comerong Island, a double bar system operates along most of the beach with an attached bar cut by periodic rips (Short, 2007). The shape of the beach is also influenced by the Shoalhaven River entrance at Shoalhaven Heads. During times when the entrance is breached, the river delivers large amounts of sediment in the form of a crescentic river-mouth bar seawards of the outlet and as broad subaqueous levees capped by swash bars, and post-depositional shoreward return of sands by shoaling waves produces a constricted outlet, leaving a pronounced dune scarp on the adjacent beach (Wright, 1977).

The Shoalhaven River drains a catchment of more than 7,000 km² into the Tasman Sea. The catchment is composed of two major geologic provinces. The upper and middle catchment lie across the Palaeozoic Lachlan Fold Belt, whereas the lower section is incised through the southern Sydney Basin (Nott, 1990). A temperate, subhumid climate (Köppen type Cfb) is experienced in most of the upper and middle catchment, with average annual rainfall of 900 mm for the whole catchment. The rainfall pattern is spatially variable with approximately twice the amount of rainfall in the lower catchment than further upstream (Carvalho and Woodroffe, 2015). The natural course of the Shoalhaven River has been modified in the lower estuary and its flow was artificially diverted to exit at Crookhaven Heads, after the construction of Berrys Canal in 1822, forming Comerong Island (Umitsu et al., 2001; Young et al., 1996). Since then, Berrys Canal directs the flow of the Shoalhaven River to exit at Crookhaven Heads. The former mouth of the river at Shoalhaven Heads has been impounded by the deposition of a sandy berm and the outlet is breached temporarily only following major floods, with the beach berm gradually re-establishing over time. A more recent modification to the catchment with direct implications for the delivery of sediments to the coast occurred after the construction of Tallowa Dam in 1976, which has smoothed the flash flooding of the river considerably, and trapped part of its fluvial sediment load (Carvalho and Woodroffe, 2017).

Fig. 1. Location of Shoalhaven progradational barrier showing onshore Quaternary and offshore main features (a), sediment samples and RTK-GPS/Total Station points (b) and zoomed in RTK-GPS/Total Station points (c, e, f) and sediment samples (d).

The beach-ridge development and beach sediments at Seven Mile Beach-Comerong Island were first examined by Wright (1970), whose investigations aimed to elucidate the depositional history and processes of formation of the barrier system. Wright concluded that the topographic and sedimentological character of the sand deposits flanking the mouth of the Shoalhaven River are related to two major control variables: the wave regime and proximity to the mouth of the river, and that the river efflux at Shoalhaven Heads was the principal source of sand to the relict ridges. Subsequently, radiocarbon dating of

shell material from the Shoalhaven barrier demonstrated that progradation had occurred from 6500 cal. yr BP to 1000 cal. yr BP (Thom et al., 1981b). 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 (Thom et al., 1981b).

Stratigraphic description of the barrier in Thom (1983) indicates an aeolian ridge cap composed of well-sorted medium to fine quartzose sand up to 3 m thick, covering the barrier. The aeolian cap overlies a coarser, beach sand facies which grades downwards into progressively finer nearshore sands. Below this regressive stratigraphy, the upper part of the transgressive sequence is characterised by wave-reworked medium to coarse moderately sorted sands, often rich in shell fragments and gravel. No distinct trend in grain size is observed vertically. A mixed lagoonal and open ocean fauna assemblage with the typical nearshore gastropod *Bankivia fasciata* is common. Early Holocene lagoonal clays containing abundant intact bivalves (*Notospisula parva*) occur at the base of this transgressive sequence.

Extensive drilling across the alluvial plains east of Nowra also revealed that the infill of the mature Shoalhaven estuary commenced around the basin margin and appears to have been largely complete by 3000 cal. yr BP (Umitsu et al., 2001; Woodroffe et al., 2000), following the broad model suggested by Roy (1984).

Seismic results from the inner continental shelf in the region provided by Roy and Ferland (1987) indicate that the nearshore adjacent to Shoalhaven Heads has a very low gradient (0.3°) formed by the seaward part of the prograded barrier, a 15-22 m thick sand unit beneath the beach that thins seawards until a depth of 25 m. Beneath this shoreface accretion wedge, a layered sequence, at least 10 m thick, extends to depths of 30 m. This unit is composed of planar, gently landward-dipping beds, and possibly represents an estuarine/backbarrier muddy sequence. Seawards of the shoreface accretion wedge, a horizontally-bedded surficial sediment blanket less than 10 m thick covers the seabed and beneath this sequence, as well as the layered sequence, chaotic bedding of a channelled sequence occurs, suggesting fluvial channelling by the meandering Shoalhaven River system during lower sea levels.

3. Methods

3.1. Barrier morphology and volume calculation

Airborne LiDAR data were acquired by NSW Land and Property Information (LPI) between December 2010 and April 2011, and provided in separate datasets of 2 x 2 km tiles (Fig. 1). Data processing consisted of converting LAS files into multi points, then to single points and finally creating a triangular irregular network (TIN). The data were processed for bare ground

using returned values with a minimum point density of 1 point/m². Volumes of barrier sediment above Mean Sea Level (MSL) were calculated from 0 m Australian Height Datum (AHD, corresponds to MSL) by splitting the barrier polygon using specific ridges, in order to compare the subaerial store of sediment through time and relate this to the barrier morphology and ridge formation process. Accuracy assessment of LiDAR-derived elevation was carried out by comparison with 270 elevation points taken at three locations with total station and RTK-GPS as indicated in Fig. 1

3.2. Sediment sampling

Locations for sediment and OSL sampling were carefully selected across the barrier width and along an existing access track with the aid of LiDAR-processed map. Ten samples in total were collected from auger holes at depths of 1 m below the barrier ridge surface, from the undisturbed aeolian cap of the regressive facies. Approximately 150 grams of sand exhumed from shallow auger holes during collection of samples for OSL dating were bagged for texture and mineralogy analyses. OSL samples were capped in light-safe plastic and metal tubes and taped to preserve soil moisture content.

3.3. OSL dating and ¹⁴C recalibration

Sample tubes were uncapped under dim red-light conditions at the University of Wollongong OSL dating laboratory. Approximately 2-4 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 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 per sample were prepared on stainless steel discs and were loaded onto a Risø TL/OSL reader for stimulation, measurement and irradiation. A preheat and cutheat combination of 180 °C and 160 °C, respectively, was adopted for all D_e measurements after Oliver et al. (2015). D_e values were estimated using a modified single-aliquot regenerative-dose (SAR) procedure (Murray and 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 and

Wintle, 2000) and OSL-IR depletion ratio test (Duller, 2003). Aliquots which had recycling ratios beyond 1.0 ± 0.1 were rejected. Additionally, only aliquots with less than 5% post-IR OSL signal depletion and less than 5% recuperation were accepted. 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).

Radiocarbon dating of "shell hash" samples taken by Thom et al. (1981b) from three transects drilled across the Shoalhaven barrier in the vicinity of profiles P1, P3 and P5 (Fig. 2) were recalibrated according to the procedure of Stuiver and Reimer (1993) using CALIB REV 7.0.1. The Delta R (11 ± 85) used for the calibration is taken from Gillespie and Polach (1979).

3.4. Sedimentary texture

In the laboratory, samples exhumed from shallow auger holes were washed for salt extraction, dried in an oven at 60° C and subsampled. Sample colour description was conducted for all samples using a Munsell soil colour chart. To determine grain size and statistical parameters, all sediment content in sample bags was dry sieved at 0.5 phi intervals down to 0 phi. Size fractions finer than 0 phi were determined by laser diffraction using a Malvern Mastersizer 2000.

Grain size statistics have been calculated using Folk and Ward (1957) formulae. Individual sample results were obtained by running the grain size distribution and statistic software GRADISTAT (Blott and Pye, 2001).

Once grain size was determined, the remaining material finer than 0 phi was dry sieved to isolate the medium sand fraction (1-2 phi), to be used for mineralogy and Scanning Electron Microscope (SEM) analysis. A qualitative analysis of roundness and sphericity of grains was carried out using images taken with a Phenom XL SEM on eight samples (SMB11b, SMB11, SMB12, SMB13, SMB13b, SMB15, SMB16 and SMB16b). Samples were mounted on a metal specimen plug with double-sided sticky tape and analysed with a four-segment BackScatter Detector (BSD) in medium vacuum mode with electrons accelerated to 10 kv after leaving the filament to generate Secondary Electron Images (SEI).

3.5. Mineralogy

Mineralogical composition for all samples was determined using X-ray diffraction (XRD). Medium sand fractions (1-2 phi) were ground using a Tema mill for 30 seconds. Disk mill was cleaned between samples to avoid cross-contamination. Following XRD analysis, results were corrected to the appropriate 2 theta spacing using Traces software, and quantification of mineral phases was performed by expressing the composition of crystalline material

within each sample as a percentage of dry weight using Siroquant software. For each sample, background values were subtracted and analysis conducted until minimum chi-square values were obtained.

Fig.2. Elevation (m AHD) of Shoalhaven prograded barrier from LiDAR-derived data showing location of topographic profiles P1- P6 (a) and OSL ages in years (b). Profiles P1, P3 and P5 are approximate locations to north, central and south profiles of Thom et al. (1981b), respectively. OSL and radiocarbon ages plotted against dimensionless barrier width (c).

4. Results

4.1. Barrier system morphology

Interpretation of LiDAR shows it to be composed of a series of 38-42 ridges (from the inner-ridge to the outer-foredune ridge) that occupy an area of 15.2 km² and an estimated volume of approximately 88,000,000 m³ above 0 m AHD, or approximately 5200 m³/m assuming the current shoreline length.

In general, the inner/older ridges are higher than the outer/younger ones (Fig.2). Individual ridges are also higher near Shoalhaven Heads than at both north (Gerroa) and south (Comerong Island) ends. The highest elevation occurs on the modern foredune, and reaches 13.6 m above AHD in the middle of the embayment. This ridge decreases in height towards the south (8.8 m) and north (5.3 m) ends of Seven Mile Beach and reaches 6.6 m in the middle of Comerong Island. The width of the beach-barrier system decreases toward Gerroa and Comerong Island. The innermost ridge is located 1190 m landwards from the foredune ridge at its widest. The sequence seems to continue towards Comerong Island despite the absence of this ridge due to past erosion caused by lateral migration of the river.

Comparison between LiDAR-derived elevation and RTK-GPS and total station indicated high accuracy of the airborne laser sensor. R² values of 0.98 (n = 47), 0.91 (n = 68) and 0.75 (n = 155) were obtained for correlations with points

collected with total station in the north, south and with the RTK-GPS, respectively. Nevertheless, missing data from the LiDAR processing can be particularly observed along a stretch of 600 m on the modern foredune, near the location where sediment samples were taken (Fig. 2b). The reasons behind the point sparsity in the area are outside the scope of this study and probably associated with processing/classification issues performed by the LiDAR contractor.

4.2. OSL chronology and progradation rates

OSL dating indicates the burial time of quartz grains collected from 1 m depths across the barrier ridges with ages systematically younging in a seaward direction (Table 1, Fig. 2), apart from the second seawardmost sample (SMB16) collected on the anomalous highest ridge. This sample is 20 years younger than SMB16b, although statistically equivalent. OSL sampling and morphostratigraphy of the most landward ridge is subject to a detailed investigation which concerns the barriers' transition from transgression to regression. Here we adopted an age of 7700 years based on the sea-level curve for the southeast coast of Australia (Sloss et al., 2007) and several other studies of barrier evolution (Oliver et al., 2017a; Oliver et al., 2015; Oliver and Woodroffe, 2016).

Table 1

Measured concentrations of radionuclide, dose rates and OSL ages for samples collected from relict ridges across Shoalhaven barrier, NSW.

Sample ID	Radionuclide concentration			Dose rates			Total Dose		Over-dispersion (%)	OSL age (years)
	U	Th	K	Beta	Gamma	Cosmic	Rate	D _e (Gy)		
	(ppm)	(ppm)	(%)	(Gy/ka)	(Gy/ka)	(Gy/ka)	(Gy/ka)			
SMB11b	0.45	1.64	0.23	0.25 ± 0.01	0.18 ± 0.003	0.17 ± 0.02	0.63 ± 0.03	3.88 ± 0.07	8 ± 1	6180 ± 330
SMB11	0.36	1.51	0.32	0.30 ± 0.01	0.18 ± 0.003	0.17 ± 0.02	0.69 ± 0.03	3.23 ± 0.1	15 ± 3	4710 ± 280
SMB12	0.34	1.66	0.32	0.30 ± 0.01	0.19 ± 0.004	0.17 ± 0.02	0.70 ± 0.03	2.45 ± 0.04	8 ± 1	3570 ± 180
SMB13	0.43	1.93	0.35	0.34 ± 0.01	0.22 ± 0.004	0.17 ± 0.02	0.76 ± 0.03	1.83 ± 0.04	11 ± 2	2400 ± 130
SMB13b	0.38	2.04	0.37	0.35 ± 0.01	0.22 ± 0.004	0.17 ± 0.02	0.77 ± 0.03	1.57 ± 0.07	12 ± 4	2030 ± 140
SMB14	0.39	1.98	0.34	0.33 ± 0.01	0.21 ± 0.004	0.17 ± 0.02	0.75 ± 0.03	1.05 ± 0.02	7 ± 2	1410 ± 70
SMB15	0.44	2.11	0.47	0.43 ± 0.02	0.26 ± 0.01	0.17 ± 0.02	0.89 ± 0.04	0.86 ± 0.01	6 ± 2	970 ± 50
SMB16c	0.35	1.64	0.34	0.31 ± 0.01	0.19 ± 0.004	0.17 ± 0.02	0.71 ± 0.03	0.43 ± 0.01	12 ± 2	600 ± 30
SMB16	0.51	2.2	0.46	0.43 ± 0.02	0.26 ± 0.01	0.17 ± 0.02	0.90 ± 0.04	0.14 ± 0.01	11 ± 5	160 ± 10
SMB16b	0.48	2.34	0.44	0.41 ± 0.02	0.26 ± 0.01	0.17 ± 0.02	0.88 ± 0.04	0.16 ± 0.01	11 ± 3	180 ± 10

* 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). Moisture content of $5\% \pm 2.5\%$ was assumed for all samples.

SMB11b, the landwardmost analysed sample, indicated that approximately 17% of the barrier width is dated $6,180 \pm 330$ years or older. Considering the 1,028 m of progradation since that time, an average progradation rate of approximately 0.17 m/yr can be calculated for the barrier system until present

time (Table 2). Sample SMB13, taken from a ridge located more than half (52 %) of the barrier's width suggests that most of the barrier was formed before 2400 ± 130 years ago. The time elapsed between these two OSL ages indicates that progradation rate slightly decreased from 0.13 to 0.12 m/yr during this period. However, due to age uncertainties these rates can be considered equivalents. From $2,400 \pm 130$ to 600 ± 30 years ago, an average progradation rate of 0.22 m/yr (or 0.2-0.24 m/yr, assuming age uncertainties) occurred. The fastest rate during this period occurred between 970 ± 50 and 600 ± 30 years ago (0.27 m/yr; or 0.22-0.34 m/yr assuming age uncertainties). In the past 600 years, an average progradation rate of 0.32 m/yr was inferred. Breaking down this 600 years using the OSL age obtained for the seawardmost ridge (SMB16b), a progradation rate of approximately 0.18 m/yr is obtained from 600 ± 30 to 180 ± 10 years ago, and 0.63 m/yr in the past 180 years.

The average ridge 'lifetime' at Shoalhaven barrier is reflective of the changing progradation rate during barrier history. Assuming that barrier initiation started 7,700 years ago, an average ridge lifetime of 183 years per ridge for the whole barrier occurred (Table 2). Breaking this average into different progradational phases, an initial average ridge lifetime of 190 years was calculated until 6,180 years ago, followed by an increase to 252 years until 2,400 years ago, then changed substantially to 120 years until 600 years ago. Four ridges developed in the past 600 years (average of 150 years per ridge).

However, the age obtained at SMB16b (180 ± 10 years ago) indicated that each of the three most recent ridges took an average of 60 years to form.

Approximately $45,000,000 \text{ m}^3$, which is equivalent to more than half of the total barrier volume of sediment stored above MSL, was deposited before 2,400 years ago. Historical accumulation rate, ignoring OSL age uncertainties, shows a constant increase towards present time with initial rates of approximately $8,000 \text{ m}^3/\text{yr}$ increasing to more than $23,000 \text{ m}^3/\text{yr}$ after 600 years. However, when sediment supply is considered as a value per meter of beach, a decreasing rate (assuming uncertain barrier initiation at 7,700 yr BP) is observed between 6,180 and 2,400 years, as a function of the barrier expansion to the north. After this period, accumulation rate per average historical beach length increased again.

Table 2

Barrier progradation metrics calculated from airborne LiDAR and OSL ages.

Time period (years ago)	Progradation rate (m/yr)	Average ridge lifetime (yr)	Volume ($10^3 \times \text{m}^3$)	Historical accumulation rate (m^3/yr)	Accumulation rate per average historical beach length ($\text{m}^3/\text{m}/\text{yr}$)
7,700* to present	0.17*	183*	~87,770	11,398*	0.92*
7,700* to 6,180	0.13*	190*	~12,230	8,048*	0.96*
6,180 to 2,400	0.12	252	~32,750	8,663	0.83
2,400 to 600	0.22	120	~28,780	15,991	1.19
600 to present	0.32	150	~13,870	23,113	1.38

*These calculations assume that barrier initiation started at 7,700 years ago.

4.3. Texture and mineralogy

Grain size analysis indicated that all samples were composed of well sorted ($0.41-0.5 \phi$), symmetrical (0), mesokurtic ($0.94-0.96$) medium sand. The mean grain size of all samples varied from 1.62ϕ to 1.93ϕ and in general, a slight decrease in size is observed in a seaward direction (Fig. 3).

Fig. 3. Mean grain size for all samples organised in a seaward direction determined using Folk and Ward (1957) logarithmic graphical measures. Vertical bars indicate standard deviation (sorting).

SEM analysis of sediment grains in the 1-2 phi fraction of selected samples (Fig. 4) showed that grains in SMB11B, SMB11, SMB12 and SMB11 samples were much more rounded and circular than the more seaward counterparts (SMB13b, SMB15, SMB16 and SMB16b). The images also indicate that angular and sub-angular sediments were observed in the old SMB11b and SMB11 samples indicating the presence of less reworked sediments of probably fluvial source as far back as 6180 ± 330 years ago. Furthermore, sediment grains in sample SMB13b are angular to very angular indicating that grains of fluvial origin masked the more rounded marine sediments by 2030 ± 140 years ago.

Mineralogy analysis was performed to a satisfactory Chi square value (Table 3) and revealed that quartz content varied from 88 % to 93.7 % in dry weight in the samples. A general decreasing trend in quartz content was observed in a seaward direction. Feldspars were observed in all samples with total concentration varying from 5.7 % to 11.5 %, and opposite to quartz, a general increase in content was observed in a seaward direction, indicating the increasing role of fluvial sediments in relation to marine material reworked from the shoreface. Microcline was the most common form of feldspar with concentration varying from 4.6 % to 7.3 %. Albite, labradorite and orthoclase were also present and concentration of these minerals was below 2.2 % and negligible/absent in several samples. The sum of K feldspars (orthoclase and microcline) concentration also increased in a seaward direction, in good

agreement with the increasing K % seawards in radionuclide concentration (Table 1).

Clay minerals were observed as illite and kaolinite in most samples and the sum of concentration of these minerals varied from 0.4 % to 1.7 %. However, no general trend in any direction could be observed. Sample colours were in the Yellow-Red hue spectrum, and samples become slightly darker (from 8/ to 7/) in value and lighter (/4, /3 and /2) in chroma, in a seaward direction.

5. Discussion

5.1. Barrier morphology formed by two distinct sediment provenances

The Shoalhaven prograded system is located within a closed compartment constrained by the headlands of Black Head at Gerroa (north) and Crookhaven Heads (south), which hinder losses of sediment to the north and contributions from the south. This inherited geology, although not unique to this system, contrasts with other studied barriers in NSW such as Moruya and Woody Bay, which possibly allowed northwards bypassing of sediment in the past, or the Tuncurry system, which had restricted or no downdrift sediment transport to the north, but received alongshore contributions to the south (Kinsela et al., 2016; Roy et al., 1997). Apart from the marine supply, the Holocene Shoalhaven

prograded system has developed as a result of sediment contribution from one of the largest catchments in southern NSW that discharges into the Tasman Sea.

The Shoalhaven barrier does not contain other landform elements such as blowouts, parabolic dunes or transgressive dunes as observed in other nearby prograded systems, such as Fens and Newcastle (240 and 270 km further north), where the northern ends developed higher ridges that evolved into transgressive dunes. This is probably due to the north-south orientation of the embayment, compared with the southeast-facing embayments further north (Short, 1988). The inner/older ridges of Shoalhaven barrier are generally higher than the outer/younger ones suggesting that more time was available to construct the ridges, as indicated by the higher average time to form the older ridges (until 2400 years ago) than the younger ones (Table 2). This is also corroborated by the low accumulation rate per average historical beach length calculated from barrier initiation until 2400 years ago, which suggests that availability of sediments to form ridges was lower in the distant past than in more recent years.

Individual ridges are also higher near Shoalhaven Heads than at both north (Gerroa) and south (Comerong Island) ends (Fig. 2). One can envisage that the reworking of the marine sediments following the last transgression associated with new inputs of sediments from the Shoalhaven River via Shoalhaven Heads have contributed to this trend of slight decrease in ridge height away from the river mouth, that is in contrast to what is observed in other prograded barriers in NSW such as Moruya, Callala and Pedros (where ridges are higher in the north

than close to the river mouth in the south) or Merimbula (where ridges are higher in the middle than close to the estuaries at both ends of embayment) as shown in (Oliver et al., 2017c). A combination of its geologic inheritance, orientation to the general waves and wind climate, associated with its varying riverine supply of sediment at Shoalhaven Heads and not in the southern end of the embayment, exerts control on its morphology. Ridge alignment, continuity and height trends corroborate previous conclusions that past processes were significantly similar to those in the present, and that the Shoalhaven River has been the principal contributor to barrier progradation (Wright, 1970). However, shape and mineralogical information presented here and also by Wearne (1984) for samples located in the vicinity of profiles P1, P3 and P5, indicate a consistent and steady increase in lithics (feldspar and rock fragments) and corresponding decrease in quartz seawards along P3 and P5, and that sediments along profile P1 have a similar mineralogy to those from modern Seven Mile Beach. Ridge alignment also suggests that the northern section of the Shoalhaven barrier is relatively modern (most ridges are younger than 2400 yr old), implying that the Shoalhaven River has become a significant contributor to barrier progradation.

These findings suggest a varying importance of marine and fluvial sediment contributions during barrier development, with the former having a major role during barrier initiation and the Shoalhaven River exerting an increasing influence on barrier progradation by supplying relatively increased amounts of

fluvial sediment to the younger ridges. It also corroborates the idea propounded by Wright (1970) that the beach-ridge sequence appears to have received fluvial input since sea-level stabilization, and that the Shoalhaven River carried sediment to the coast throughout the mid- and late Holocene, as indicated by the fluvial sediment associated with molluscs dating 6090 ± 60 cal. yr BP adjacent to the northern part of Berrys Canal, collected by Young et al. (1996). It is also easy to envisage that fluvial contribution increased after the infill of the estuarine basin that appears to have been largely complete by 3000 cal. yr BP according to Woodroffe et al. (2000), which broadly corresponds to the switch in progradation rate observed around 2400 ago.

Despite the anomalously high foredune fronting Seven Mile Beach being a common feature in several other barriers including Fens, Moruya, Boydtown, Wonboyn (NSW), Guichen Bay (South Australia), and Keppel Bay (Queensland), the difference in heights and OSL ages is evident when compared with the foredune of most prograded systems. At Shoalhaven barrier, the high foredune reaches 13.6 m above AHD, whereas at Boydtown it is less than 6 m, at Wonboyn less than 8 m (Oliver et al., 2017a), and at Guichen Bay less than 10 m (Murray-Wallace et al., 2002). Height differences between the anomalous foredunes of these progradational systems in NSW, may be partially related to the average height of beach-ridge plains, especially the younger ridges, as it seems that the lower the plain, the lower the anomalous foredune as indicated by profiles shown in Oliver et al. (2017c). At Boydtown the average plain

height is approximately 4 m AHD, at Wonboyn is 5 m, at Moruya is 6 m, whereas the foredunes are approximately 6 m, 8 m and 8 m AHD, respectively. Pedros Beach, whose younger ridges are higher than the older ones, has an average elevation plain of approximately 6 m AHD and an anomalous foredune that reaches 12 m. These heights are approximately 1 m lower than the ones found at Shoalhaven.

OSL samples taken at the ridge immediately behind the high foredune, on top of the foredune ridge, and at the ridge immediately seaward of the foredune returned ages of 600 ± 30 , 160 ± 10 and 180 ± 10 years, respectively, indicating the recent depositional history at Seven Mile Beach. These ages are considered older than OSL ages obtained from the ridge immediately behind the high foredune (450 ± 40 years) and at the crest of the high foredune (70 ± 5 years) at Wonboyn (Oliver et al., 2017a), but corresponds very closely with ages of around 170 years ago obtained at Moruya (Tamura et al., 2019) for instance.

The reversal of ages between the high foredune and the seaward ridge at Seven Mile Beach, although statistically equivalent, can be explained by the fact that the high foredune was still actively receiving sediment while the ridge seaward was forming. This seems logical given that the high foredune is so much higher than the ridges to either side and is likely to be active for some time while the shoreline moved further seaward. After several years or a few decades, the high ridge became inactive (not receiving sand anymore) because

the shoreline translated a significant distance seaward of the high foredune position.

Fig. 4. SEM images of medium sand (1-2 ϕ) fraction of selected samples. More circular and rounded individual grains observed on the landward ridges (SMB11b, SMB11, SMB12 and SMB13) than on the seaward ridges (SMB13b, SMB15, SMB16 and SMB16b). See supplementary material for a complete set of SEM images for each sample.

Table 3

Mineralogy of sediments in the medium sand (1-2 phi) fraction (wt. %)

determined by x-ray diffraction (XRD) analysis, and sediment colours.

Sample	Chi square	Quartz	Feldspars				Clay minerals		Munsell
			Albite	Labradorite	Orthoclase	Microcline	Illite	Kaolinite	Colour
SMB11b	3.51	92.4	0.1	0.6	0	6.4	0.2	0.2	10 YR 8/4
SMB11	2.68	93.7	1.1	0	0	4.6	0.6	0	10 YR 8/4
SMB12	4.34	93.6	1.3	0	0	5.2	0	0	10 YR 7/4
SMB13	3.07	90.6	1.2	0.8	0	5.7	1	0.7	10 YR 7/4
SMB13b	3.77	91.1	2.2	0	0	5.3	0.8	0.5	10 YR 7/4
SMB14	2.52	92.1	1	0.6	0	5.1	0.9	0.3	10 YR 7/4
SMB15	2.97	90.6	1.6	0.3	0	6.1	1.3	0.2	10 YR 7/3
SMB16c	3.04	88	1.3	1	1.2	6.7	1.2	0.5	10 YR 8/2
SMB16	2.93	87.4	1.5	1.7	1	7.3	0.7	0.4	10 YR 7/2
SMB16b	3.29	88.5	1.8	1	0.9	7	0.3	0.6	10 YR 7/2

5.2. Shoreline progradation compared to other barriers

Average progradation rates for the Shoalhaven barrier are considerably lower than the other studied barriers in similar coastal environments around Australia (Table 4). The average progradation rate of approximately 0.17 m/yr for Shoalhaven is only higher than the one for Callala (which is situated at the northwest margin of Jervis Bay, a site less exposed wave energy), and considerably lower than other barriers such as Wonboyn, Boydtown and

Moruya, whose chronology, and therefore progradation rates, were derived from ages dating back to barrier initiation.

Table 4

Holocene prograded systems studied with OSL chronologies and their respective average progradation rates. * Average progradation rate assuming barrier initiated at 7700 years ago.

Prograded barrier	Age range (years)	Average progradation rate (m/yr)	Reference
Shoalhaven (NSW)	7700* - present	~0.17	This study
Wonboyn (NSW)	7770 - 450	~0.24	Oliver et al. (2017a)
Boydton (NSW)	7940 - 90	~0.25	Oliver et al. (2017a)
Seven Mile (TAS)	3620 - 1390	~0.4	Oliver et al. (2017b)
Callala (NSW)	7460 - present	~0.1	Oliver and Woodroffe (2016)
Moruya (NSW)	7220 - 390	~0.27	Oliver et al. (2015)
Beachmere (QLD)	1700 -190	~0.32	Brooke et al. (2008)
Woody Bay (NSW)	1690 - 230	~0.24	Goodwin et al. (2006)
Guichen Bay (SA)	3900 - present	~0.39	Murray-Wallace et al. (2002)

Progradation rates for different chronological phases within the Shoalhaven barrier, discussed in section 4.2, followed an increasing pattern observed at other prograded systems in the region, such as at Wonboyn and Boydton. Rates for Wonboyn increased from 0.08 m/yr to 0.32 m/yr around 4480 years

ago, despite the small size of the Wonboyn River catchment (320 km²) that discharges into the barrier system. Differently from the Shoalhaven, sediment sources contributing to the Wonboyn barrier appear to be from the inner shelf and possibly from the large shelf sand body to the southeast (Oliver et al., 2017a).

The increase in progradation rates from 0.16 m/yr to 0.65 m/yr around 1500 years ago for Boydtown barrier appears to have been driven by sediment input from the Towamba River catchment (1026 km²) instead of the Nullica River (50 km²), which discharges at Boydtown (Oliver et al., 2017a). Hudson (1991) suggested that the infilling of the inlet at the mouth of the Towamba River increased the progradation rate of the Boydtown barrier.

The Moruya River catchment occupies an area of approximately 1450 km², which is equivalent to 20 % the Shoalhaven catchment. At Moruya, however, shoreline progradation occurred at a relatively uniform rate (~0.27 m/yr) since barrier initiation (Oliver et al., 2015). The fact that most of this small catchment is covered in forested areas suggests that fluvial sediment input may not have had a dramatic impact on barrier progradation, as the Shoalhaven River did.

At Guichen Bay, OSL ages indicate an extremely rapid initial phase of progradation of at least 3 m/yr, followed by a linear rate of 0.39 m/yr for the past 4000 years (Murray-Wallace et al., 2002). However, no river system discharges into the bay, and sediments accumulating at this prograded sequence

are derived from a mix of modern and early Holocene-formed carbonates, erosion of the adjacent aeolinite cliffs and quartz (Bristow and Pucillo, 2006).

The difference in progradational rates from these different sites that were subjected to similar sea-level history throughout the Holocene (Belperio et al., 2002; Sloss et al., 2007), indicates that these barriers evolved in different ways as a function of many factors (which can change as barriers evolve) including inherited geology, accommodation space, headland bypassing, fluvial discharge, adjacent landscape erosion, estuarine infill, and amount of fluvial and marine material available.

5.3. OSL and radiocarbon recalibration results –derived chronologies comparison

Age estimates from the dating of “shell hash”, as well as recalibrated radiocarbon ages are presented in Table 5. Recalibrated radiocarbon ages are not significantly different to the calibrated ages previously reported (Thom et al., 1981b), as the Delta R values (Gillespie and Polach, 1979) for the marine reservoir correction are the same as those used originally.

Using results from the upper regressive facies (close to 0 m AHD), Thom et al. (1981b) indicated that more than half of the barrier width has been formed since 4000 years ago, and that a possible rapid progradation followed by a slower rate (inflection point centred at 2000 years ago) occurred. Our findings,

however, point to more time needed for the formation of the initial half of the barrier (52 % of the barrier's width was formed before 2400 ± 130 years) and that progradation rate increased after 2400 ± 130 years. This contrasting pattern of barrier progradation using OSL dating of quartz dune sands and previous radiocarbon dating of shell fragments had been identified for Guichen Bay (Murray-Wallace et al., 2002) and Moruya (Oliver et al., 2015). The disparate pattern seems to be related to the depths within the barrier stratigraphy from which samples were dated more than dating uncertainties.

5.4. Barrier formation model

Based on this study and available information on the formation of the Shoalhaven deltaic-estuarine plains (Umitsu et al., 2001; Woodroffe et al., 2000), ^{14}C dating (Thom et al., 1981b) and Shepherd's model (1987) of foredune and beach ridge development, four different periods of barrier formation can be identified (Fig. 5). Six profiles (P1–P6; Fig. 2) have been selected to explain the different periods and their relationship to sediment sources.

Table 5

Recalibrated radiocarbon samples from Thom et al. (1981b). Radiocarbon age corresponds to 'Laboratory age' and is corrected for isotopic fractionation only.

Calibrated ages with 95 % confidence limit using procedure of Clark (1975) as reported in Thom et al. (1981b).

Laboratory code	Dated material	Radiocarbon age (yr BP)	95 % Confidence Interval	Recalibrated
			Calibrated radiocarbon age (cal. yr BP)	radiocarbon age (cal. yr BP)
SUA-1086	Shell hash	1190 ± 65	720 ± 170	740 ± 100
SUA-1087	Shell hash	2670 ± 65	2230 ± 210	2350 ± 160
SUA-1088	Shell hash	4475 ± 75	4590 ± 330	4660 ± 140
SUA-1089	Shell hash	2110 ± 70	1600 ± 160	1680 ± 130
SUA-1090	Shell hash	2565 ± 70	2120 ± 260	2210 ± 140
SUA-1091	Shell hash	2455 ± 70	2030 ± 290	2110 ± 140
SUA-1092	Shell hash	2980 ± 70	2640 ± 250	2750 ± 140
SUA-1093	Shell hash	2925 ± 70	2600 ± 240	2650 ± 140
SUA-1094	Shell hash	4885 ± 85	5160 ± 290	5150 ± 160
SUA-1213	Shell hash	4540 ± 70	4680 ± 320	4700 ± 140
SUA-1214	Shell hash	3090 ± 65	2790 ± 220	2860 ± 120
SUA-1215	Shell hash	2835 ± 65	2540 ± 220	2570 ± 130
SUA-1216	Shell hash	4675 ± 65	4870 ± 330	4920 ± 150
SUA-1217	Shell hash	7590 ± 75	-	8050 ± 110
SUA-1218	Shell hash	6890 ± 75	-	7390 ± 100
SUA-1219	Shell hash	3640 ± 65	3480 ± 260	3530 ± 130
SUA-1221	Shell hash	5090 ± 65	5400 ± 250	5430 ± 120
SUA-1222	Shell hash	5270 ± 65	5600 ± 230	5620 ± 120
SUA-1223	Shell hash	6235 ± 70	6640 ± 240	6660 ± 140
SUA-1244	Shell hash	3090 ± 70	2780 ± 230	2860 ± 120

Period 1 initiated around 7,700 years ago with a strong sediment supply of marine source (Cowell et al., 2001; Kinsela et al., 2016), whereas the estuarine basin was still infilling (Woodroffe et al., 2000), as demonstrated by the low angularity of individual quartz grains in Fig. 4, low feldspars content analysed in this study and also by Wearne (1984). This allowed the development of a high coastal barrier of approximately 8 m (AHD) in elevation. After barrier initiation, this period was characterised by a slowly prograding coastline (0.12 m/yr) that required a long period before each foredune was succeeded by a younger one, enabling each ridge to develop to a greater size and the average height of the barrier to be high. During the first period, accommodation space was limited by the high elevation area to the west of P2 (Fig. 2) and demanded a continuing supply of marine sediments from the shoreface. Some sand bypassing probably occurred to the north but barrier development was in its infancy there. Assuming that the beach profile remained constant, during period 1, the barrier accumulated approximately 51.2 % (44,980,000 m³ of sand) of today's barrier volume above 0 m AHD.

The sea-level highstand continued throughout this period and some minor oscillation might have occurred (Baker and Haworth, 2000a, 2000b; Sloss et al., 2007). However, negative and positive oscillations for the Shoalhaven were impossible to detect using LiDAR data. Sand supply from the shoreface should have produced a lowering of the shoreface through time (Cowell et al., 2001).

Period 2 starts around 2,400 years ago and was characterised by a faster progradation rate (0.22 m/yr), which resulted in the rapid growth of successive ridges (average of 120 years for individual ridge formation). The difference between the height of the ridges and swales is greater to the north of Shoalhaven Heads (P4 and P5) than in Period 1. However, an average decrease in the height of the barrier was observed, which is indicative of rapid growth of successive foredunes with each new foredune depriving the landward older dune of its sand supply (Shepherd, 1987). The historical accumulation rate of almost 16,000 m³/yr between 2,400 and 600 years ago suggests that an increase in fluvial sediment supply occurred (shoreface supply would have been decreasing or becoming less significant). Sediment supply from marine sources was probably reduced compared to the previous period as the shoreface became deeper and more concave (Kinsela et al., 2016). Part of the approximately 29 million m³ of sediments added to the barrier were deposited further north and south, as the barrier expanded towards Gerroa and Crookhaven Heads, respectively, increasing the accommodation space. A recalibrated ¹⁴C age of 2350±160 cal. yr BP in the middle core of profile 1 (Fig. 5) also supports this northwards expansion.

This rapidly prograding period is likely to be associated with an increase in the fluvial supply of sediments to the coast after most of the estuarine had infilled 3000 yr BP (Woodroffe et al., 2000), as evidenced by the increase in angularity of individual quartz grains in Fig. 4. Furthermore, the mineralogical

data presented by Wearne (1984) supports the idea of an increasing fluvial influence on barrier accretion after 4000 yr BP, as indicated by the lithics (feldspar and rock fragments) content increase along P3 and P5 (Figs. 2 and 5), despite the drier climatic conditions experienced in southeastern Australia in the past 2,500 years, as suggested by Fitzsimmons and Barrows (2010).

A re-activation of the sediment supply from a marine source, by the process of forced regression caused by the late-Holocene relative sea-level fall to present sea level (Sloss et al., 2007) may have contributed to this rapid progradation as suggested for the Tuncurry barrier (Kinsela et al., 2016). The accumulation of approximately 32.8 % (28,780,000 m³ of sand) of today's barrier volume above 0 m AHD occurred during Period 2.

Period 3 started before 600 years ago and finished around 160 years ago, resulting in the accumulation of approximately 7.3 % (6,435,000 m³ of sand) of today's barrier volume above 0 m AHD. This period started before, but encompasses the formation of the anomalous foredune observed along the barrier. This is a typical feature observed at several barriers along the coast of Australia (Goodwin et al., 2006; Oliver et al., 2017c; Thom et al., 1981b). According to Shepherd (1987), a large foredune like the one that reaches 13.6 m at profile 5, is the result of a barrier that prograded rapidly and became stable or very slowly receded. The first part of this hypothesis appears to be correct for Shoalhaven barrier based on the prior fast prograding period experienced.

However, the formation of three successive low-lying ridges in a seaward direction suggests that the barrier continued to prograde over the past 600 years. The large foredune dated 160 years ago was likely forming up as a discrete foredune 100 years or so before, and it is possible that the foredune sequestered sand that might have been used for shoreline progradation (hence the slight slowing of shoreline progradation rate (0.18 m/y) between 600 and 180 years ago. Further investigation of this high feature using detailed chronology and stratigraphic analysis in the Shoalhaven and other prograded systems would provide further insights into timing and mode of its formation, as pointed out by Oliver et al. (2017a). Textural and mineral data presented in this study and also by Wearne (1984) supports the idea of continuity of fluvial supply, despite the modifications that occurred in the lower estuary after the construction of Berrys Canal in the 1820s diverting flow from the Shoalhaven River to the Crookhaven estuary.

Period 4 initiated approximately 180 years ago and has resulted in the formation of a few successive ridges that are normally lower than 6 m AHD and can be better observed along P2 and P3. This period resulted in the accumulation of approximately 8.7 % (7,700,000 m³ of sand) of today's barrier volume above 0 m AHD. The rapid progradation rate (0.63m/yr) experienced during this period may also be linked with land clearing and European settlement starting in the first decades of the nineteenth century (Shoalhaven Historical Society, 1996). During Period 4, a series of extratropical cyclones in the 1970's

caused significant erosion along the NSW coast (Bryant and Kidd, 1975; Callaghan and Helman, 2008; Chapman et al., 1982). However, the morphological expression of these events is not easily distinguishable in Fig. 5, and exact ridge location of the scarp generated from these storms can only be possibly identified with morphostratigraphic analysis or historical aerial photographs.

The existence of a concave shaped sandy deposit adjacent to Shoalhaven Heads (Carvalho and Woodroffe, 2017), suggests that a considerable amount of fluvial material available for coastal progradation is still being delivered to the shoreface during flood events, despite the damming of the Shoalhaven River, following the construction of Tallowa Dam, 30 km upstream of Nowra, approximately 50 years ago.

Another interesting aspect of Fig. 5 is that during period 1 the average height of the barrier remained constant, whereas the following periods witnessed a gradual fall in height. This may be related to the fact that the culmination of the Holocene marine transgression was followed by sea-level highstand of +1.5 m that lasted until approximately 2000 years ago, followed by a relatively slow and smooth fall to present level (Sloss et al., 2007). The timing of this sea-level fall is consistent with the increase in progradation rate around 2400 years ago (Table 2). This aspect, however, needs to be investigated further to check whether this gradual fall is detectable in other prograded barriers on the east coast of Australia.

Fig. 5. Four different periods of formation for Shoalhaven barrier system. Profiles extracted from LiDAR data and locations (P1- P6) are shown in Fig. 2. Profile axis in meters. P1, P3 and P5 correspond to profiles in Thom et al. (1981b) and Wearne (1984). ^{14}C ages correspond to recalibrated radiocarbon ages (Thom et al., 1981b).

6. Conclusion

Regressive barriers along the NSW coast first occupied their present position towards the end of Postglacial Marine Transgression. Since the time sea level stabilised at or near present, shoreline progradation has occurred at Shoalhaven barrier as demonstrated by OSL dating of quartz grains at 10 different ridges. Rates of progradation were different from that inferred from radiocarbon dating of buried shell material conducted in the 1980s, and appear to be lower than other OSL dated barriers along the eastern coast of Australia. An increase in progradational rate from 0.12 m/yr to 0.22 m/yr was observed from 2400 ± 130 to 600 ± 130 years ago, and more recently to 0.32 m/yr.(despite an observed fall to 0.18 m/yr until 180 ± 10 years ago).

Initial progradation was driven by onshore transport of marine sand during initial stages of barrier formation due to a large offshore sediment repository, and gradually replaced by fluvial material as indicated by the increase in

feldspar content in barrier samples and in quartz angularity. This has led to the formation of this confined regressive system on the southeastern coast of Australia composed of high older ridges, followed by lower ones when progradation rate increased, and an anomalously high foredune of almost 14 m above sea level approximately 160 years ago. More recently in the past two centuries, the formation of lower ridges suggests that the system still experiences a significant supply of material for beach progradation, despite the contemporary modifications in the catchment which will have an effect on the reduction of sediment reaching the coastline.

Our results support the evolutionary model of Holocene sequences on embayed high energy coast proposed for barrier estuaries by Roy et al. (Jones and Davies, 1979; Roy et al., 1980). However, the Shoalhaven progradational history unveiled here, indicates that many other factors contribute to the way that barriers evolved throughout the Holocene.

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References

- Anthony, E.J., 1991. Beach-ridge plain development: Sherbro Island, Sierra Leone. *Zeitschrift fur Geomorphologie*, NF, Supplementband, 81, 85-98
- Anthony, E.J., 2008. Shore processes and their palaeoenvironmental applications. *Developments in Marine Geology Series*, 4. Elsevier, Amsterdam
- Baker, R., Haworth, R., 2000a. Smooth or oscillating late Holocene sea-level curve? Evidence from cross-regional statistical regressions of fixed biological indicators. *Mar. Geol.* 163 (1–4), 353–365.
- Baker, R., Haworth, R., 2000b. Smooth or oscillating late Holocene sea-level curve? Evidence from the palaeo-zoology of fixed biological indicators in east Australia and beyond. *Mar. Geol.* 163 (1–4), 367–386.
- Belperio, A., Harvey, N., Bourman, R., 2002. Spatial and temporal variability in the Holocene sea-level record of the South Australian coastline. *Sedimentary Geology*, 150(1-2), 153-169. [https://doi.org/10.1016/S0037-0738\(01\)00273-1](https://doi.org/10.1016/S0037-0738(01)00273-1).
- Bird, E.C., Jones, D.J., 1988. The origin of foredunes on the coast of Victoria, Australia. *Journal of Coastal Research* 4(2), 181-192
- Bird, E.F.C., 1960. The formation of sand beach-ridges. *Australian Journal of Science*, 22, 349-350
- Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26(11), 1237-1248. <https://doi.org/10.1002/esp.261>.
- Brooke, B., Lee, R., Cox, M., Olley, J., Pietsch, T., 2008. Rates of shoreline progradation during the last 1700 years at Beachmere, Southeastern Queensland, Australia, based on optically stimulated luminescence dating of beach ridges. *Journal of Coastal Research*, 640-648. <https://doi.org/10.2112/04-0375.1>.
- Bristow, C.S., Pucillo, K., 2006. Quantifying rates of coastal progradation from sediment volume using GPR and OSL: the Holocene fill of Guichen Bay, south-east South Australia. *Sedimentology* 53 (4), 769–788.
- Brooke, B., Lee, R., Cox, M., Olley, J., Pietsch, T., 2008. Rates of shoreline progradation during the last 1700 years at Beachmere, Southeastern Queensland, Australia, based on optically stimulated luminescence dating of beach ridges. *J. Coast. Res.*, 640–648 <https://doi.org/10.2112/04-0375.1>.
- Bowler, J.M., Johnston, H., Olley, J.M., Prescott, J.R., Roberts, R.G., Shawcross, W., Spooner, N.A., 2003. New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421 (6925), 837–840.
- Bryant, E.A., Kidd, R., 1975. Beach erosion, May-June, 1974, Central and South Coast, NSW. *Search* 6 (11–12), 511–513.

- Bryant, E., Young, R., Price, D., Short, S., 1994. Late Pleistocene dune chronology: near-coastal New South Wales and eastern Australia. *Quaternary Science Reviews*, 13(3), 209-223
- Burges, A., Drover, D., 1953. The rate of podzol development in sands of the Woy Woy District, NSW. *Australian Journal of Botany*, 1(1), 83-94.
- Callaghan, J., Helman, P.M., 2008. Severe storms on the east coast of Australia 1770–2008. 1921291508. Griffith Centre for Coastal Management-Griffith University, Gold Coast
- Carter, R., 1986. The morphodynamics of beach-ridge formation: Magilligan, Northern Ireland. *Marine Geology*, 73(3-4), 191-214
- Carvalho, R.C., Woodroffe, C.D., 2015. Rainfall Variability in the Shoalhaven River Catchment and its Relation to Climatic Indices. *Water Resources Management*, 29(14), 4963-4976. <https://doi.org/10.1007/s11269-015-1098-4>.
- Carvalho, R.C., Woodroffe, C.D., 2017. Modifications to the Shoalhaven estuary and the coastal sediment budget over the past 40 years, *Australasian Coasts & Ports 2017: Working with Nature*. Barton, ACT: Engineers Australia, PIANC Australia and Institute of Professional Engineers New Zealand, Cairns, pp. 233-239.
- Chapman, D., Geary, M., Roy, P.S., Thom, B.G., 1982. Coastal Evolution and Coastal Erosion in New South Wales. Coastal Council of New South Wales, Sydney
- Clark, R.M., 1975. A calibration curve for radiocarbon dates. *Antiquity*, 49(196), 251-266. <https://doi.org/10.1017/S0003598X00070277>.
- Costas, S., Ferreira, Ó., Plomaritis, T.A., Leorri, E., 2016. Coastal barrier stratigraphy for Holocene high-resolution sea-level reconstruction. *Scientific reports*, 6, 38726. <https://doi.org/10.1038/srep38726>.
- Cowell, P.J., Stive, M.J., Roy, P.S., Kaminsky, G.M., Buijsman, M.C., Thom, B.G., Wright, L.D., 2001. Shoreface sand supply to beaches, Coastal Engineering Conference. ASCE-American Society of Civil Engineers, pp. 2495-2508.
- Curry, J., Emmel, F., Crampton, P., 1969. Holocene history of a strand plain, lagoonal coast, Nayarit, Mexico. In: A.A. Castanares, F.B. Phleger (Eds.), *Coastal lagoons- A symposium*. Universitas Nacional Autonoma de Mexico/ UNESCO, Mexico City, pp. 35-43.
- Davies, J., 1957. The importance of cut and fill in the development of sand beach ridges. *Australian Journal of Science*, 20, 105-111
- De Beaumont, L., 1845. Septieme leçon. Leçons de géologie pratique. Paris: Bertrand, 221-252
- Dominguez, J., 1996. The Sao Francisco strandplain: a paradigm for wave-dominated deltas? In: M. de Batist, P. Jacobs (Eds.), *Geology of Siliciclastic Shelf Seas*. Geological Society London Special Publications, London, pp. 217-231. <https://doi.org/10.1144/GSL.SP.1996.117.01.13>.
- Dougherty, A.J., 2014. Extracting a record of Holocene storm erosion and deposition preserved in the morphostratigraphy of a prograded coastal barrier. *Continental Shelf Research*, 86, 116-131
- Duller, G., 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiation measurements*, 37(2), 161-165. [https://doi.org/10.1016/S1350-4487\(02\)00170-1](https://doi.org/10.1016/S1350-4487(02)00170-1).
- Fitzsimmons, K.E., Barrows, T.T., 2010. Holocene hydrologic variability in temperate southeastern Australia: an example from Lake George, New South Wales. *The Holocene*, 20(4), 585-597. <https://doi.org/10.1177/0959683609356589>.
- Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Research*, 27(1). <https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D>.

- Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry*, 41(2), 339-364. <https://doi.org/10.1111/j.1475-4754.1999.tb00987.x>.
- Gillespie, R., Polach, H.A., 1979. The suitability of marine shells for radiocarbon dating of Australian prehistory. In: R. Berger, H.E. Suess (Eds.), *Radiocarbon Dating, Proceedings of the ninth international conference on radiocarbon dating*. University of California Press, Berkeley, CA, pp. 404-421
- Goodwin, I.D., Stables, M.A., Olley, J.M., 2006. Wave climate, sand budget and shoreline alignment evolution of the Iluka–Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. *Marine Geology*, 226(1-2), 127-144. <https://doi.org/10.1016/j.margeo.2005.09.013>.
- Goslin, J., Clemmensen, L.B., 2017. Proxy records of Holocene storm events in coastal barrier systems: Storm-wave induced markers. *Quaternary Science Reviews*, 174, 80-119
- Goy, J.L., Zazo, C., Dabrio, C., 2003. A beach-ridge progradation complex reflecting periodical sea-level and climate variability during the Holocene (Gulf of Almeria, Western Mediterranean). *Geomorphology*, 50(1-3), 251-268
- Guérin, G., Mercier, N., Adamiec, G., 2011. Dose-rate conversion factors:update. *Ancient TL*, 29(1), 5-8
- Hails, J., 1969. The origin and development of the Umina—Woy Woy Beach ridge system, Broken Bay, NSW. *Australian Geographer*, 11(1), 1-12
- Hesp, P., 2006. Sand beach ridges: definitions and re-definition. *Journal of Coastal Research*, 39, 72-75
- Hesp, P.A., 1984. Foredune Formation in Southeast Australia. In: B.G. Thom (Ed.), *Coastal geomorphology in Australia*. Academic Press, Sydney, pp. 69-97
- Hesp, P.A., Short, A.D., 1999. Barrier Morphodynamics. In: A.D. Short (Ed.), *Handbook of beach and shoreface morphodynamics*. John Wiley & sons Ltd, Chchester, England
- Hudson, J.P., 1991. Late Quaternary Evolution of Twofold Bay, Southern NewSouthWales. *Masters of Science*. University of Sydney, Sydney, p. 210.
- Huntley, D., Hutton, J., Prescott, J., 1993. The stranded beach-dune sequence of south-east South Australia: a test of thermoluminescence dating, 0–800 ka. *Quaternary Science Reviews*, 12(1), 1-20
- Huntley, D., Hutton, J., Prescott, J., 1994. Further thermoluminescence dates from the dune sequence in the southeast of South Australia. *Quaternary Science Reviews*, 13(3), 201-207
- Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L., 1985. Optical dating of sediments. *Nature*, 313(5998), 105
- Jacobs, Z., 2008. Luminescence chronologies for coastal and marine sediments. *Boreas*, 37(4), 508-535
- Jones, B.G., Young, R.W., Eliot, I.G., 1979. Stratigraphy and chronology of receding beach-barrier deposits on the northern Illawarra coast of New South Wales. *Geological Society of Australia*, 26, 255-264
- Jones, H., Davies, P., 1979. Preliminary studies of offshore placer deposits, eastern Australia. *Marine Geology*, 30(3-4), 243-268. [https://doi.org/10.1016/0025-3227\(79\)90018-5](https://doi.org/10.1016/0025-3227(79)90018-5).
- Kinsela, M.A., Daley, M.J., Cowell, P.J., 2016. Origins of Holocene coastal strandplains in Southeast Australia: Shoreface sand supply driven by disequilibrium morphology. *Marine Geology*, 374, 14-30. <https://doi.org/10.1016/j.margeo.2016.01.010>.
- McKenzie, P., 1958. The development of beach sand ridges. *Australian Journal of Science*, 20, 213-214

- Møller, J.J., Yevzerov, V.Y., Kolka, V.V., Corner, G.D., 2002. Holocene raised-beach ridges and sea-ice-pushed boulders on the Kola Peninsula, northwest Russia: indicators of climatic change. *The Holocene*, 12(2), 169-176
- Moslow, T.F., Heron, S.D., 1979. Quaternary evolution of Core Banks, North Carolina. Cape Lookout to New Drum Inlet. In: S.P. Leatherman (Ed.), *Barrier Islands*. Academic Press, New York, pp. 211-246
- Murray-Wallace, C., Banerjee, D., Bourman, R.P., Olley, J., Brooke, B., 2002. Optically stimulated luminescence dating of Holocene relict foredunes, Guichen Bay, South Australia. *Quaternary Science Reviews*, 21(8-9), 1077-1086.
[https://doi.org/10.1016/S0277-3791\(01\)00060-9](https://doi.org/10.1016/S0277-3791(01)00060-9).
- Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation measurements*, 32(1), 57-73.
[https://doi.org/10.1016/S1350-4487\(99\)00253-X](https://doi.org/10.1016/S1350-4487(99)00253-X).
- Nossin, J.J., 1965. Analysis of younger beach ridge deposits in eastern Malaya. *Zeitschrift für Geomorphologie*, 9, 186-208
- Nott, J., Forsyth, A., Rhodes, E., O'Grady, D., 2015. The origin of centennial-to millennial-scale chronological gaps in storm emplaced beach ridge plains. *Marine Geology*, 367, 83-93
- Nott, J.F., 1990. Cainozoic landform evolution on the Shoalhaven plain NSW with special reference to the alluvial and aeolian history over the last 45 million years. Doctor of Philosophy, University of Wollongong, Wollongong.
- Oliver, T., Tamura, T., Hudson, J., Woodroffe, C.D., 2017a. Integrating millennial and interdecadal shoreline changes: Morpho-sedimentary investigation of two prograded barriers in southeastern Australia. *Geomorphology*, 288, 129-147.
<http://dx.doi.org/10.1016/j.geomorph.2017.03.019>.
- Oliver, T.S., Donaldson, P., Sharples, C., Roach, M., Woodroffe, C.D., 2017b. Punctuated progradation of the Seven Mile Beach Holocene barrier system, southeastern Tasmania. *Marine Geology*, 386, 76-87.
<https://doi.org/10.1016/j.margeo.2017.02.014>.
- Oliver, T.S., Dougherty, A.J., Gliganic, L.A., Woodroffe, C.D., 2015. Towards more robust chronologies of coastal progradation: optically stimulated luminescence ages for the coastal plain at Moruya, south-eastern Australia. *The Holocene*, 25(3), 536-546.
<https://doi.org/10.1177/0959683614561886>.
- Oliver, T.S., Woodroffe, C.D., 2016. Chronology, morphology and GPR-imaged internal structure of the Callala Beach prograded barrier in southeastern Australia. *Journal of Coastal Research*, 75(sp1), 318-322. <https://doi.org/10.2112/SI75-064.1>.
- Oliver, T.S.N., Thom, B.G., Woodroffe, C.D., 2017c. Formation of beach-ridge plains: an appreciation of the contribution by Jack L. Davies. *Geographical Research*, 55(3), 305-320
- Otvos, E.G., 2000. Beach ridges—definitions and significance. *Geomorphology*, 32(1-2), 83-108
- Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiation measurements*, 23(2-3), 497-500. [https://doi.org/10.1016/1350-4487\(94\)90086-8](https://doi.org/10.1016/1350-4487(94)90086-8).
- Redman, J.B., 1852. On the alluvial formations, and the local changes of the south coast of England, *Minutes of the Proceedings of the Institution of Civil Engineers*. Thomas Telford-ICE Virtual Library, pp. 162-204.
- Redman, J.B., 1864. The east coast between the Thames and the Wash estuaries, *Minutes of the Proceedings of the Institution of Civil Engineers*. Thomas Telford-ICE Virtual Library, pp. 186-224.

- Roy, P., 1984. New South Wales estuaries: their origin and evolution. In: B.G. Thom (Ed.), Coastal geomorphology in Australia. Academic Press, Sydney
- Roy, P., Cowell, P., Ferland, M., Thom, B., 1994. Wave-dominated coasts. In: R. Carter, C. Woodroffe (Eds.), Coastal evolution: Late Quaternary shoreline morphodynamics, pp. 121-186
- Roy, P., Ferland, M., 1987. Seismic results from the inner continental shelf of the Shoalhaven/Jervis Bay/Ulladulla region, southern NSW- A progress report, Geological Survey of NSW/Department of Mineral Resources and University of Sydney/Department of Geography, Sydney.
- Roy, P., Thom, B., 1981. Late Quaternary marine deposition in New South Wales and southern Queensland—an evolutionary model. *Journal of the Geological Society of Australia*, 28(3-4), 471-489
- Roy, P., Thom, B., Wright, L., 1980. Holocene sequences on an embayed high-energy coast: an evolutionary model. *Sedimentary Geology*, 26(1-3), 1-19.
[https://doi.org/10.1016/0037-0738\(80\)90003-2](https://doi.org/10.1016/0037-0738(80)90003-2).
- Roy, P.S., 1997. Cainozoic geology of the coast and shelf. In: E. Scheibner (Ed.), *Geology of New South Wales—Synthesis: Volume 2 Geological Evolution*. Geological Survey of New South Wales. Department of Mineral Resources, Sydney, pp. 361-385
- Roy, P.S., Crawford, E.A., 1977. Significance of sediment distribution in major coastal rivers, northern New South Wales., 3rd Australian conference on coastal and ocean engineering. Department of Mineral Resources, pp. 177-184.
- Roy, P.S., Zhuang, W.-Y., Birch, G.F., Cowell, P.J., Congxian, I., 1997. Quaternary Geology of the Forster-Tuncurry Coast and Shelf, Southeast Australia, Geological Survey of New South Wales - Department of Mineral Resources, St Leonards, NSW.
- Sanderson, P.G., Eliot, I., Fuller, M., 1998. Historical development of a foredune plain at Desperate Bay, Western Australia. *Journal of Coastal Research*, 14(4), 1187-1201
- Scheffers, A., Engel, M., Scheffers, S., Squire, P., Kelletat, D., 2012. Beach ridge systems—archives for Holocene coastal events? *Progress in Physical Geography*, 36(1), 5-37
- Shand, T., Wasko, C., Carley, J., You, Z., Cox, R., 2011. Long-term trends in NSW coastal wave climate and derivation of extreme design storms, NSW Coastal Conference, Tweed Heads, pp. 8-11.
- Shepherd, M., 1987. Sandy beach ridge system profiles as indicators of changing coastal processes, New Zealand geography conference. 14, pp. 106-112.
- Short, A., 1988. Holocene coastal dune formation in southern Australia: a case study. *Sedimentary geology*, 55(1-2), 121-142
- Short, A.D., 2007. *Beaches of the New South Wales coast: a guide to their nature, characteristics, surf and safety*. Sydney University Press
- Short, A.D., Woodroffe, C.D., 2009. *The coast of Australia*. Cambridge University Press
- Sloss, C.R., Murray-Wallace, C.V., Jones, B.G., 2007. Holocene sea-level change on the southeast coast of Australia: a review. *The Holocene*, 17(7), 999-1014.
<https://doi.org/10.1177/0959683607082415>.
- Stuiver, M., Reimer, P.J., 1993. Extended 14 C data base and revised CALIB 3.0 14 C age calibration program. *Radiocarbon*, 35(1), 215-230.
<https://doi.org/10.1017/S0033822200013904>.
- Tamura, T., 2012. Beach ridges and prograded beach deposits as palaeoenvironment records. *Earth-Science Reviews*, 114(3-4), 279-297.
<https://doi.org/10.1016/j.earscirev.2012.06.004>.
- Tamura, T., Cunningham, A.C., Oliver, T.S., 2019. Two-dimensional chronostratigraphic modelling of OSL ages from recent beach-ridge deposits, SE Australia. *Quaternary Geochronology*, 49, 39-44. <https://doi.org/10.1016/j.quageo.2018.03.003>.

- Tanner, W.F., 1988. Beach ridge data and sea level history from the Americas. *Journal of Coastal Research*, 81-91
- Tanner, W.F., 1995. Origin of beach ridges and swales. *Marine Geology*, 129(1-2), 149-161
- Taylor, M., Stone, G.W., 1996. Beach-ridges: a review. *Journal of Coastal Research*, 12(3), 612-621
- Thom, B., 1983. Transgressive and regressive stratigraphies of coastal sand barriers in southeast Australia. *Marine Geology*, 56(1), 137-158
- Thom, B.G., 1964. Origin of sand beach-ridges. *Australian Journal of Science*, 26, 351-352
- Thom, B.G., 1978. Coastal sand deposition in southeast Australia during the Holocene. In: J.L. Davies, M.A.J. Williams (Eds.), *Landform Evolution in Australasia*. Australia National University, Canberra, pp. 197-214
- Thom, B.G., Bowman, G., Roy, P., 1981a. Late Quaternary evolution of coastal sand barriers, Port Stephens-Myall Lakes area, central New South Wales, Australia. *Quaternary Research*, 15(3), 345-364. [https://doi.org/10.1016/0033-5894\(81\)90035-1](https://doi.org/10.1016/0033-5894(81)90035-1).
- Thom, B.G., Bowman, G.M., Gillespie, R., Temple, R., Barbetti, M., 1981b. Radiocarbon dating of Holocene beach-ridge sequences in south-east Australia. Department of Geography, University of New South Wales at Royal Military College
- Thom, B.G., Polach, H.A., Bowman, G.M., 1978. Holocene Age Structure of Coastal Sand Barriers in New South Wales, Australia. Royal Military College, Duntroon
- Umitsu, M., Buman, M., Kawase, K., Woodroffe, C.D., 2001. Holocene palaeoecology and formation of the Shoalhaven River deltaic-estuarine plains, southeast Australia. *The Holocene*, 11(4), 407-418. <https://doi.org/10.1191/095968301678302841>.
- Wearne, I., 1984. Patterns of sedimentation in the Shoalhaven delta. Master of Science thesis, University of Sydney, Sydney.
- Woodroffe, C.D., Buman, M., Kawase, K., Umitsu, M., 2000. Estuarine infill and formation of Deltaic Plains, Shoalhaven River. *Wetlands (Australia)*, 18(2), 72-84
- Wright, L., 1970. The influence of sediment availability on patterns of beach ridge development in the vicinity of the Shoalhaven River delta, NSW. *The Australian Geographer*, 11(4), 336-348. <https://doi.org/10.1080/00049187008702570>.
- Wright, L., 1977. Morphodynamics of a wave-dominated river mouth. *Coastal Engineering Proceedings*, 1(15). <https://doi.org/10.9753/icce.v15.%25p>.
- Young, R., Bryant, E., Price, D., Wirth, L., Pease, M., 1993. Theoretical constraints and chronological evidence of Holocene coastal development in central and southern New South Wales, Australia. *Geomorphology*, 7(4), 317-329
- Young, R., White, K., Price, D., 1996. Fluvial deposition on the Shoalhaven deltaic plain, southern New South Wales. *The Australian Geographer*, 27(2), 215-234. <https://doi.org/10.1080/00049189608703169>.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at <https://doi.org/10.1016/j.geomorph.2019.05.010>. Data include a complete set of SEM images for each sample and a KMZ file containing the sample locations.