A REVISED CHRONOLOGY FOR THE COASTAL PLAIN AT MORUYA, NSW: IMPLICATIONS FOR MODELLING AND MANAGEMENT

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Abstract

Holocene progadational coastal barriers are depositional environments, comprising a sequence of beach ridges, which preserve a record of progradation and coastal sediment delivery. The prograded barrier at Moruya, NSW consists of a sequence of 60 distinct relict foredune ridges formed during the mid to late Holocene as a bedrock valley infilled after the rapid postglacial sea-level rise. In this study, the Holocene evolution of the Moruya plain is described using high resolution elevation data (LiDAR), Ground Penetrating Radar (GPR), and an Optically Stimulated Luminescence (OSL) chronology. OSL dating indicates a linear trend of progradation from 7200 yrs to present at an average rate of 0.27 m/yr and implies that individual ridges were active for an average of around ~110 years. This is in contrast to the earlier radiocarbon-based chronological evidence which had been interpreted to indicate a decelerating rate of progradation with little shoreline build-out since ~2500 yrs BP. We show that the sand comprising the oldest ridge was deposited ~7200 yrs ago, which corresponds to the published age at which sea level stabilised after the post-glacial marine transgression. A large foredune dominates the seaward margin of the ridge sequence which is shown to be < 400 yrs old. Incremental progradation of the barrier is apparent from relict beachface reflectors extracted from GPR, and volumetric calculations from LiDAR provide new insights into sediment delivery to this portion of the coastline over time. Moruya has been a benchmark site for models of shoreface retreat using projected sea-level rise and this revised chronology has significant implications for such modelling as well as the ongoing management of coastal amenity and property in New South Wales.

Introduction

Radiocarbon dating has been at the forefront of long-term coastal barrier evolution studies around the world (Bernard and LeBlanc, 1965; Curray et al., 1969; Hayes, 1994; Nummendal, 1983; Timmons et al., 2010). In Australia, chronological and morphostratigraphic analysis of NSW prograded barriers based on radiocarbon dating (Roy and Thom, 1981; Roy et al., 1980; Thom, 1983; Thom and Roy, 1985) has provided a foundation for management and modelling over the past 4 decades. Moreover, detailed understanding of processes and feedbacks responsible for long-term coastal behaviour has formed the basic building blocks of coastal recession modelling along the NSW coast (Cowell et al., 2003)

The Moruya prograded barrier has been the site of numerous studies over the past 40 years and contains a record of coastal behaviour since the late Holocene sea-level stillstand around ~7000 years ago. An extensive drilling program incorporating radiocarbon dating of marine sediments and stratigrapahic interpretation was undertaken in the 1970's (Thom et al., 1981a). As well as this, a long-term beach monitoring program with almost 40 years of beach profile data has led to important advances in understanding the role of storms and beach morphodynamics in relation to coastal management. Shoreface equilibrium based coastal recession modelling has been based directly on the radiocarbon chronology and stratigraphic interpretations of the Moruya barrier and especially the age model for the central drilling transect (Daley, 2012; Kinsela, 2014). The pioneer studies and the ongoing derivative work has meant that Moruya has become an extremely important site for NSW coastal science.

However, two major concerns have been identified relating to radiocarbon chronologies in NSW. Firstly, overestimation of radiocarbon ages when dating marine ‘shell hash’ due to the potential for contamination of older reworked shell material to be included in any given sample. This issue was highlighted by Nielsen and Roy (1981) who concluded that

> “The difference between the environmentally corrected radiocarbon date of a shell hash sample, taken from within the barrier, and its true age of deposition, as a result of shell contamination, can be thousands of years.” Nielsen and Roy (1981) p.128

A second potential issue with radiocarbon dating of marine shells within prograded barriers is the accuracy of ischrons drawn based on radiocarbon ages form depths of >10 m. Roy et al. (1994) demonstrated the potential use of Ground Penetrating Radar (GPR) to image beach faces and understand the changes in geometry of a receding shoreface moving toward equilibrium. However, the validity of the interpretation of the surface position of any given radiocarbon age from depth, will directly influence the accuracy of a pattern of progradation based on a surface measure, such as barrier width.

However, the advancement of dating techniques such as optically stimulated luminescence (OSL) provides the opportunity to reinvestigate prodgraded barrier chronologies in NSW. This study aims to use OSL dating on samples from the upper metre of the barrier surface, and provide an age estimate for individual sand ridges representing past shoreline positions over the Holocene. In addition, preliminary GPR data is presented along with LiDAR in order investigate sediment delivery patterns over the interval defined by the OSL dates.

Site description and past studies

The Moruya coastal plain is located approximately 240 kilometres south of Sydney on the tectonically stable NSW south coast. Sixty distinct relict foredune ridges spanning a maximum of almost 2km are evidence of a prograding shoreline. The ridges are low relief (1-2 m difference between crest and swale) shore parallel and laterally persistent. The bedrock embayment is a Palaeozoic turbidite sequence (Rose 1966). At the southern end of the barrier complex the Moruya river (upstream the Deua river) drains a densely vegetated upper catchment and in the lower reaches meanders through extensive floodplains used for agricultural purposes.

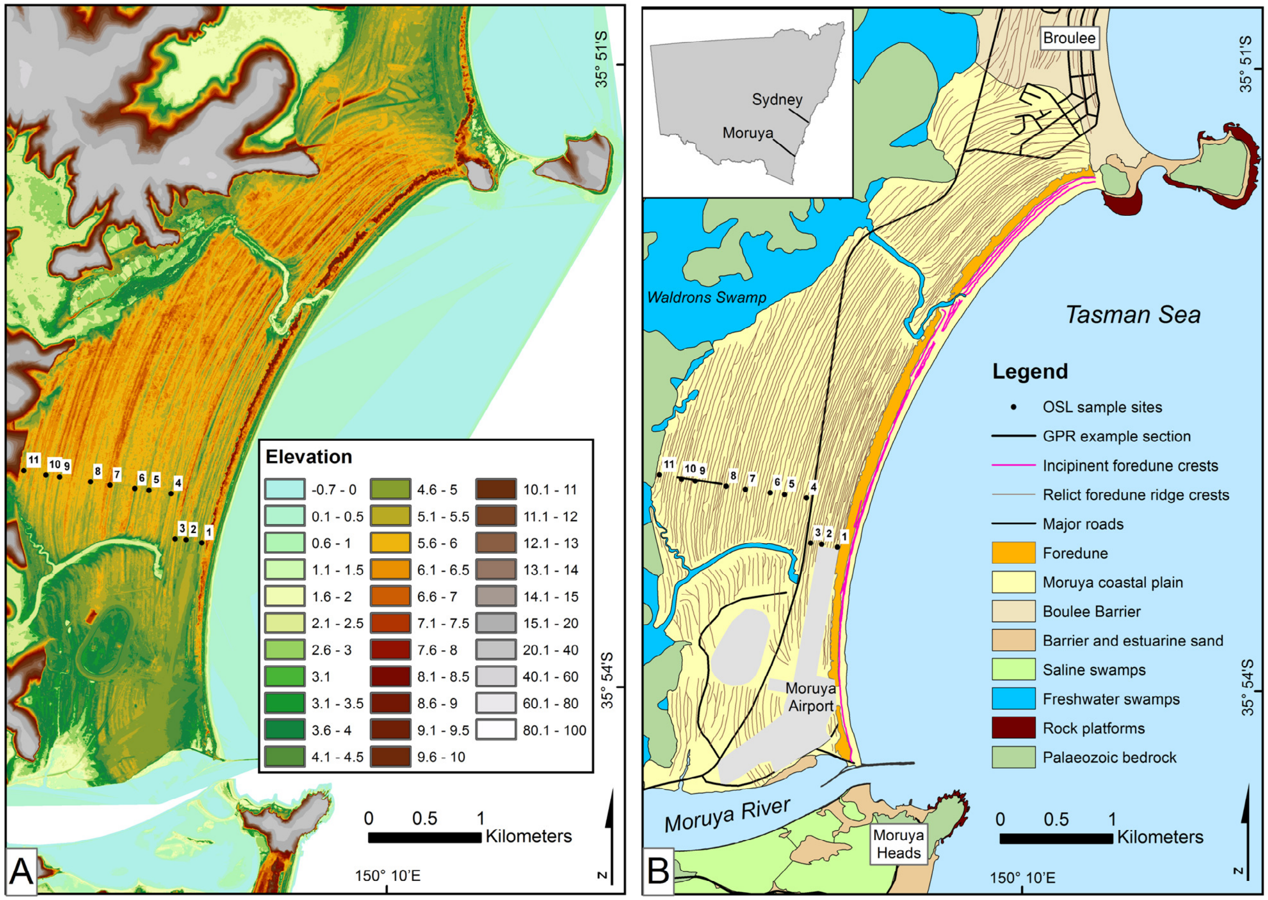

Figure 1. Location of the prograded barrier at Moruya showing the Holocene embayment fill. Ridge crests (in part B) have been derived from high-resolution LiDAR (© Land and Property Information, NSW) seen in part A, and show the progradation pattern with the modern foredune reaching a higher elevation along the seaward margin of the plain. The freshwater swamps behind the barrier are shown as well as the truncated Palaeozoic bedrock.

The ridge sequence was first described by Thom et al. (1978) who carried out extensive drilling and sampling coupled with topographic surveying to establish a stratigraphy and chronology based on radiocarbon dating. Three transects of drill holes with associated topographic profiles were established at the south, centre and north of the barrier. The facies model for the central drill transect identifies four distinct units. Samples for radiocarbon dating for this central transect were collected from the 'nearshore shelly sand' as differentiated in cores from the 'beach-ridge dune sand'.

The radiocarbon dating results for Moruya were published in a series of papers and monographs which detailed the long-term barrier evolution. The chronology for the central transect indicated commencement of progradation of the shoreface at ~6500 cal yr BP with progradation culminating around ~2500 cal yr BP (Thom et al., 1981a). For the central transect, an overall decelerating trend of progradation was observed when barrier width was plotted over time using isochrons drawn according to the radiocarbon ages (Thom et al., 1981a,b). The large foredune adjacent to the present day beach is almost twice the height of the landward ridges for most of its length, and a charcoal sample from its northern end yielded an age of 720 ± 270 cal yr BP (Thom et al., 1981a). This younger age for the foredune is in accord with the radiocarbon ages for the northern transect at Moruya (Thom et al., 1981b). Bowman (1989) found good agreement between proxy measures of soil age and the radiocarbon chronology.

Luminescence dating of coastal facies

Basic principles of OSL dating of quartz sands

OSL dating is a method used to determine the elapsed time since quartz grains were exposed to sunlight and subsequently buried. Exposure to sunlight releases electrons from traps in the crystal lattice of the quartz and the OSL signal is reset. While buried, quartz grains are exposed to cosmic rays and ionizing radiation from and the decay of ^{238}U, ^{235}U, ^{232}Th (and their daughter products), ^{40}K and ^{87}Rb in the sediment surrounding the grain. Therefore, energy accumulates in the traps at a rate proportional to the flux of the cosmic rays and ionizing radiation within the surrounding environment (i.e. the environmental dose rate). Stimulation of these quartz grains in the laboratory releases the stored energy as photons (i.e. OSL) which is measured and used to calculate the equivalent dose (D_e) stored in the grain since burial. A burial age is calculated by diving the D_e (Gy) by the environmental dose rate (Gy/ka).

OSL dating of coastal barriers globally

Coastal barrier chronologies have been investigated using OSL dating at many locations globally (Jacobs, 2008; Mallinson et al., 2008; Nielsen et al., 2006; Reimann et al., 2010; Reimann et al., 2011; Rendell et al., 2007; Rink and Forrest, 2005; Rink and Lopez, 2010; Roberts and Plater, 2007; Choi et al., 2014). The demonstrated reliability of marine sands for OSL dating has led to the acceptance of this technique as an accurate method for determining coastal barrier chronologies and these international investigators encourage its application for similar locations.

OSL dating of coastal barriers in Australia

In Australia, OSL has also been used successfully to date relict foredune ridge plains since the early 2000's (Brooke et al., 2008a, 2008b; Forsyth et al., 2010; Forsyth et al., 2012; Goodwin et al., 2006; Murray-Wallace et al., 2002; Nott et al., 2009). Broader scale patterns of Holocene infill and rates of shoreline progradation have also been examined using OSL (Brooke et al., 2008a; Goodwin et al., 2006).

However, only at Guichen Bay has there been a direct comparison between OSL and radiocarbon chronologies across a prograded barrier. The OSL chronology at Guichen Bay is in broad accordance with radiocarbon chronology (Murray-Wallace et al., 2002), although there are disparities of more than a thousand years between OSL and radiocarbon age estimates at the rear of the plain (Tamura, 2012). An explanation for this disparity is the reworking (in the first 2000-3000 years after the sea-level still stand) of a Late Pleistocene carbonate aeolian sands eroded form the Robe and Woakwine Ranges surrounding Guichen Bay (Murray-Wallace et al., 2002). Radiocarbon dating is particularly suited to calcareous ridge plains, such as Guichen Bay, where carbonate material is actively produced biogenically in the nearshore zone (hence reasonable agreement of OSL and radiocarbon ages in the seaward portion of the barrier). Carbonate poor sites such as Moruya, require deeper cores to recover shell fragments able to be dated from the nearshore facies.

Methods

Radiocarbon recalibration and reporting

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

LiDAR analysis

Airborne LiDAR, flown in 2012 by the NSW Government (Land and Property Information) was acquired in order to better understand barrier morphology. A Digital Elevation Model (DEM) of the ground surface was produced using the Triangular Irregular Network (TIN) method in ArcGIS 10.2. Relict foredune ridge crests and geomorphic unit boundaries were digitized from this DEM with the aid of georectified aerial photography. Field inspection involving ridge crest counting along shore normal transects indicated good agreement between the DEM and the location of ridge crests. Real Time Kinematic GPS measurements for additional ground truthing of ridge crest locations was impeded due to high vegetation coverage across much of the barrier complex.

Volumetric analysis of barrier progradation involved digitizing of polygons in ArcGIS 10.2 along ridge swales to demark 'slices' corresponding to OSL ages. Each polygon defined the barrier area accreted between OSL ages. Volume was calculated using the Polygon volume tool found in the 3D Analyst extension for ArcGIS 10.2. This tool allows the calculation of volume in m^3 between a given reference plane (in this case mean sea level (MSL) or 0 m AHD) and the DEM surface (Fig.2).

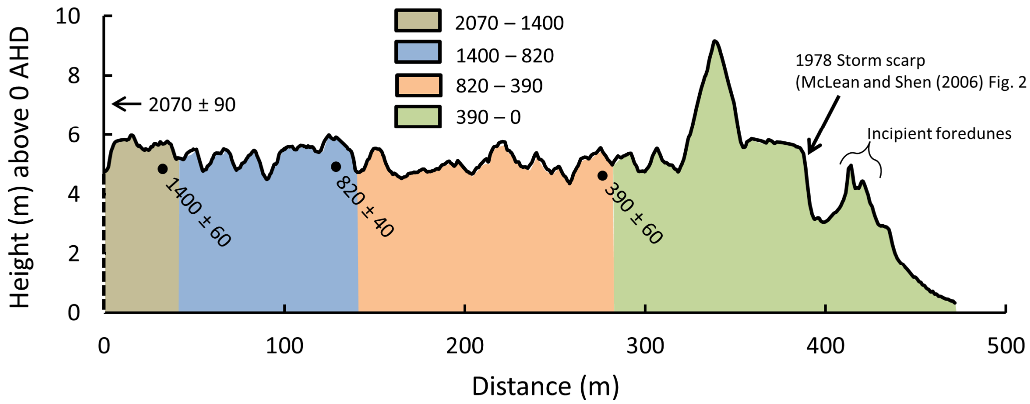

Figure 2: 2D representation of the sediment volume slices bounded by the OSL ages used for sediment volume calculation. Volume is calculated between the DEM surface (here represented by the topographic profile across a short section of the barrier) and MSL or 0 AHD.

GPR

GPR data was collected along a shore normal transect (see Figure 1) using a Mala ProEx System with a 250 MHz antenna. Data collected was then processed using RadExplorer v. 1.41. Standard processing procedures were applied including DC removal, background removal, and amplitude correction. Interpretation of topography involved correction for water table undulation and referencing and cross checking with a topographic profile taken across the DEM.

OSL

Eleven samples of undisturbed aeolian facies (>80% quartz) were collected for OSL dating from between 70-100 cm depth within the relict foredune ridges in 2012 and 2013. Table 1 lists sample names and numbers, with samples listed by their geographic position from east to west.

Samples were prepared using standard laboratory proceedures (Wintle, 1997) in order to isolate the 180-212 µm grain size fraction of quartz. Single quartz grains and multi-grain aliquots were loaded into a Risø TL/OSL reader and were stimulated, measured and irradiated as reported by Gliganic et al. (2012a,b).

For three samples (samples 1, 6, and 10, Table 1) 500 individual quartz grains were measured (180/180 preheat combination) to identify and eliminate those with unsuitable OSL properties and to allow the identification of incomplete bleaching and post-depositional mixing prior to age calculation. In doing so, these three samples served to assess the suitability of using multi-grain aliquots to determine ages for this depositional environment.

For the remaining eight samples (Table 1) 24 aliquots, each comprised of 50-60 grains, were measured (180/160 preheat combination) to estimate D_e values. Dose response curves were fitted with a linear function. The final D_e and overdispersion (spread in D_e data beyond that expected based on the standard error of each D_e value) values for each sample were calculated using the central age model (CAM; Galbraith et al., 1999).

For samples 1,6 and 10 (Table 1), dose rates for each sample were measured using a beta counter and the gamma contributions were measured by thick source alpha counting. For samples 2-5, 7-9 and 11 (Table 1), ICP-MS analysis (completed by Intertek Genalysis) was used to measure uranium, thorium, and potassium concentrations. All dose rates were calculated using the conversion values of Guérin et al. (2011) and an assumed water content of 5±2.5% was used for all samples. 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).

Results

OSL results

The single grain measurements indicate that these deposits do not suffer from post-depositional mixing or partial bleaching. Consequently, multi-grain aliquots were used to estimate D_e values for samples from this study area. Combined, these results demonstrate that young marine sands from SE Australian are ideally suited to OSL dating (Jacobs, 2008). OSL age data is presented in Table 1. There was no discernible trend either seawards or landwards in the total dose rates. The overdispersion results (Table 1) are within the normal bounds expected for well bleached marine quartz samples (Olley et al., 2004).

Table 1. OSL ages for relict foredune ridges across the Moruya Barrier, NSW. The samples are ordered according to sample position with respect to the ocean, so that the first sample listed in the table corresponds to the sample closest to the shore. 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).

	-------Radionuclide Concentrations------			------------------Dose Rates-------------------						
Sample Code	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)
1) Seaward*	-	-	-	0.53 ± 0.03	0.27 ± 0.01	0.18 ± 0.02	1.00 ± 0.05	0.39 ± 0.05	23 ± 3	390 ± 60
2) Mor1	0.24 ± 0.01	1.12 ± 0.04	0.83 ± 0.02	0.64 ± 0.02	0.27 ± 0.01	0.18 ± 0.02	1.12 ± 0.04	0.93 ± 0.02	11 ± 1.7	820 ± 40
3) Mor2	0.20 ±0.01	1.04 ±0.04	0.65 ± 0.01	0.50 ± 0.02	0.22 ± 0.003	0.18 ± 0.02	0.94 ± 0.03	1.31 ± 0.03	10 ± 1.6	1400 ± 60
4) Mor3	0.21 ± 0.01	1.17 ± 0.05	0.58 ± 0.01	0.45 ± 0.02	0.21 ± 0.004	0.18 ± 0.02	0.88 ± 0.03	1.82 ± 0.02	6 ± 0.9	2070 ± 90
5) Mor7	0.23 ± 0.01	1.27 ± 0.05	0.55 ± 0.01	0.44 ± 0.02	0.21 ± 0.004	0.18 ± 0.02	0.87 ± 0.03	2.24 ± 0.04	8 ± 1.2	2580 ± 110
6) Middle*	-	-	-	0.79 ± 0.05	0.35 ± 0.01	0.18 ± 0.02	1.34 ± 0.07	3.17 ± 0.06	8 ± 3	2380 ± 150
7) Mor6	0.20 ± 0.01	0.87 ± 0.03	0.52 ± 0.01	0.41 ± 0.02	0.18 ± 0.003	0.18 ± 0.02	0.80 ± 0.03	2.89 ± 0.05	7 ± 1.2	3610 ± 160
8) Mor5	0.25 ± 0.01	1.19 ± 0.05	0.62 ± 0.01	0.49 ± 0.02	0.23 ± 0.004	0.18 ± 0.02	0.93 ± 0.03	4.45 ± 0.1	11 ± 1.7	4770 ± 220
9) Mor4	0.25 ± 0.01	1.12 ± 0.04	0.75 ± 0.01	0.58 ± 0.02	0.26 ± 0.004	0.18 ± 0.02	1.04 ± 0.04	5.20 ± 0.06	5 ± 0.8	4980 ± 210
10) Landward*	-	-	-	0.52 ± 0.03	0.28 ± 0.01	0.17 ± 0.02	1.02 ± 0.06	5.59 ± 0.17	18 ± 3	5500 ± 360
11) MorLAND	0.20 ± 0.01	0.82 ± 0.03	0.30 ± 0.01	0.25 ± 0.01	0.13 ± 0.002	0.18 ± 0.02	0.60 ± 0.03	4.31 ± 0.11	12 ± 1.8	7220 ± 390

*The beta and gamma dose rates for these samples were measured directly in the laboratory with GM-25-5 beta counting and thick source alpha counting. The other samples were measured with ICP-MS (U and Th) and ICP-OES (K).

Radiocarbon recalibration results

The recalibrated radiocarbon ages from Thom et al. (1981a) are presented in Table 2 and Figure 4. The recalibrated ages are not significantly different to the calibrated ages previously reported (Polach et al., 1979; Thom et al., 1981a) as the Delta R values (Gillespie and Polach, 1979) for the marine reservoir correction are the same as those used by Thom et al. (1981a) in the original calibration.

Table 2. Radiocarbon Samples from Thom et al. (1981a) ordered seaward to landward and shallowest to deepest ('Ref. No.' corresponds to Figure 4). 'Radiocarbon Age' is the 'Laboratory age' and is corrected for isotopic fractionation only. The calibrated age is presented in cal yr BP according the calibration of Stuiver and Reimer (1993) using CALIB REV 7.0.1. The Delta R used for the calibration is taken from Gillespie and Polach (1979).

Ref. No.	Sample Code	Facies[1]	Sample Depth (m)	Dated Material	Radiocarbon Age (yr BP)	Radiocarbon Age (cal yr BP)
1)	ANU-1117	NSS	7	Shell hash	6100 ± 80	6530 ± 250
2)	ANU-1118	NSS	9	Shell hash	5920 ± 70	6340 ± 260
3)	ANU-1197	NSS	16	Shell hash	5860 ± 70	6240 ± 250
4)	ANU-1119	NSS	9	Shell hash	5820 ± 90	6200 ± 270
5)	ANU-1198	NSS	8	Shell hash	5830 ± 70	6220 ± 250
6)	ANU-1116	NSS	9	Shell hash	4930 ± 70	5200 ± 300
7)	ANU-1199	NSS	14	Shell hash	5120 ± 80	5460 ± 270
8)	ANU-1200	NSS	21	Shell hash	6290 ± 80	6730 ± 290
9)	ANU-1400	NSS	22	Shell hash	5410 ± 90	5790 ± 280
10)	ANU-1115	NSS	9	Shell hash	4100 ± 60	4130 ± 280
11)	ANU-1137	NSS	13	Shell hash	3760 ± 60	3690 ± 270
12)	ANU-1138	NSS	17	Shell hash	5180 ± 60	5520 ± 230
13)	ANU-1139	NSS	22	Shell hash	5150 ± 60	5500 ± 220
14)	ANU-1140	SSG	28	Shell hash	8490 ± 170	9040 ± 460
15)	ANU-1141	SSG	33	Shell hash	9130 ± 210	9920 ± 550
16)	ANU-1133	ECOM	44	Organic mud	8960 ± 80	9740 ± 350
17)	ANU-1114	NSS	11	Shell hash	3810 ± 80	3760 ± 310
18)	ANU-1398	NSS	20	Shell hash	4920 ± 80	5180 ± 310
19)	ANU-1132	ECOM	49	Organic mud	9700 ± 110	10600 ± 370
20)	ANU-1397	NSS	7	Shell hash	2740± 70	2450 ± 270
21)	ANU-1399	NSS	25	Shell hash	4950 ± 100	5240 ± 330

[1]NSS – Nearshore Shelly Sand, SSG – Shelly sand with gravel, ECOM – Estuarine clay with organic mud

GPR Results

GPR data for the transect marked in Figure 1 is presented in Figure 3. The slightly curved seaward dipping reflectors seen in Firgure 3 were interpreted to be relict beachfaces. No obvious relationship was found between the ridge crests and the beachfaces and this transect illustrates the complexity sediment supply to a dynamic beach environemnt. The top of each beachface reflector seems to correspond closely to the water table and thus the transition between beach face and dune sands is not distinguishable.

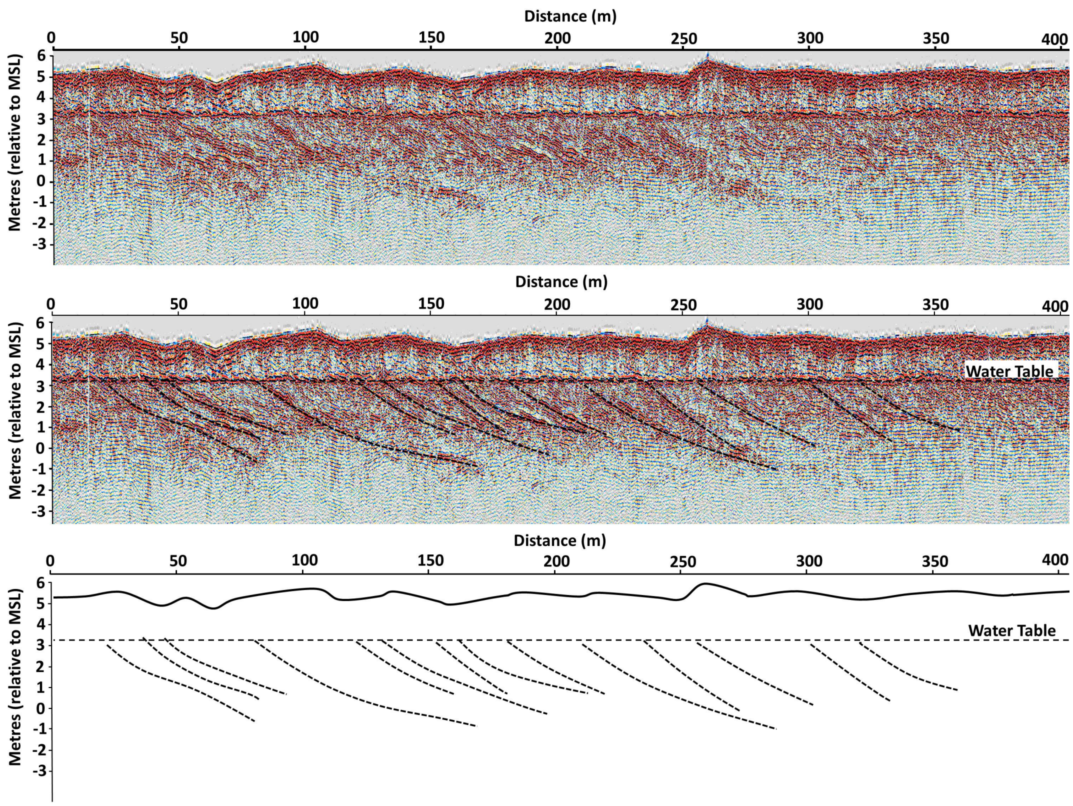

Figure 3. GPR data collected for the transect shown in Figure 1. The top figure shows the processed data, the second section, the processed data with interpretation, and the third, only the interpretation.

Discussion

The OSL age estimates presented in this study show a different pattern of Holocene shoreline progradation than the central transect age model based radiocarbon ages reported by Thom et al. (1981a) (Figure 4A). The OSL chronology shows a linear rate of seaward shoreline movement for this same transect. The sequence of ridges according to OSL dating spans from 7220 yr ago to 390 yr ago at a linear rate of 0.27 m/yr (Figure 4B). The youngest age of 390 yr ago indicates that the large foredune must be a feature less than 390 years old. There does not appear to be any cessation or slowing of shoreline progradation over the past 3000 years (Figure 4B). This linear pattern of progradation is aligned more closely with the northern radiocarbon dating transect at Moruya which shows a linear trend of progradation beginning at ~6000 cal yr BP and ceasing at ~1000 cal yr BP (Roy et al., 1994; Thom et al., 1981b) (Figure 4B).

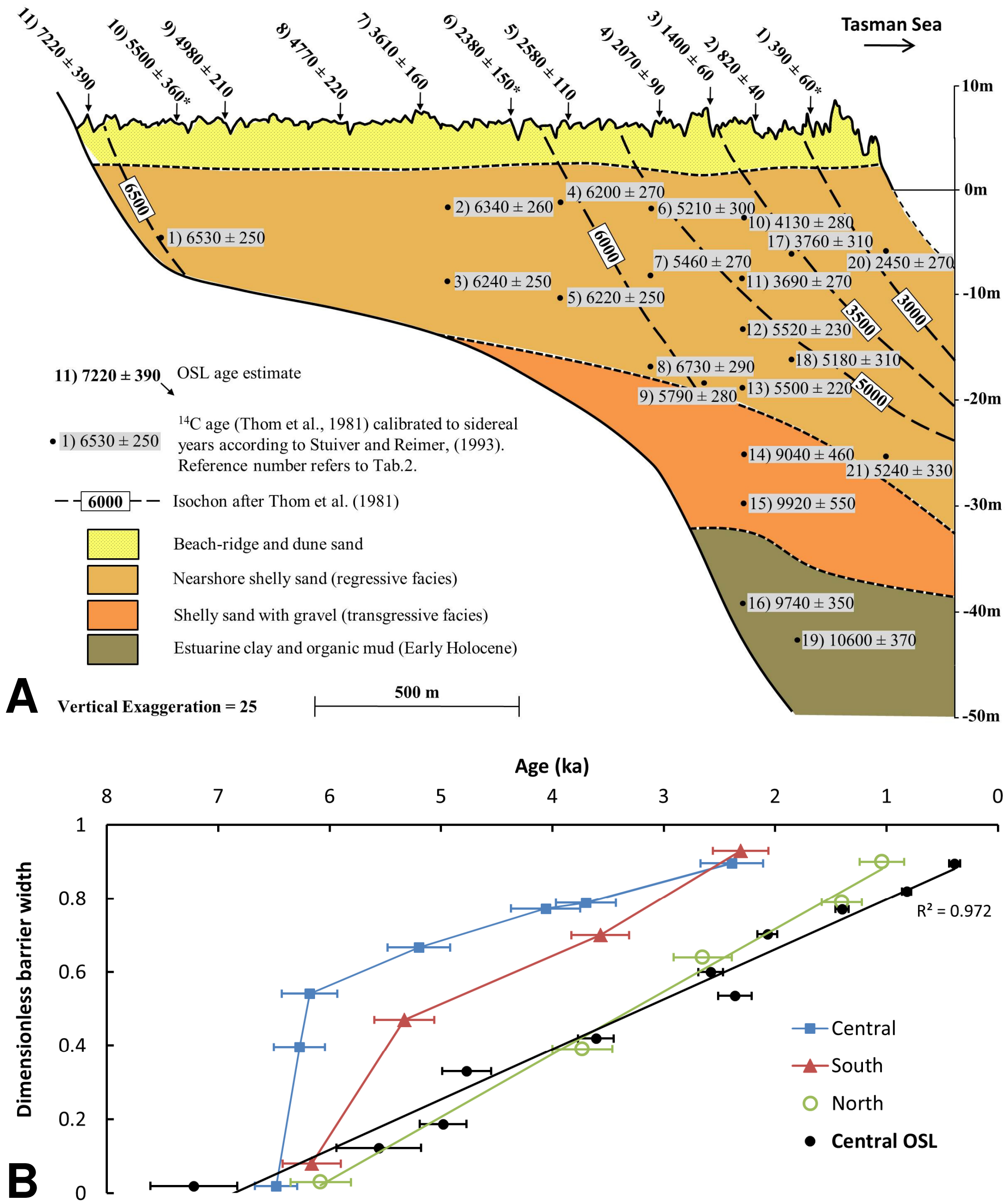

Figure 4. (A) Comparison between the published central transect radiocarbon based age and facies model according to Thom et al. (1981a), and the OSL age estimates presented in this study. The topographic barrier profile is taken from LiDAR data (© Land and Property Information, NSW) acquired for this region in 2012 and was drawn adjacent to the OSL sampling sites. *Refers to age estimates determined using single grain OSL techniques. (B) Plot of age and dimensionless barrier width, after Roy et al. (1994) also showing the OSL ages. While the two central transect (OSL and radiocarbon contrast markedly), the northern radiocarbon transect is comparable to the OSL dates.

It is important to distinguish between the shoreline progradation measured by the OSL dates, and the radiocarbon dates which relate to nearshore progradation. An ‘adjustment phase’ involving emplacement of the nearshore sand is likely to have occurred immediately post sea-level stillstand during the Holocene, while concurrently the progradation of beachface and dune facies proceeded at a linear rate.

For each of the 60 ridges in this sequence, an average “lifetime” of ~110 years was calculated. This is comparable to the average lifetime of 80 years inferred for each ridge for the linear portion of the Holocene ridge sequence at Guichen Bay (Murray-Wallace et al., 2002). This formation time of approximately 110 years per ridge needs further qualification with additional dates, especially multiple dates along individual ridges. However, these preliminary results are significant motivation for the continuation of the already informative 40-year beach survey program conducted at this site (McLean and Shen, 2006; McLean et al., 2010) if the full lifetime of ridge formation is to be documented. Further OSL dating would shed light on problems of alongshore variation of progradation patterns first identified by the three radiocarbon dating transects for this site (Thom et al., 1981a). No OSL ages were obtained within the nearshore sands at depths comparable to those of Thom et al. (1981a). OSL ages for samples from depths comparable to those sampled by Thom et al. (1981a) would be of great benefit and highlight differences in precision and utility of the two techniques for constructing prograded barrier chronologies.

The differences between the radiocarbon age model and the OSL dates presented in this study may be explained by a number of factors as mentioned earlier: overestimation of ages due to shell reworking and isochron uncertainty. However an alternative explanation for the older radiocarbon ages involves the early stillstand emplacement of shoreface sand creating a disequilibrium profile, the upper portion of which was then reworked onto the accreting beachface over the interval defined by the OSL dates.

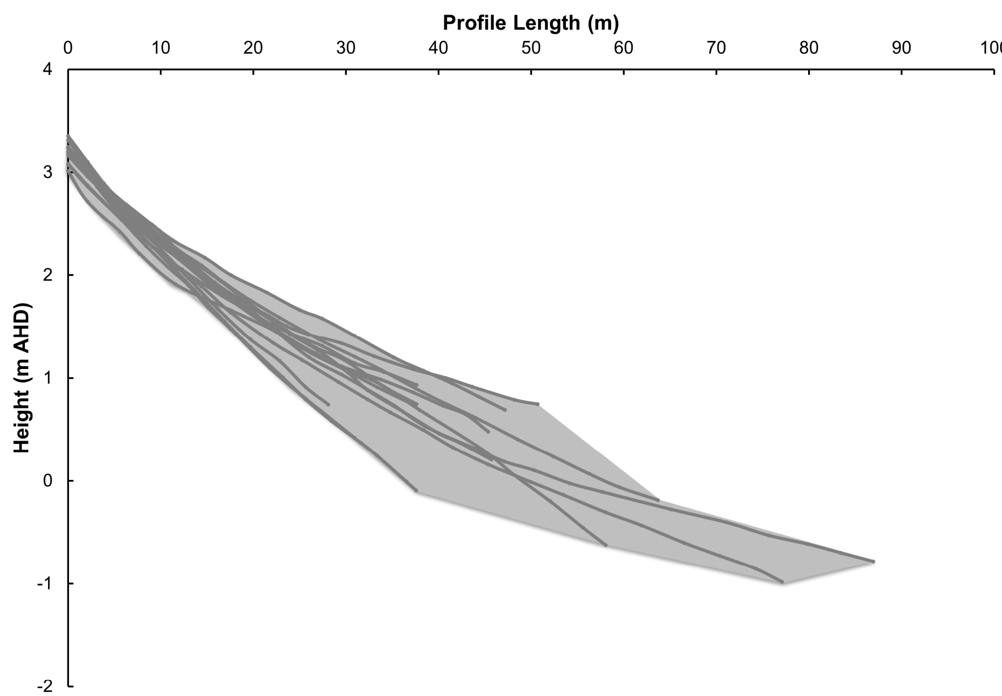

Figure 5. Profile envelope in grey for the GPR beachfaces shown in Figure 3.

The profile envelope of the GPR imaged beachfaces (Figure 5) extracted from the transect shown in Figure 3 establish a ‘first pass’ analysis of profile geometry. Ongoing analysis is underway to compare profile envelopes according for differing distances from the shoreline and compare this to the recent storm scarps both from beach profiling and GPR across the modern beach and incipient dunes. Current depths achieved by the GPR equipement do not reach the depths at which the samples for radiocarbon dating were collected, thus using GPR beachfaces to inform isochrons relating to the radiocarbon dates is not yet possible. However comparison of known offshore gradient at Moruya could provide insight into where the radiocarbon ages correspond to on the barrier surface.

Dimensionless barrier width (Figure 4B) has typically been used for comparative analysis with other prograded barriers in NSW (Roy et al., 1994). However, this measure of progradation makes no allowance for factors such as changing embayment size. As can be clearly seen from the morphology of the Moruya coastal plain (Figure 1), the size and shape of the embayment has changed considerably (Figure 6B).

Calculation of sediment volumes using LiDAR also shows a linear pattern of sediment delivery to the embayment at a rate of 7400 m^3/yr (Figure 6A). However, as embayment size changes the distribution of this sediment on the accreting beach surface is uneven. For example when the embayment was close to 7km long approximately 3500 years ago (Figure 6B), the delivery of 7400 m3/yr equates to 1.05 m^3/m/yr. However, earlier in the Holocene around 7000 years ago when the embayment was approximately 2 km in length (Figure 6B), the sediment delivery would be 3.7 m^3/m/yr. This complexity of sediment delivery on the embayment scale (Bristow and Pucillo, 2006) requires ongoing examination.

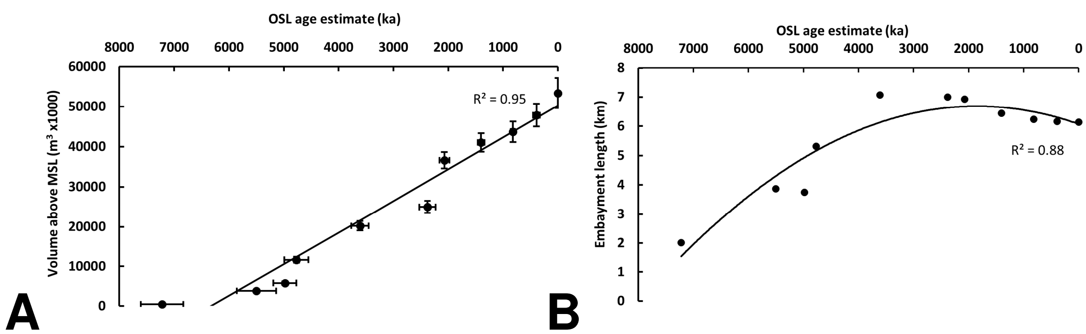

Figure 6. (A) Volume of sediment delivery according to the OSL ages calculated using LiDAR. A linear trend line has been applied with the R^2 value displayed. Horizontal error bars depict error of OSL dates, vertical error bars depict errors inherent in the LiDAR surface and digitizing errors. (B) A plot of embayment length over time according to the OSL ages. Points are fitted with a 3rd order polynomial.

With regard to recent advances in coastal barrier behavior modelling, see (Daley and Cowell, 2012; Kinslea, 2014; Lorenzo-Trueba and Ashton, 2014): the new OSL ages presented in this paper offer continued scope for model reconfiguration. New questions arising from this work regarding the timing and mode of the emplacement of shoreface sand and beachface and dune sand will benefit from a barrier modelling approach.

Conclusions

(1) Optically stimulated luminescence dating is a suitable method for dating the timing of deposition of quartz-rich marine sands in this region of southeastern Australia.

Coupled single-grain and multi-grain aliquot measurements indicate that quartz grains in this setting have good luminescence characteristics.

(2) The OSL ages indicate that shoreline progradation of the central transect on the Moruya barrier has occurred at a relatively uniform rate (~0.27 m/yr) from approximately 7000 yr ago to present, giving an average lifetime of ~110 yrs for each relict foredune ridge.

(3) These OSL results suggest the need for a more cautious approach to chronological interpretation of coastal barriers based on radiocarbon dating in Australia and worldwide and encourage the use of OSL dating to enhance our understanding of Holocene coastal evolution.

(4) LiDAR provides new insights into volumes of sediment delivery to the Moruya barrier over the Holocene.

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