CHANGING RATES OF SAND DEPOSITION AT PEDRO BEACH, SOUTHEASTERN AUSTRALIA: IMPLICATIONS FOR COMPARTMENT-BASED MANAGEMENT

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Abstract

Understanding the key factors which have influenced past shoreline behaviour at differing temporal and spatial scales is crucial for more accurately determining the potential for future erosion and coastal set-back within defined coastal compartments. In light of this recent focus on compartment-scale coastal management, this work emphasises the importance of considering the longer-term sediment movements and redistributions which are inherited by modern shorelines.

The Broulee secondary compartment on the NSW south coast contains both spatially and scientifically significant deposits of marine sediments deposited over past millennia. This study presents an optically stimulated luminescence (OSL) chronology and ground penetrating radar (GPR) surveys for Pedro Beach in order to reconstruct the historical deposition of marine sediments and consider the formation of the higher outer foredune. These datasets show that initial embayment filling between 7000-6000 years ago formed a series of shore-parallel ridges and a large flood-tide delta. Between 6000-3500 years ago rapid shoreline progradation moved the active beach-dune zone close to its present position. In the past 800 years a high foredune vertically accreted with contributions of sediment to this feature occurring in the past 100 years.

It is well established in southeastern Australia that an inherited disequilibrium shoreface profile drives onshore accumulation of sandy sediments forming a prograded barrier. However if there is no longer ‘accommodation space’ for sediment, this will be an overriding factor leading to the cessation of progradation. At Pedro Beach progradation effectively ceased 4000-3500 years ago when the shoreline reached at or near its present position. In the past ~3500 years the bounding headlands of the embayment have been far less effective in ‘trapping’ excess sediment from the disequilibrium shoreface profile and any sediment reserves in this zone are likely to have moved alongshore nourishing other beaches within the broader compartment.

Introduction

Long term shoreline behaviour along the NSW coast is controlled by local and regional geology and inherited embayment configuration, sediment supply and the interplay of energy sources such as tides, waves and wind (Wright & Thom 1977). These environmental factors interact through a series of morphodynamic relationships operating at differing spatial and temporal scales (Wright & Thom 1977). This foundational approach to understanding shoreline dynamics has provided an important framework for coastal management in NSW (Chapman et al. 1982). In recent years, approaches to coastal management encompassing legislative and regulatory frameworks have culminated in the

Coastal Management Act 2016 which incorporates a new coastal management manual and a revised State Environmental Planning Policy (SEPP).

In the context of these recent legislative changes, which recognise the importance of coastal compartments as a more robust scientific framework for management, there is an increasing need to understand regional sediment budgets, transport pathways and inherited shoreline dynamics. Datasets which capture compartment-scale coastal morphodynamics place specific coastal management actions on individual beaches in a more science-based regional and temporal context: which is a key objective of the recent reforms. Such an approach to management will enhance regional sustainable coastal planning ensuring better environmental and economic outcomes into the future.

This paper considers geochronological, geophysical and spatial datasets for Pedro Beach within the Broulee secondary compartment. Within this compartment several low-lying coastal plains have formed over recent millennia and preserve a record of past coastal processes and sediment budget dynamics. By reconstructing the depositional history of the coastal plain at Pedro Beach, this work aims to better constrain morphodynamic processes and sediment distribution within this broader compartment and enhance the scientific rigour of coastal management decisions at a regional scale.

Study Area

The Pedro Beach prograded barrier is located in southeastern Australia 250 km south of Sydney (Fig.1) and ~4 km south of the Moruya River which flows into the Tasman Sea at the southern end of Bengello Beach. A complex dendritic drainage system has formed in the Palaeozoic geology with Holocene sediments filling inherited embayments separated by rocky promontories. These Holocene coastal barriers impound freshwater swamps and saline estuaries which connect to the sea via small tidal channels. The Moruya River (upstream called the Deua River) has a catchment size of 1550 km^2 and the entrance position is fixed and trained by rock training walls. Tidal influence reaches more than 17 km upstream. Wave climate in this region of the Tasman Sea NSW is dominated by southeast swell with average significant wave height ~1.5 m (McLean et al., 2010) and the spring tidal range is ~2 m (Thom, 1984).

The secondary compartment comprises a sequence of beaches (tertiary compartments) separated by rocky headlands. Interpretation from aerial photographs and from limited multibeam survey lines indicates that subaqueous rocky outcrops form reefs proximal to many of these headlands. Between these areas of reef, nearshore sand dominates the seafloor substrate. Directly east of Pedro Beach in approximately 50 m water depth a topographic rise forms a substantial reef structure with other reef patches outcropping southeast of the Moruya River entrance. Further to the north, east of Bengello Beach, areas of sandy substrate appear to dominate the offshore environment.

The Pedro Beach coastal plain comprises a series of low-relief ridges which preserve past shoreline positions. Airborne LiDAR surveys show that these ridges steadily increase in height seaward and become less curved with the modern shoreline showing a markedly different planform geometry to past ridge alignments. The plain is bisected by a small tidal inlet (Congo Creek) which, during the progradational history of the shoreline, has exhibited substantial entrance variability in planform.

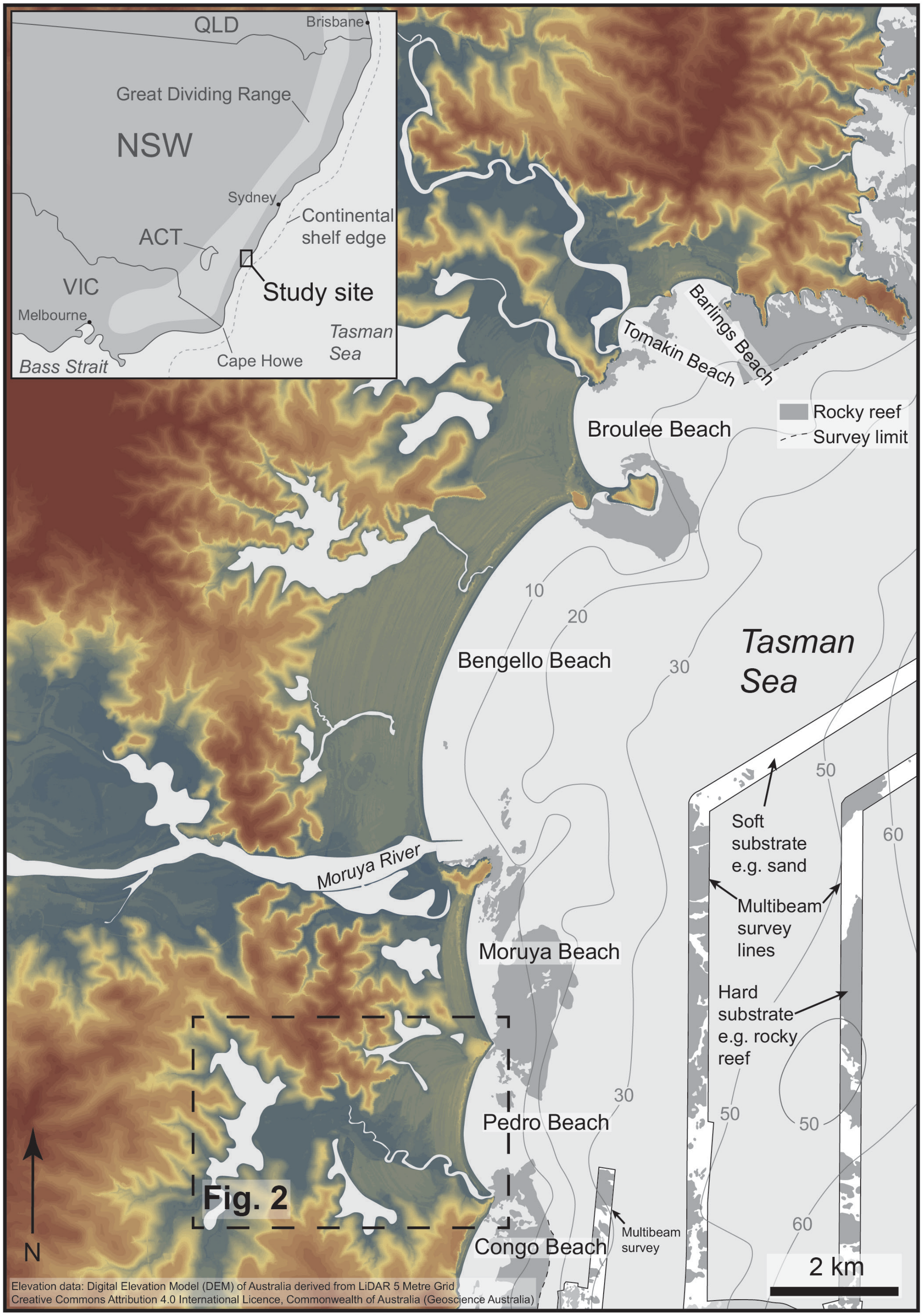

Figure 1. Map showing Pedro Beach in relation to other significant beaches in the region forming the Broulee secondary compartment. Multibeam survey data and airphoto based mapping of rocky reef is courtesy of the Office of Environment and Heritage (OEH). Isobaths derived from mapping by the AHO.

A foredune stands up to 12 meters high close to the present shoreline and has a distinctive lobed inner margin suggesting landward lee slope migration of dune sands by wind action. This foredune preserves a prominent relict dune scarp from the 1974 storm event, seawards of which is a low sparsely vegetated incipient foredune adjacent to the active beach. During severe storms this incipient dune is cut back by wave action and then recovers with a prominent beach berm common in fair weather conditions. Short et al. (2014) describe the longer term behaviour of the beach.

Methods

LiDAR topography and barrier volume analysis

LiDAR topography was obtained through Land and Property Information (LPI) as a 1 m grid derived from a survey completed in 2011 for the Batemans Bay region. This dataset was utilised for analysis of barrier topography and for the calculation of volumes of subaerial sand stored in the barrier sequence. Sediment volume calculations used the 'Polygon volume' tool in ESRI ArcGIS 10.2 whereby polygons traced according to the chronological dataset and ridge alignment were defined with the tool computing a volume between the LiDAR ground surface and defined horizontal plane; in this case 0 m AHD (which approximates MSL on this coastline). Volume of the higher foredune was calculated by tracing the outline of this feature and calculating the volume of sediment above +7 m AHD, which represents an average height of the ridges immediately landwards. The final value in m^3 for the foredune is thus the additional contribution of sediment contained in this feature.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) surveys were undertaken in December 2015 and January 2017. Shore-normal transects were constructed across the seaward-most 200-300 m of the coastal plain in the central and southern portions of the coastal plain capturing the stratigraphy of the most recently deposited ridges and the higher foredune. GPR was collected using a Mala Pro Ex system with a 250 MHz shielded antenna. Topographic survey data for each profile was collected with an RTK GPS or dumpy level. GPR data processing was completed in RadExplorer Version 1.42 and standard processing routines were applied including desaturation, time-zero correction, horizontal background removal, amplitude correction, bandpass filtering, migration and topography. A two-layer velocity structure was adopted for conversion of two-way travel time (y axis) to depth so as to take into account the change in water content due to the ground water table. Depth corrected profiles were referenced to mean sea level (MSL) by overlaying the topographic profile from each transect.

Optically stimulated luminescence (OSL) dating

Samples for OSL dating were collected in December 2015 and January 2017 using light-impenetrable black plastic and aluminium tubes which were hammered into the end of an auger sampling head which extracted light safe grains from depths of up to 5 m below the ground surface. Sample locations were spaced across the coastal plain targeting key ridges or depositional features interpreted from airborne LiDAR imagery. OSL samples were also collected at strategic points over the higher foredune along the two GPR transects in the central and south of Pedro Beach. Auger holes also allowed ground truthing of subsurface features.

Samples for OSL dating were processed at the OSL laboratory at the Geological Survey of Japan. Sediment within 20–25 mm of the ends each sample tube was removed and used for measurements of moisture content and dosimetry. Quartz grains were extracted from bulk samples following the method of Bateman and Catt (1996) and mounted on stainless steel disks to form large aliquots. These disks were then measured with a TL-DA-20 automated Risø TL/OSL reader equipped with blue LEDs for stimulation and a 90Sr/90156 Y beta source for laboratory irradiation.

The single-aliquot regenerative-dose (SAR) protocol was used to determine the equivalent dose (*De*) using the OSL response to a test dose to monitor and correct for sensitivity changes (Murray and Wintle, 2000). OSL measurements were made at 125 °C with a stimulation time of 20 s. Standard sample testing procedures were carried out resulting in the adoption of a preheat/cutheat temperature combination of 180 °C/ 160 °C for the OSL measurements. Standard SAR protocol measurement tests were applied during sample measurement to asses recycling, recuperation and feldspar contamination.

The contributions of both natural radioisotopes and cosmic radiation were considered for determination of the environmental dose rate. Concentrations of potassium, uranium, thorium, and rubidium were quantified by inductively coupled plasma mass spectrometry and were converted to dose rate based on data from Adamiec and Aitken (1998) and Marsh et al. (2002). Past changes of moisture content are unknown, so an uncertainty value of 5% was applied to the measured moisture content values. Cosmic dose rate was estimated based on Prescott and Hutton (1994). The final *De* value was determined by applying the Central Age Model (Galbraith et al., 1999) for individual sample and further divided by an environmental dose rate to obtain OSL ages.

Results

OSL dating

An OSL age from the southern section of the coastal plain on the most inland relict ridge indicate that deposition commenced approximately 7200 years ago consistent with the time at which sea level reached at or near present level on this coastline (Fig.2). The coastal plain north of Congo Creek began forming around 6000 years ago. Between 7000 years and 6000 years ago progradation rate was 0.29 m/yr and it is hypothesised that large amounts of sediment, which might have resulted in rapid shoreline progradation, formed the large flood-tide delta during this time period (Fig.2).

Progradation of the shoreline was rapid between 6000 and 5500 years ago at a rate of 0.75 m/yr and then slowed slightly to 0.49 m/yr between 5500 and 4000 years ago (Fig.2). During this phase of progradation the crest elevation of the ridges increased and the shoreline straightened (Fig. 2 & Fig. 3) Minimal progradation has occurred from 3000-4000 years ago until present. Several OSL ages between 800-500 years were obtained for sediment deposited just landward of the 1974 storm scarp position and beneath the higher foredune. The proximity of ages between 800-500 to the ages of 4000-3000 immediately landward would imply that the shoreline has been stationary for a few thousand years with material likely eroded and redeposited within a narrow zone, as monitored by Short et al. (2014) in recent years. Samples collected from the upper 1 m of the foredune itself returned ages of <100 years.

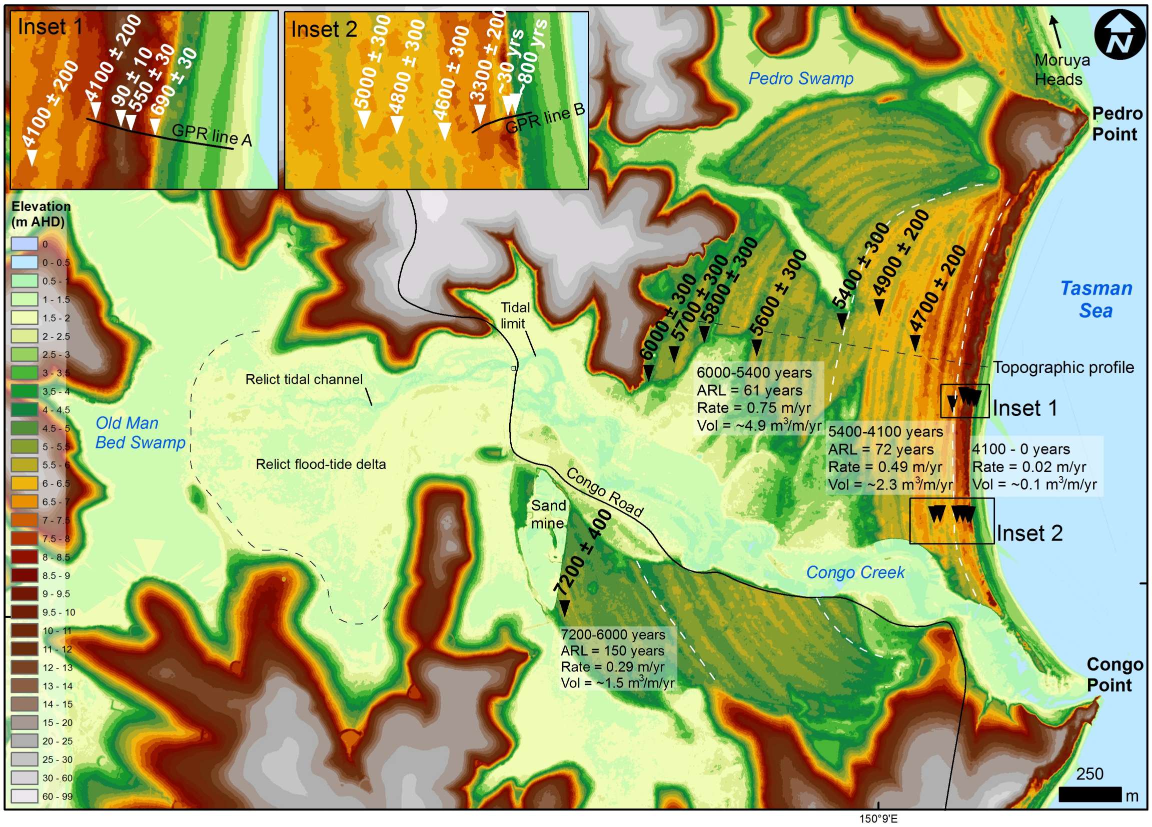

Figure 2. Topographic map of the Pedro coastal barrier derived from airborne LiDAR showing the OSL age estimates with respect to key landform features. The location of GPR lines A and B are shown in Inset 1 and Inset 2 respectively. Average ridge lifetime (ARL), progradation rate in m/yr and volume in m^3/m/yr is stated for each barrier 'section'. Note: OSL ages in inset 2 are preliminary.

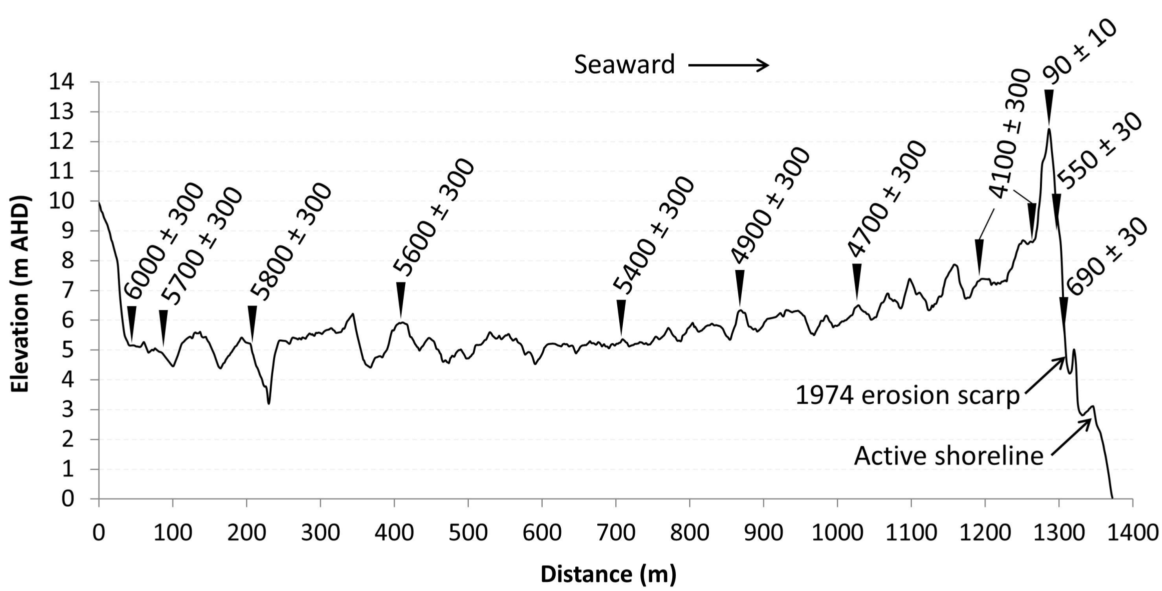

Figure 3. Topographic profile (see Fig.1 for location) across the central portion of the Pedro barrier showing OSL ages in their sampled locations.

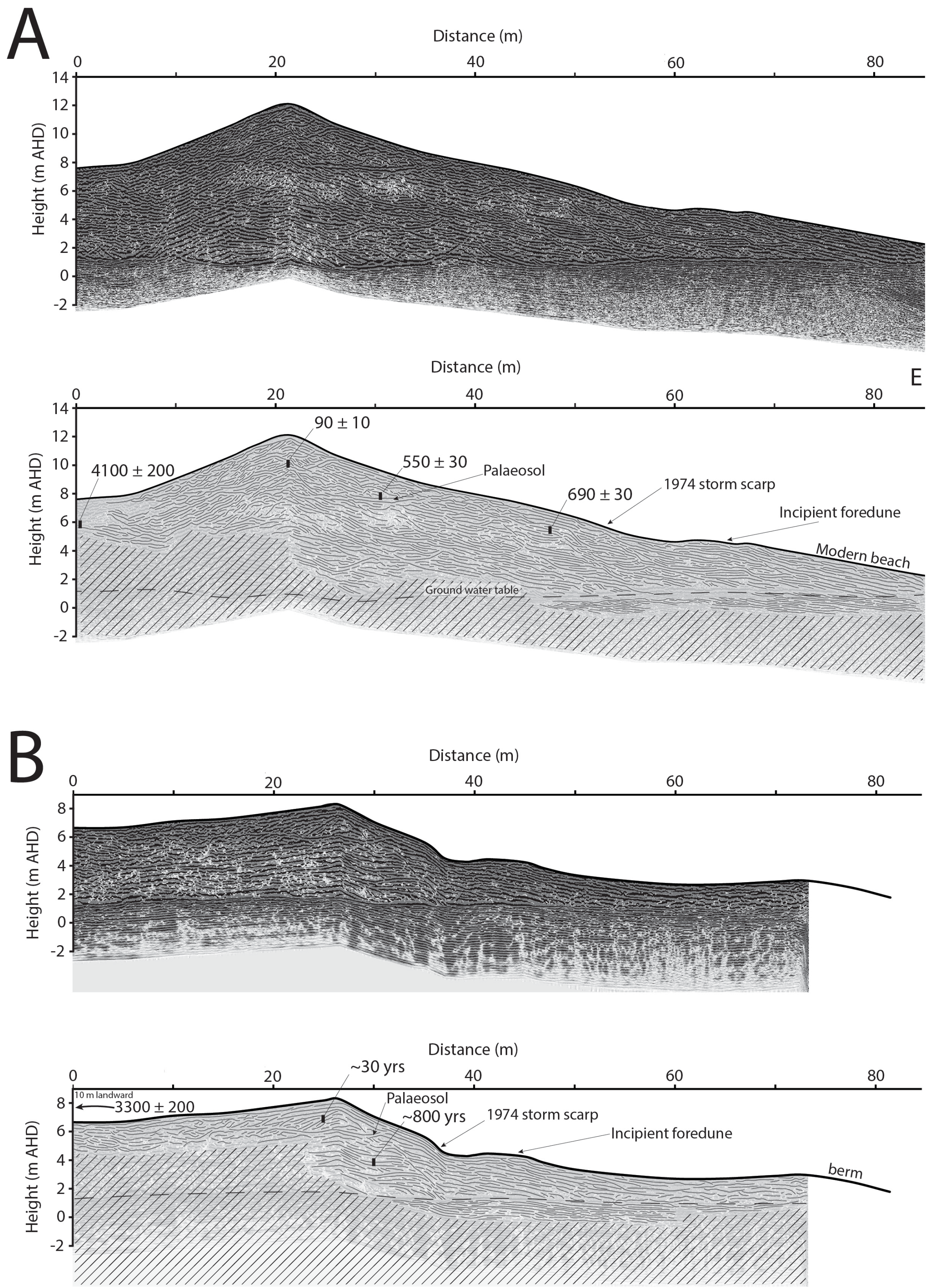

Figure 4. GPR line A and B (see Inset 1 and 2 respectively in Fig.2 for locations) traversing the higher foredune and active beach zone. OSL ages are placed at their respective depth and position on each transect. OSL ages for transect B are preliminary.

GPR surveys

The two GPR shore normal transects covering the outer ~100 m of the coastal plain demonstrate a complex dune stratigraphy for the higher foredune where a series of relict beach scarps and upper beachface surfaces are overlain by a sub-horizontal palaeosol above which are complex interbedded dune surfaces (Fig. 4). This stratigraphy of the upper portion of the high foredune contains many landward dipping reflections providing evidence for lee slope accretion and landward movement of this dune by wind action. The OSL ages below the palaeosol are between 800-500 years ago and this feature represents a pre-modern surface with the sediments above dated to <100 years. The 1974 storm scarp is a prominent feature in the central transect and several other storm scarps with a similar subsurface signature are evident immediately landwards.

Barrier sediment volume

Between 7200 and 6000 years ago when barrier deposition commenced south of Congo Creek, the shoreline accreted sediment at rate of 1575 m^3/yr. Expressed as a value relative to approximate shoreline length at that time this equates to 1.5 m^3/m/yr. During this early phase of barrier deposition, a flood-tide delta was forming accumulating at a rate of 1963 m^3/yr (assuming an average thickness of 2 m). This volume of sediment is greater than that which was being accreted on the active shoreline demonstrating the importance of this environment as a sediment sink. After approximately 6000 years ago the central and northern portion of the barrier accumulated sediment rapidly at 4.9 m^3/m/yr and then slowed to 2.3 m^3/m/yr after 5500 years ago. After approximately 3000-4000 years ago barrier progradation has been minimal with volumes of sediment accumulated on the barrier are in the order of 0.1 m^3/m/yr.

The higher foredune, which stands up to 12 m above the relict ridges immediately to the landward, contains an additional 158400 m^3 of sand (above 7 m elevation; the approximate height of the relict ridges immediately landward). If this feature has formed over the past 800-500 years then this amounts to a volume contribution of approximately 260 m^3/yr, or 0.12 m^3/m/yr (expressed according to current shoreline length). However, if the high foredune has formed in the past 100 years, as could be argued from the OSL ages, then this constitutes a volume of sediment in the order of 1600 m^3/yr, or 0.72 m^3/m/yr, which is far more significant in the context of the barrier's history.

Discussion

The deposits preserved behind Pedro Beach afford the opportunity to examine the coastal morphodynamic processes operating over the millennial and the centennial timescale with relevance to broader compartment-based coastal management. Cowell and Thom (1994) and Roy et al. (1994) emphasise the expanding need for empirical morphostratigraphic data from prograded coastal barriers in order to test morphodynamic models, both theoretical and computational: this site offers this opportunity.

An inherited disequilibrium shoreface profile may drive onshore accumulation of sandy sediments forming a prograded barrier (Kinsela et al. 2016). The progressive down-wearing of the shoreface as sediment is moved onshore to form the barrier may have exposed much of the rocky reef now evident to the east and southeast of the current shoreline position. Approximately 4000 years ago at Pedro Beach, progradation halted as the embayment had filled with sediment and there was no longer subaerial 'accommodation space'. Any sediment reserves in the nearshore zone are likely to have been moved alongshore (northwards around Pedro Point) as the marginal headlands of the embayment are no longer impeding sediment transport.

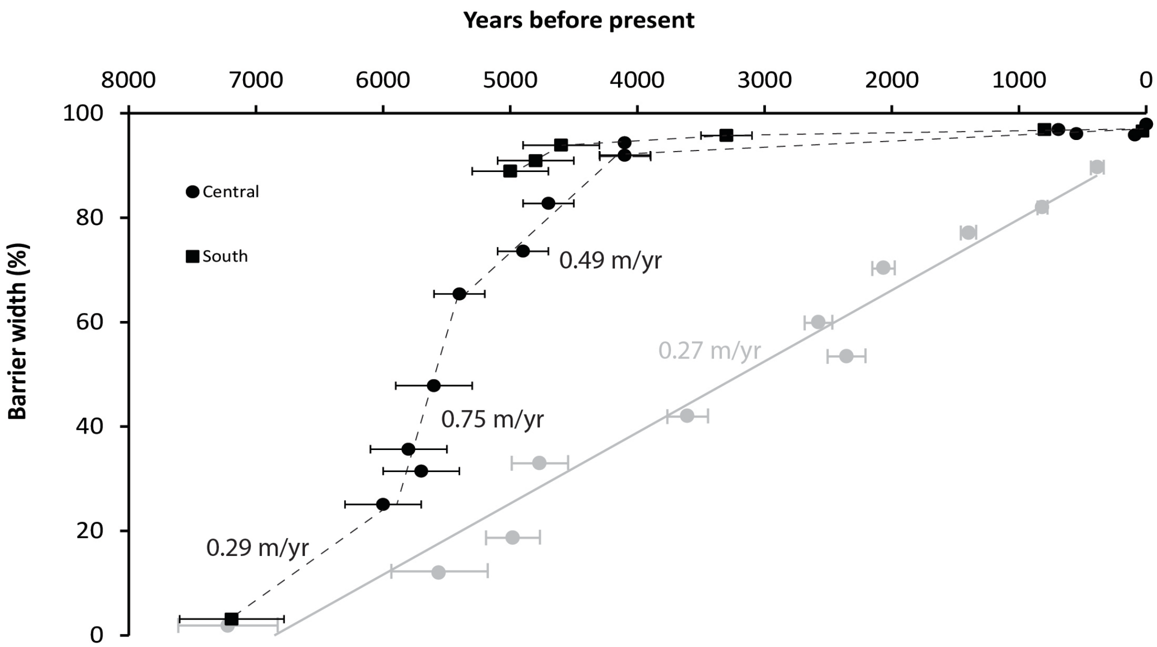

Figure 5. Barrier width for Pedro Beach (black) as a percentage expressed according to time showing OSL ages from the central dating transect (Fig.2) and preliminary OSL ages from the southern dating transect. Progradation rates expressed in m/yr are shown (c.f. Fig.2). For comparison, Moruya (Bengello Beach) OSL ages are plotted in light grey after Oliver et al. (2015).

Comparison of progradation rate between the Pedro Beach barrier system with the Moruya (Bengello Beach) system to the north (Fig.1) reveals that Pedro Beach accumulated sediment far more rapidly prior to progradation ceasing 4000 years ago. At Moruya, shoreline progradation rate was at an average of 0.27 m/yr over the entire depositional history of the plain (Oliver et al. 2015), compared to 0.75 m/yr and 0.49 m/yr between 6000-5400 and 5400-4100 years respectively at Pedro Beach (Fig.5). The initial phase of barrier deposition at Pedro Beach (between 7200-6000) was at a similar rate to Moruya, 0.29 m/yr (Fig.5). Figure 5 demonstrates that almost the full width of the current barrier was deposited by ~4000 years ago.

This comparison of shoreline progradation rate is also reflected in differences in subaerial barrier volume. Moruya maintained a volume rate of 1.35 m^3/m/yr (using an average shoreline length), also comparable to the initial phase of barrier deposition at Pedro Beach (1.5 m^3/m/yr) (Fig.2). However the volumes calculated for the rapid phase of progradation between ~6000 and ~4000 years ago at Pedro Beach are substantially greater than Moruya (Fig.2, Fig.5).

It has been suggested that the height of a given relict ridge is a result of shoreline progradation rate whereby rapid progradation results in low ridge relief and slower progradation rate higher ridge relief (Shepherd 1987). The pattern of increasing ridge height with decreasing progradation rate at Pedro Beach between ~6000 to ~4000 years ago is consistent with this hypothesis; however other factors such as increasing wave and wind exposure during progradation and shoreline straightening (reducing shoreline length) are likely to affect beach state and hence dune building potential (Short and Hesp 1982).

The planform configuration of the Pedro Beach ridge system exemplifies concepts first put forward by Jennings (1955) and Davies (1958) where wave refraction into an embayment controls the planform configuration of the shoreline (see Oliver et al. (2017) for review). The prior shorelines indicated by the foredune ridges at Pedro Beach are configured to the southerly swell regime of the Tasman Sea and the refraction pattern of these waves moving into the originally deep embayment. The preserved ridges may be envisaged as the 'wave refraction diagram' for the most landward shoreline in the system with subsequent ridges showing distinct straightening of the shoreline in planform as seaward progradation occurred, the embayment infilled and refraction decreased.

The dynamic interaction between wave and wind energy and a sandy beach/dune system, is moderated by boundary conditions (positive sediment supply) which produces shoreline progradation, leading to an increase in energy level (as the sheltering effect of headlands to the north and south is diminished), resulting in a change in beach/dune form. This change in beach/dune form to a more energetic state, in turn enables a new set of processes further modifying the beach/dune configuration. Consideration of this complex interplay of inherited geology, sediment availability and changing morphodynamic interactions is important in assessment of future shoreline behaviour.

Between 4000-3500 and 800-700 years ago the shoreline appears to have limited shoreline advance or retreat, with likely oscillation of the active beach zone. Beach profiling records suggest that an interdecadal shoreline rotation signature (Short et al. 2014) may be superimposed on the relatively stationary shoreline position on the millennial to centennial timescale. The higher foredune has formed during the most recent phase of stable shoreline conditions with the upper portion of this dune receiving sediment in the past century. Since a stable shoreline position has prevailed during this time, the foredune is likely a result of anthropogenic disturbance of the beach/dune equilibrium.

Conclusion

This study demonstrates that coastal barrier systems can transition from a lower energy system with rapid progradation to a higher energy but relative shoreline stability due to inherited geological controls on embayment configuration. The role of this beach within the broader Broulee secondary compartment is also significant given the possibility that this barrier ceased to be a significant sink for marine sediments after 3500 years ago allowing excess sediment to more longshore into adjoining compartments. This study also suggests that interconnectivity between individual beaches can vary over time and effective management of this and other similar areas along the NSW coast requires consideration of adjacent systems. Establishing the sediment transport pathways and sediment abundance in the nearshore zone is imperative for future management on a regional scale.

References

Adamiec, G., Aitken,M., 1998. Dose-rate conversion factors: update. Ancient TL 16, 37–50.

Bateman, M.D., Catt, J.A., 1996. An absolute chronology for the raised beach and associated deposits at Sewerby, East Yorkshire, England. Journal of Quaternary Science, 11, 389–395.

Chapman, D.M., Geary, M., Roy, P.S., Thom, B.G., 1992. Coastal Evolution and Coastal Erosion in New South Wales. Coastal Council of New South Wales, Sydney, p. 341.

Cowell, P.J., Thom, B.G., 1994. Morphodynamics of coastal evolution, in: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary shoreline morphodynamics. Cambridge University Press, Cambridge, pp. 33-86.

Davies, J.L., 1958. Wave refraction and the evolution of shoreline curves. Geographical Studies 5, 1-14.

Galbraith, R., Roberts, R., Laslett, G., Yoshida, H., Olley, J., 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, 339-364.

Jennings, J.N., 1955. The influence of wave action on coastal outline in plan. Australian Geographer 6, 36-44.

Kinsela, M.A., Daley, M.J.A., Cowell, P.J., 2016. Origins of Holocene coastal strandplains in Southeast Australia: Shoreface sand supply driven by disequilibrium morphology. Marine Geology 374, 14-30.

Marsh, R.E., Prestwich, W.V., Rink, W.J., Brennan, B.J., 2002. Monte Carlo determinations of the beta dose rate to tooth enamel. Radiation Measurements 35, 609–616.

Murray, A., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57-73.

Oliver, T.S.N., 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, 536-546.

Oliver, T.S.N., Thom, B.G., Woodroffe, C.D., 2017. Formation of Beach-Ridge Plains: An Appreciation of the Contribution by Jack L. Davies. Geographical Research 55, 305-320.

Prescott, J.R., Hutton, J., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. Radiation Measurements 23, 497-500.

Roy, P.S., Cowell, P.J., Ferland, M.A., Thom, B.G., 1994. Wave Dominated Coasts, in: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 121-186.

Shepherd, M.J., 1987. Sandy Beach Ridge System Profiles as Indicators of Changing Coastal Processes, New Sealand Geographical Society Conference Series, pp. 106-112.

Short, A.D., Bracs, M.A., Turner, I.L., 2014. Beach oscillation and rotation: local and regional response on three beaches in southeast Australia. Journal of Coastal Research SI 70, 712-717.

Short, A.D., Hesp, P., 1982. Wave, beach and dune interactions in southeastern Australia. Marine Geology 48, 259-284.

Wright, L.D., Thom, B.G., 1977. Coastal depositional landforms: a morphodynamic approach. Progress in Physical Geography 1, 412-459.