THE POTENTIAL OF UTILISING GPR WITH OSL TO PROVIDE INSIGHT ON THEORETICAL AND PRACTICAL ASPECTS OF COASTAL CHANGE

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Abstract

Change is a constant along the world's coasts, but with respect to the increasing rate of global warming, future shoreline behaviour is unknown. This uncertainty adds difficulty to an already challenging task of managing such dynamic environments. Storms and the estimated 1-meter sea level rise over the next century pose the greatest threats of erosion to vulnerable sandy environments. It has been the practice in New South Wales (NSW) to predict deterministic setback lines along coasts based on sea-level trend, long-term sediment budget, and short-term variability (storms). Computer models used to forecast coastal change over the next century integrate empirical data detailed over decades with that generalised over millennia. Ground-Penetrating Radar (GPR) has the potential to fill this gap in knowledge by imaging paleo-beachfaces preserved throughout the stratigraphy of Holocene prograded barriers; thus enabling our understanding of morphodynamics along the present-day beach to be extended back through time. Acquiring Optically-Stimulated Luminescence (OSL) ages of these paleo-beachfaces can then provide the chronology necessary to decipher centennial-scale patterns of coastal behaviour. The aim of this paper is to demonstrate the potential of using GPR and OSL on prograded barriers of NSW to: 1) provide a record of storms records over the Holocene, 2) construct a detailed sea-level curves, 3) calculate sediment supply to the coast, 4) locate buried structures, and 5) extract snapshots a beach's 'sweep' zone where no topographic profiling surveys exist. In order to achieve this, decades of data from the United States, New Zealand and Australia are analysed. Combining these techniques on NSW barriers can help modellers accurately predict coastal response to climate change, and communities to best prepare for it. Expanding this research to prograded systems around the world could provide Holocene records of storms and sea level change that can assist in contextualising current and future patterns influenced by global warming.

Introduction

When will a Super Storm hit Sydney and the southeast coast? What will be the response of vulnerable sandy coasts to storm erosion when coupled with predicted sea-level rise? With more than 80% of the Australian population living along the coast, the largest concentration of which is in New South Wales (NSW), answering questions like these will help coastal communities and infrastructure best prepare for the impacts of climate change. Australia has a well-established protocol for coastal geomorphic hazard assessment which determines setback limits from beaches and foredunes. The approach requires consideration of three components necessary for future predictions: 1) long-term sediment budget, 2) short-term variability (storms), and 3) sea-level trend (Woodroffe et al., 2012). Researchers have developed intricate computer models to predict coastal behaviour and quantitatively analyse risk (e.g. Woodroffe et al., 2012; Wainwright et al., 2015). To forecast shoreline response to ~1 m sea-level rise predicted over the next 100 years these models upscale short-term, wave-morphology interaction along beaches and downscale long-term coastal landscape evolution (Figure 1). Even though these models are empirically based, detailed information is restricted in location and duration to historical beach and wave data while longer-term net shoreline movements are generalised from chronostratigraphy reliant on point source core data.

Detailing sea level, sediment supply and storms over thousands of years, and the impact they have on coastal evolution, is key to forecasting future shoreline behaviour. The largest 'super storm' on record for the southeast coast of Australia was a series of 8 events in the 1970s. Contextualising this storm within a Holocene record is crucial to determine when another storm of equal or greater magnitude will hit Sydney, like the 2012 Super Storm Sandy in New York City or 2013 Typhoon Haiyan in the Philippines. Despite extensive research, recurrence intervals of large-magnitude erosional events are poorly understood due to limited historical documentation and instrumental records restricted to short-term timescales. Similarly there has been a concerted effort in Australia, and around the world, to determine relative sea level change over the 7000 years, yet debate exists of fluctuations up to 2 m higher (e.g. Thom and Roy, 1985; Murray-Wallace and Woodroffe, 2014). The necessity of deciphering sub meter to meter sea level fluctuations, and the coastal response to them, is accentuated by the projection of a ~1m rise by 2100. Since Australia is a 'far-field' sites, such information could help study the relationship of global ice-equivalent and sea-level changes in order to model their response to future climate change. Resolving these smaller scale fluctuations is difficult as most sea-level curves combine a wide variety of biological indicators and other intertidal material, with varying error bars, which obscure any recorded minor elevation changes.

Long-term shoreline behaviour is a function of the relationship between the sea-level change and the availability of sediment, such that falling seas and/or an increase in sand supplied to the coast causes it to build (prograde) where rising seas or negative sediment budget cause retreat landward (transgress). The general trend of beaches can be determined by the type of coastal landform that it fronts (Woodroffe, 2003). Where there are accumulations of beach and dune sediments behind the active beaches, these landforms are referred to as coastal barriers. Inherent in the names of the three main types of barriers, is the trend of its shoreline (Figure 2). Transgressive barriers gradually migrate landwards as a result of storm overwash usually in response to sea-level rise. Stationary barriers occur along stable shorelines. Progradational barriers occur when there is a relative fall of sea level or a substantial supply of sediment to the coast. Coastal barriers have been extensively studied in NSW providing some of the best models available (e.g. Figure 2: Roy and Thom, 1981; Thom et al., 1981b; Chapman et al., 1982; Thom, 1984;).

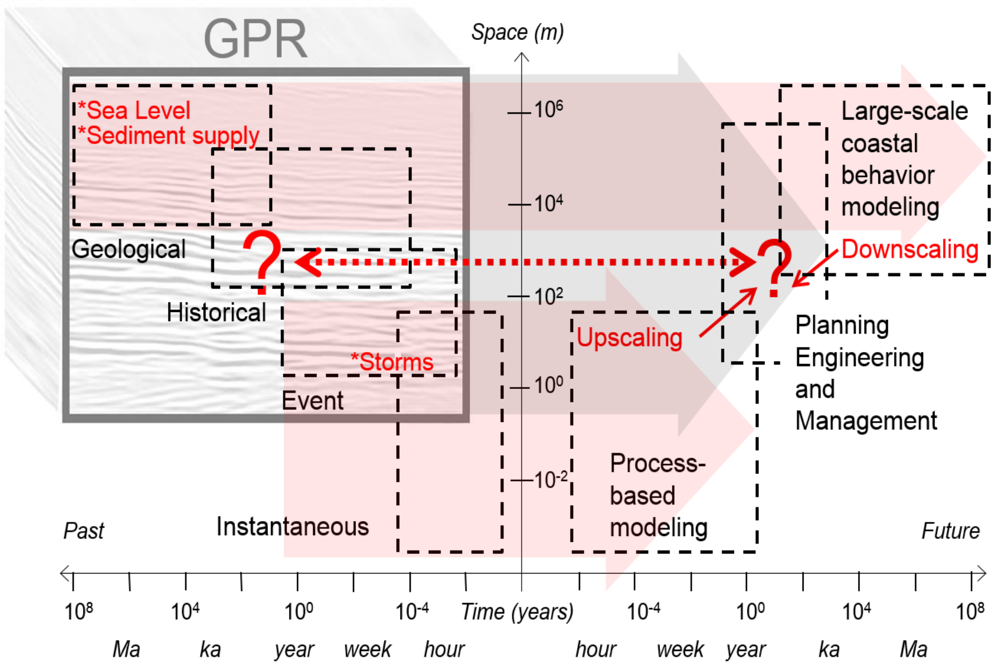

Figure 1: Scale cascade of the spatial and temporal range pertinent to coastal processes (in black). The left hand side of the diagram shows the scales coastal researchers have focused their investigations on and developed conceptual understanding of past coastal evolution. The right hand side explores the scales relevant to a consideration of the future. The large red arrows illustrate how empirical studies of past behaviour on short and long timescales feed into process-based modelling and behaviour models that are upscaled and downscaled, respectively, to predict future shoreline evolution over the coming century. The knowledge gap at this intermediate/centennial scale can be filled using GPR and OSL to span all four domains (symbolised with 3-D GPR image in grey). From Dougherty et al., 2016 (modified using Gelfenbaum and Kaminsky, 2010; Woodroffe and Murray-Wallace, 2012).

Prograded barriers (also called strandplains, beach-ridge plains, or a plain of relict foredune ridges) retain the highest preservation potential of all other barrier types to record beachface behaviour over the Holocene (Dougherty, 2011; Scheffers et al., 2012; Tamura, 2012). The classic models of these systems used today are from initial studies in North America over 50 years ago and extensive research in Australia performed more than 30 years (e.g. Bernard et al., 1962; Curray et al., 1969; Thom et al., 1978; Roy and Thom, 1981; Thom et al., 1981a&b). The resulting cross-sections have detailed dune morphology profiles from topographic surveys, but the chronostratigraphies are more generalised due to the restriction to point-source drill hole data (e.g. Figure 9&11). Subsurface facies boundaries were mapped by interpolating between a series of core logs. Chronologies were constructed from radiocarbon dating organic material recovered within the cores and extrapolating ages to the barrier surface to form isochrons. However, within these sandy environments organics are scarce with shells being the most common datable material, the majority of which are not in-situ. Moreover, if shells exist, they are commonly contained within lagoonal or shelf sediments and are not part of the barrier lithesome and the shallow subsurface stratigraphy lacks the resolution to track the stratigraphic layer dated directly to the.

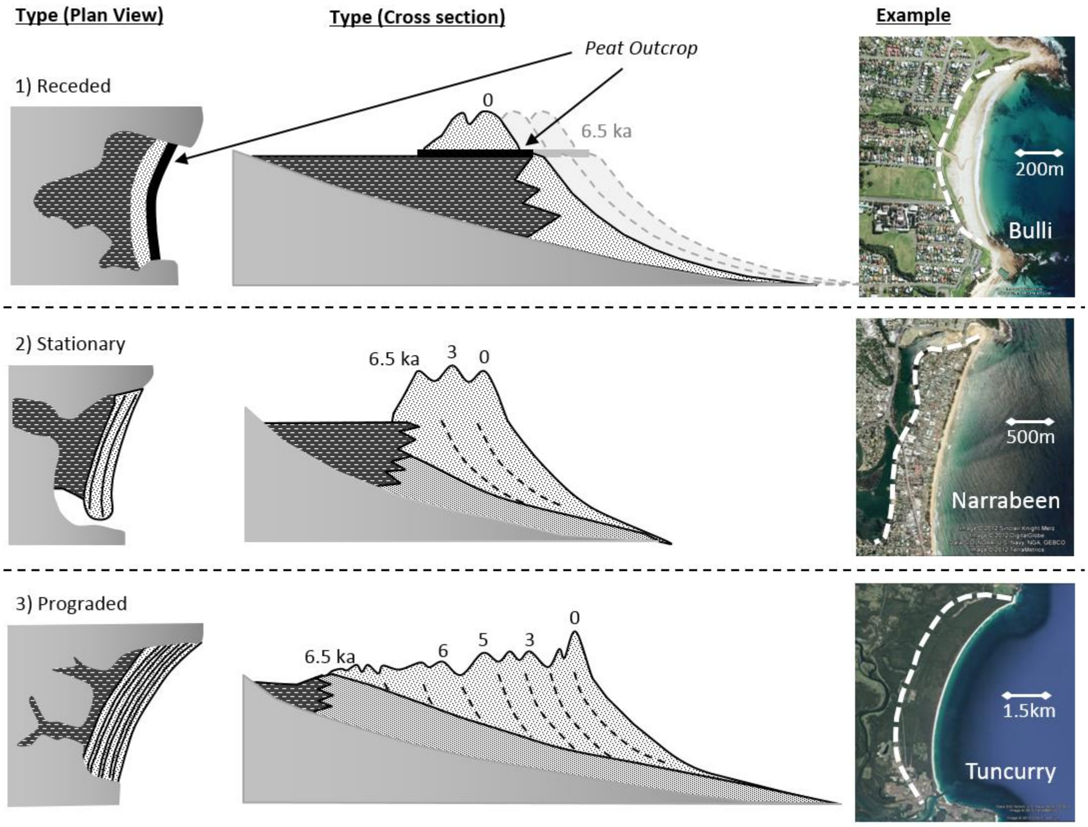

Figure 2: Classification, morphology, and evolutionary history of barrier types. Right panel: satellite images (source: Google Earth) show representative NSW examples of each barrier type, with white dashed lines marking their landward extent landward. Modified from Dougherty et al., 2012a.

This paper aims to demonstrate how shallow geophysics combined with luminescence dating across prograded barriers has the potential to fill the knowledge gap about coastal change within intermediate temporal and spatial scales. The resulting chronostratigraphic models will make it possible to utilise the meticulous beach-profile records of storms collected along present-day coasts and extend it throughout the Holocene by comparing them to detailed images of paleo-beachfaces preserved beneath the series of beach ridges. Since beachface morphology is a reflection of wave energy and their elevations directly relates to sea level, mapping and dating the paleo-beachfaces can provide records of past storms and insight into changes in the elevation of the oceans over time. The detailed stratigraphy can also better quantify the volume of sand within the barrier, which when combined with luminescence ages can yield accurate rates of sediment supply. Ultimately, by producing a detailed evolution of the barrier, the influence of storms, sea level and sediment supply can be determined. Such detailed information about past coast behaviour is crucial to predicting the future response of beaches to climate change. The combination of geophysical and geochronological techniques also have more immediate practical applications like detecting buried objects, such as sea walls, and extracting a snapshot a beaches 'sweep' zone where no beach profiling surveys exist. In order to illustrate the prospect of combing these two techniques this paper synthesises findings published on sites in the United States, New Zealand and Australia. The reader is invited to refer to the original publications for a detailed explanation of these findings and more comprehensive references.

Methodology

Ground-Penetrating Radar (GPR) is an accepted tool among coastal researchers (e.g. Buynevich et al., 2009). This high-resolution geophysical technique can image barrier stratigraphy with decimetre resolution over kilometres of coast (e.g. Dougherty, 2011). Ground-penetrating radar provides an image of barrier stratigraphy by emitting short pulses of electromagnetic energy into the ground (Jol, 2009). The transmitted pulses are limited in their depth by such variables as mineralogy, grain size, water content and saline concentrations. These factors control the electrical conduction properties of the material being penetrated (dielectric permittivity) and cause energy pulses to reflect back to the receiver, therefore recording facies changes by travel-time within the waveform (Figure 3). This time measurement is converted into depth by entering the dielectric constant of the material that it is travelling through. The resulting individual waveforms display changes within the subsurface by recording a wave-amplitude spike at a stratigraphic boundary surface, such that low wave-amplitude represents homogenous sediments and any increase in amplitude is associated with greater contrast in sediment characteristics (e.g. change in water content, mineralogy, grain-size, sorting, etc.). By collecting GPR data along a transect, individual wave traces stack laterally and peaks of high-amplitude merge to form reflections of stratigraphic boundaries (Figure 3&4). These strong or high-amplitude reflections show up as prominent coupled lines of black and white, for example beachfaces resulting from heavy mineral layers concentrated during a storm (Figure 4). Alternatively, areas where the substrate is similar in composition produce low-amplitude frequencies resulting in weak reflections or reflection-free areas, such as the opaque grey at the top of Figure 4C, indicating massive well-sorted dune sands in Figure 4D.

Optically-Stimulated Luminescence (OSL) dating is a geochronology technique that determines the time elapsed since buried sand grains were last exposed to sunlight (e.g., Huntley et al., 1985). Upon burial, ionising radiation from surrounding sediment (by radioactive decay of U, Th, Rb & K) and cosmic rays, is absorbed by the mineral grains and stored in traps within their crystal lattice. Exposure to sunlight bleaches away any luminescence signal and resets the 'clock' to zero. This stored radiation dose can also be evicted with light stimulation in the laboratory and the energy of photons being released can be measured. Calculating the age of when the grain was last exposed to sunlight, is based on quantifying both the radiation dose received by a sample since its zeroing event, and the dose rate which it has experienced during the accumulation period. Dating of coastal systems using OSL has been very successful on a global scale and shown to work particularly well in Australia (e.g. Murray-Wallace et al., 2002; Rink and Forrest, 2005; Neilsen et al., 2006; Jacobs, 2008; Cunninham et al., 2011; Choi and Choi, 2014; Oliver et al., 2015). Since quartz is both a principle mineral used in luminescence dating and abundant in coastal barriers, the reliance on deep or scarce organic material is eliminated and specific stratigraphic layers can be targeted in a strategic manner.

Combing GPR and OSL on prograded barriers has the ability to extract shoreline behaviour in great detail over millennia. Collecting GPR across the entire width of a prograded barrier can extract a high-resolution stratigraphic record that details the paleo-beachfaces deposited during the Holocene (e.g. Dougherty, 2011). This geophysical data can be used to map paleo-beachface elevation (which is intrinsically linked to sea level) and morphology (which is inherently affected by storms). In order to perform analysis, the paleo-beachfaces are digitised to accurately assign elevations and slopes, while certain stratigraphic layers or perimeters are digitised to calculate sediment volumes. GPR can also be used to target sediments associated with specific beachfaces for OSL dating. Since OSL dates the time elapsed since grains were last exposed to daylight, this technique can best determine when certain paleo-beachfaces were along the active coast. Ultimately, augmenting the high-resolution stratigraphic data with the luminescence chronology resolves the temporal component necessary to determine sea-level curves, storm frequencies and sediment supply/progradation rates.

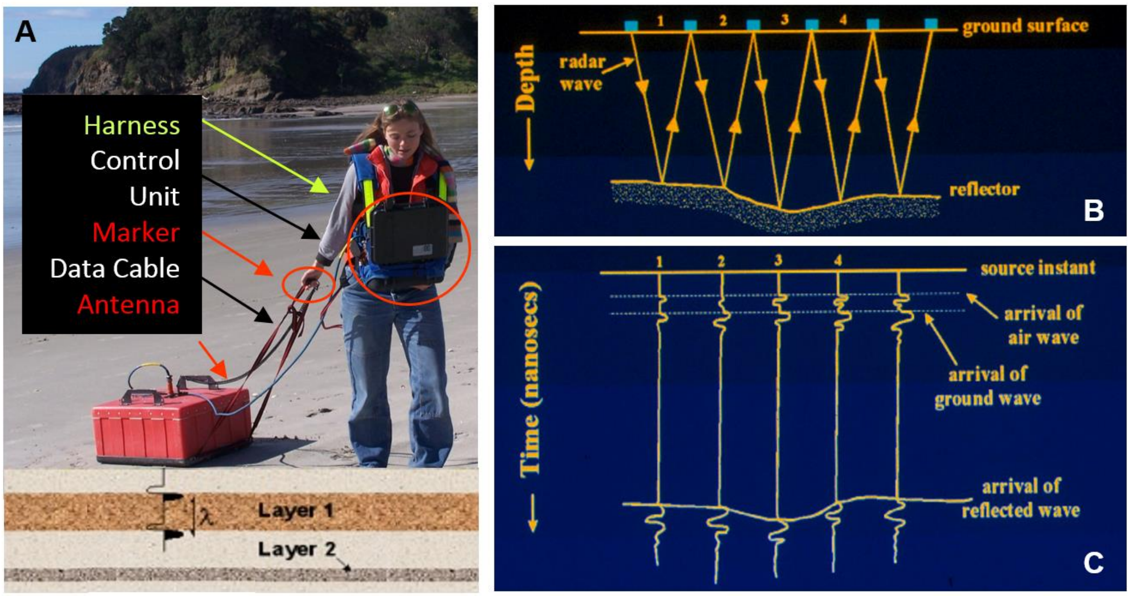

Figure 3: (A) GSSI SIR-2000 GPR system with a 200 MHz transceiver antenna. Diagrams A-C depict how radar waves emitted from the transmitter penetrate the subsurface interacting with a stratigraphic layers at depth and the reflected waves are recorded by the receiver upon return to the surface (from Jol and Smith, 1992). Modified from Dougherty, 2011.

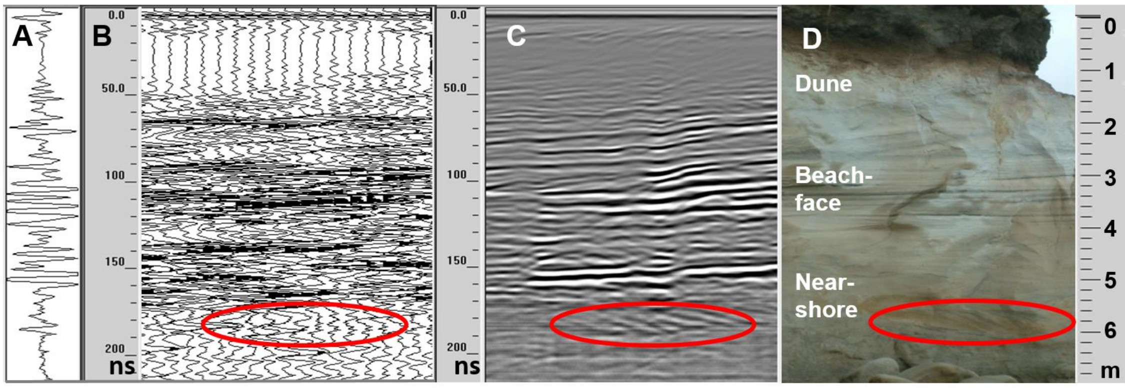

Figure 4: Sample of GPR data. (A) Record of a single radar waveform, similar to that in Figure 3. (B) Series of waveforms staked laterally to produce a GPR record. (C) The same GPR record shown in what is called 'Linescan Greyscale Mode' which is preferred data display due to its ability to show small-scale structures (e.g. steeply dipping beds in the red oval). (D) Photograph of an outcrop of the three barrier facies imaged in the geophysical record (dune, beachface and nearshore). Modified from Dougherty, 2011.

Larger-scale theoretical and practical applications

Storms

Beaches are constantly changing as a result of the dynamic force of wind, waves and tidal conditions, with storms producing some of the most dramatic change. These high energy events erode sand from the beach transporting it either landward or offshore into nearshore bars. This results in storms leaving behind signatures such as washovers, dune scarps and flattened beach profiles with concentrations of coarse-grained sediment and heavy-minerals (e.g. Figure 5: Smith and Jackson 1990). After the high-energy waves subside, post-storm recovery occurs whereby lower-energy swell waves return sediment onshore burying the evidence of erosion (Komar, 1998). The distinct morphology and contrasting sediment characteristics of these buried erosional features produce distinctive reflections in GPR records. Barriers that have prograded over time preserve a record of these storms within their accreting layers of sand. At Castle Neck barrier in Massachusetts, USA, GPR first imaged paleo-beachfaces in a prograded barrier stratigraphy that displayed similar geometry to beach profiles collected from the active beach after a large storm in 1978 (Figure 5: Dougherty et al., 2004). Around the same time in Maine, USA, OSL was used to date eroded beach surfaces imaged in GPR (Buynevich et al., 2007).

Collecting GPR and OSL across the width of a prograded barrier has the potential of yielding a storm record over the Holocene which could indicate the recurrence interval of these erosive events (Dougherty, 2014). GPR transecting a prograded barrier in Omaha, New Zealand, imaged a storm-cut paleo-beachface known to have been eroded by a series of storms in 1978 (Figure 6B-E). Twenty-four other storm-cut paleo-beachfaces were mapped across Omaha (Figure 6E in solid red lines) with post-storm recovery beachfaces in-between (Figure 6E in dashed brown lines). Thirteen of the 25 storm-cut beachfaces eroded out the swales forming the low-lying beach ridges. From this a hierarchy of storm intensity was hypothesised whereby higher-energy events imprint the morphology (Dougherty, 2014). Existing carbon chronology was used to construct speculative reoccurrence intervals of storms with increasing intensity that nearly doubles from ~250 to ~500 years. Acquiring detailed OSL ages of these paleo-beachfaces would test this hypothesis of storm frequency and intensity. Performing similar studies using OSL and GPR on classic prograded barriers along the NSW coast could image the eroded beachface from the 1970’s events and construct a Holocene storm record that would determine if indeed it was a 1-in-100 year storm.

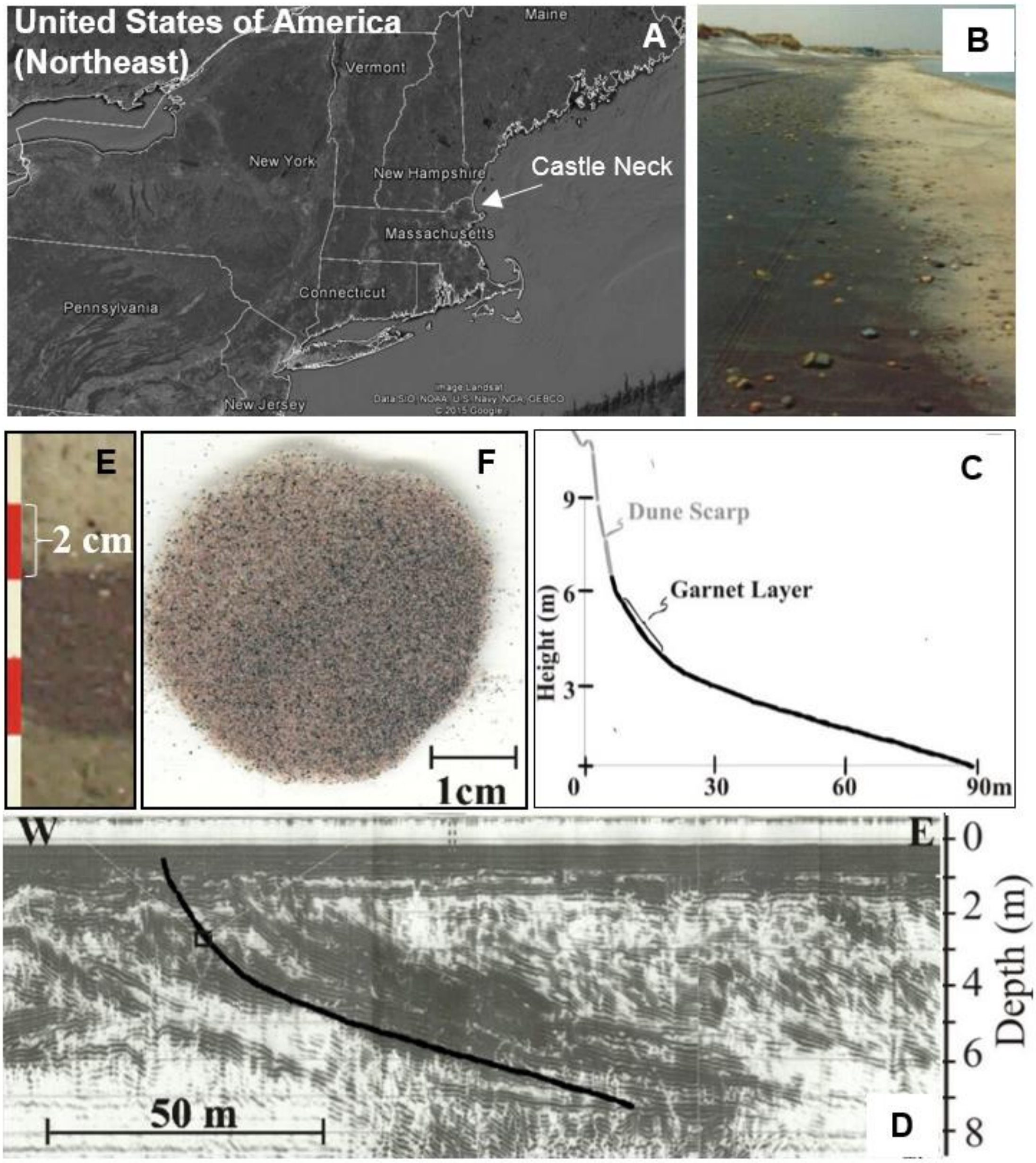

Figure 5. (A) Location of Castle Neck barrier in Massachusetts, USA. (B) Photograph of a storm-cut beach on nearby Block Island, RI, showing classic concentration of heavy-minerals along the steeped upper beachface. (C) Beach profile from the active shoreline of Castle Neck barrier collected a large Northeast storm in 1978 (Hayes and Boothroyd, 1969). (D) Shore-perpendicular GPR record from Castle Neck barrier showing a series of strong reflection surfaces that representing paleo-beachfaces with the same geometry as the storm-cut profiles taken after 1978 event. (E) Photograph of a heavy mineral layer collected by GeoProbe to ground-truth the upper beachface. (F) Picture of heavy mineral layer sampled: garnet, ilmenite and magnetite with only 20% 'rose' quartz. Modified from Dougherty et al., 2004.

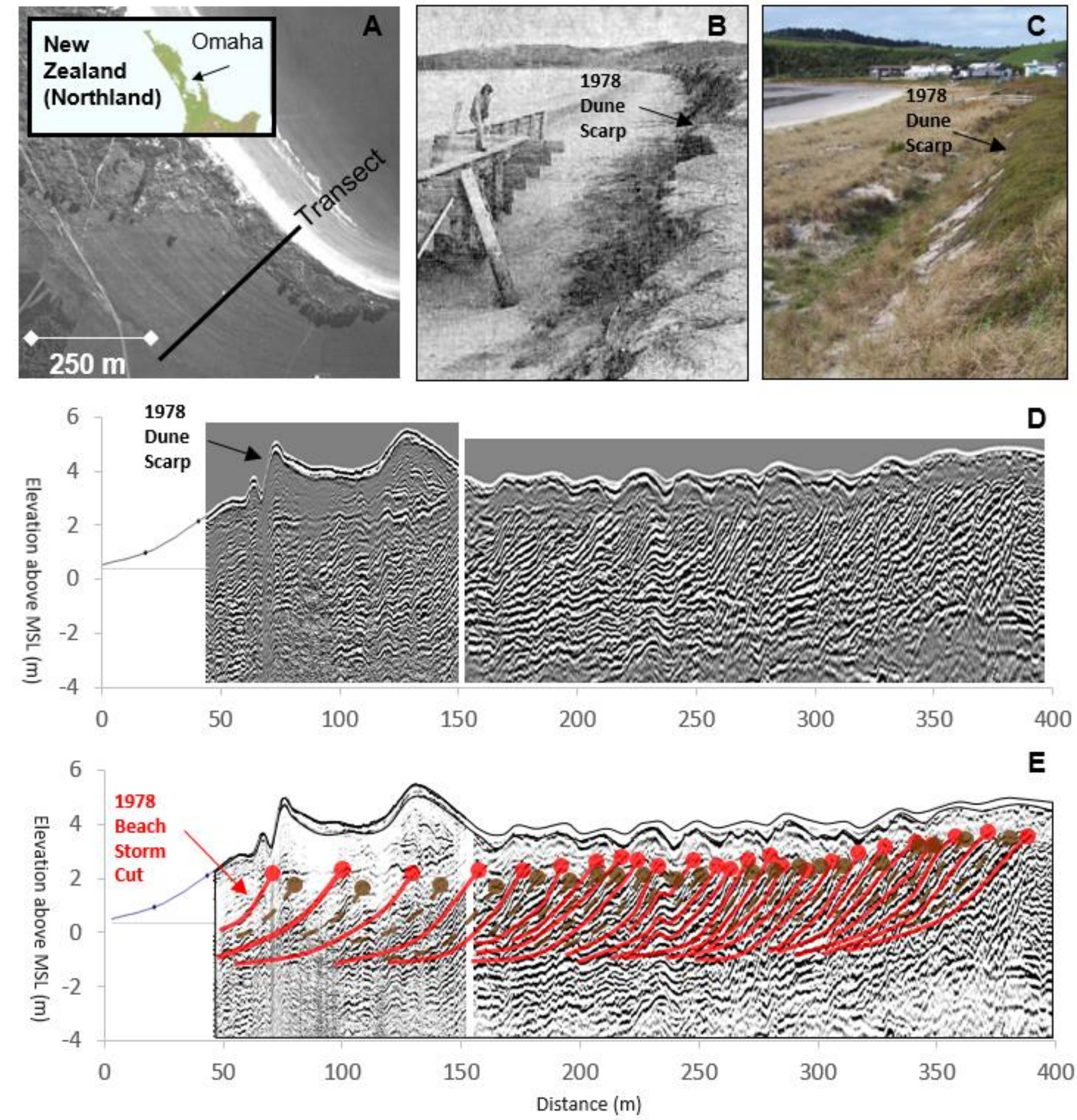

Figure 6. (A) Aerial view of the southern portion a prograded barrier in Omaha, New Zealand. (B) Oblique photograph of erosion after a storm hit Omaha in 1978. (C) Similar photo taken in 2007 showing the 1978 dune scarp preserved within subsequent progradation. (D) GPR record collected across southern section of Omaha. (E) Annotated GPR highlighting paleo-beachfaces with storm-cut morphology in red and lower-energy swell shorelines in dashed brown, with beach-dune interface depicted by dots. Modified from Dougherty et al., 2013.

Sea level

Ancient shoreface–shelf facies have been used to infer long-term processes such as relative sea-level change (Rodriguez and Meyer, 2006). Two previous studies have used GPR to map the elevation of beachfaces preserved within Holocene prograded barriers to infer past sea-level changes (van Heteren and van de Plassche, 1997; van Heteren et al., 2000; Rodriguez and Meyer, 2006). Both methodologies used the prominent dune-beach facies boundary as the sea level marker. The resulting sea level history constructed by van Heteren et al. (2000) compares favourably with the accepted curve derived from more conventional methods using basal salt-marsh peat deposits. Since this dune-beach facies provides a well-constrained sea level marker, then mapping and dating it in detail over prograded barriers along the same coast could result in a regional sea curve. The abundance and consistency of the proxy data has the potential to resolve small-scale fluctuations that might be masked in more commonly used amalgamation plots of multiple types of biological indicators.

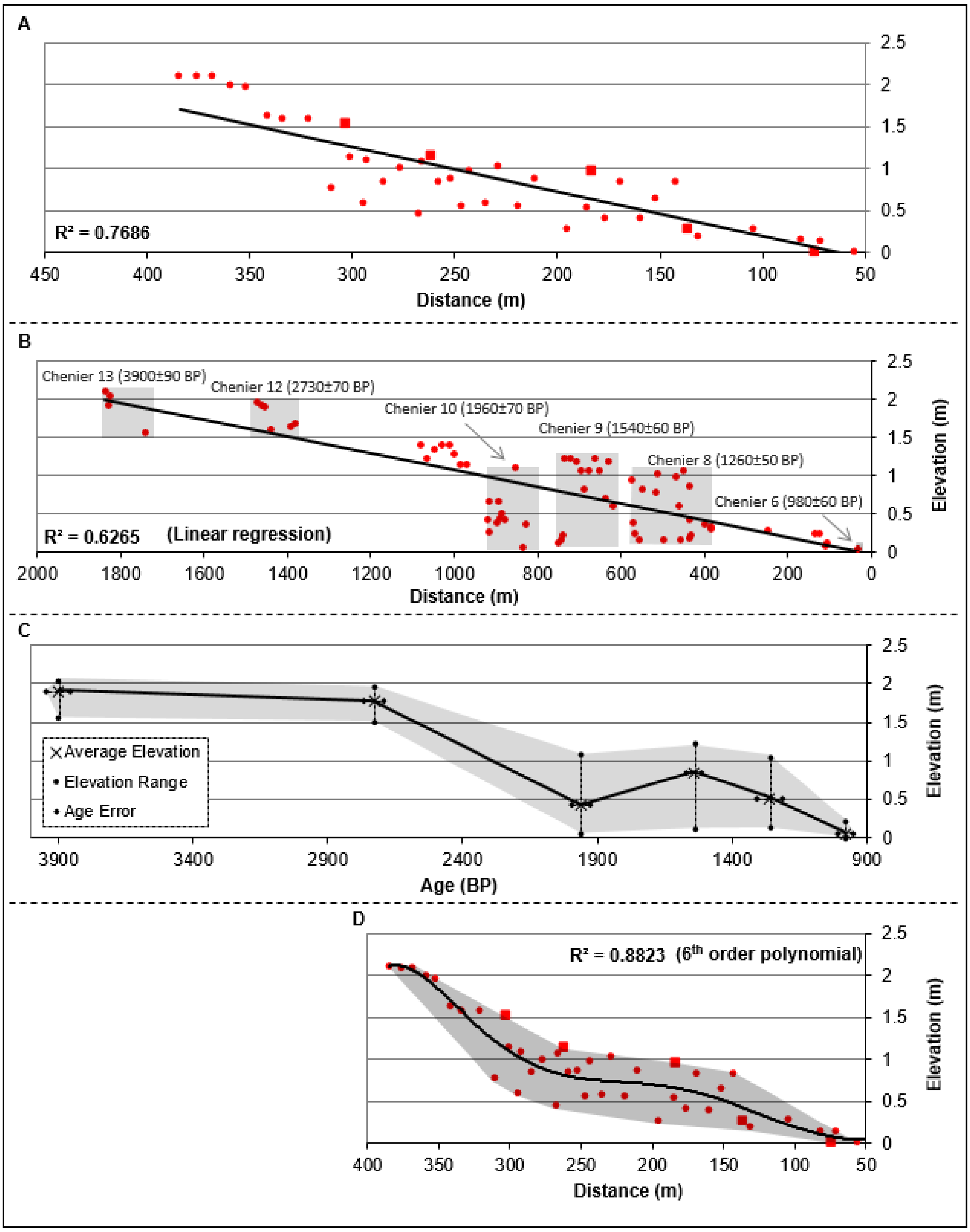

Figure 7: (A) Distance-elevation plot of beach-dune interface from Omaha. (B) Distance-elevation plot of beach-nearshore contacts with associated ages from the Miranda Chenier Plain. (C) Age-elevation plot of cheniers indicating a nonlinear sea-level fall from~2 meters. (D) Analysis of the distance-elevation plot from Omaha potentially recording a similar nonlinear fall in sea level over the Holocene. Modified from Dougherty and Dickson, 2012 and Dougherty et al., 2013.

The Holocene sea level curve for New Zealand is ambiguous with respect to the last 6000 years (Gibb, 1986), similar to Australia. GPR from Omaha barrier was used to digitise the dune-beach interface and the boundary was used as a proxy to reconstruct historical changes in sea level during the Holocene (Dougherty, 2014). The digitised points plot an increase in elevation of the landward points to about 2 meters above their seaward counterparts (Figure 6). This is interpreted as corresponding to a general fall in sea level from a ~2 m highstand. While there is no detailed chronology throughout this barrier, the nature of the trend is similar to the latest New Zealand sea level curve published (Figure 7: Dougherty and Dickson, 2012). This most recent curve was produced using existing radiocarbon ages and mapping the beachface-nearshore contact across Miranda chenier plain, located 100 km south along the same coast as Omaha (Figure 8). The results show a drop in sea level from ~2 m around 4,000 years ago (mid-Holocene highstand) to near-present level about 1,000 years ago (Dougherty and Dickson, 2012). Analysis on the data indicate a nonlinear fall form a ~2-meter highstand at both sites (Figure 7), which interestingly is similar to some of the contentious sea-level curves from Australia (e.g. Sloss et al., 2007; Lewis et al., 2013; Murray-Wallace and Woodroffe, 2014). The same OSL collected across Omaha to determine storm frequency can be used to construct a time-elevation plot and comparison with Miranda could determine a regional sea level signal. Replicating this methodology on NSW barriers would contribute to the Australian sea level debate and test whether there is any trans-Tasman correlation.

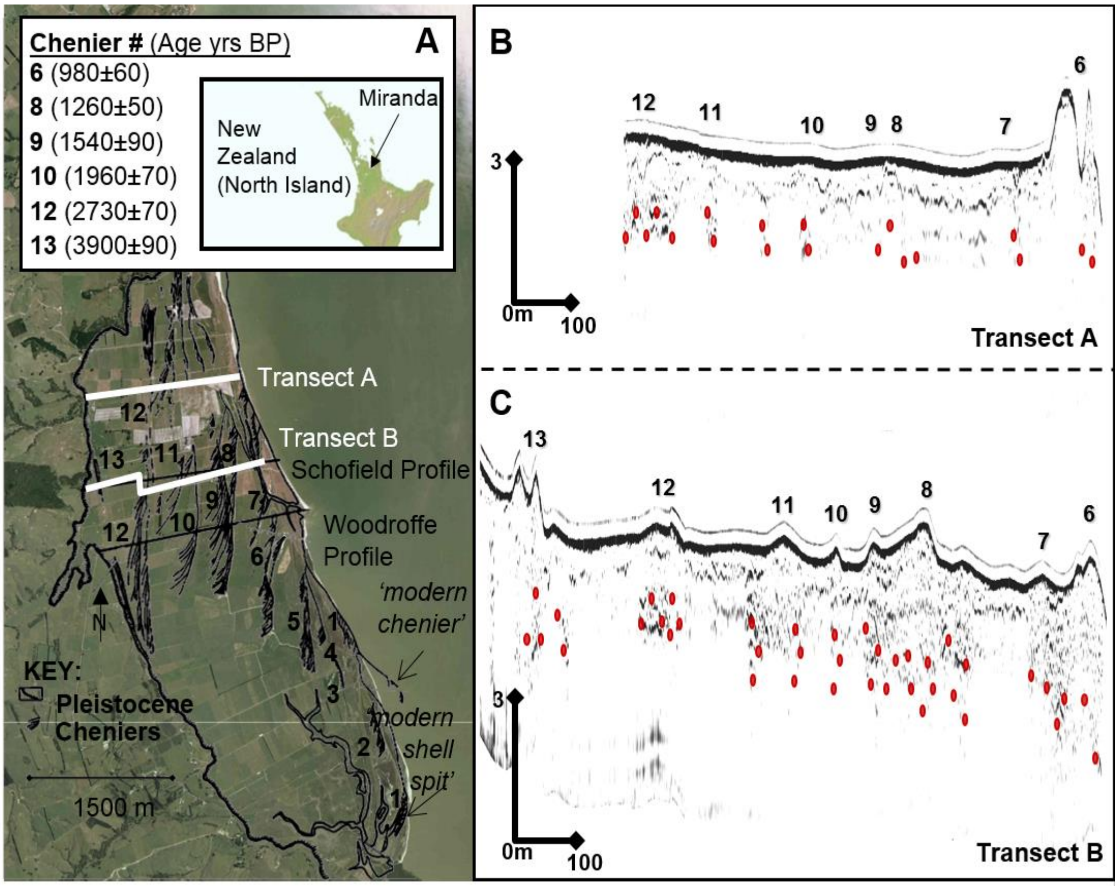

Figure 8: (A) Air photograph of the Miranda Chenier Plain, New Zealand, with the location of the 13 ridges overlain and associated ^{14}C ages. (B&C) GPR profile across cheniers 6-13 with the beach and nearshore contacts highlighted in red. Modified from Dougherty and Dickson, 2012.

Sediment supply

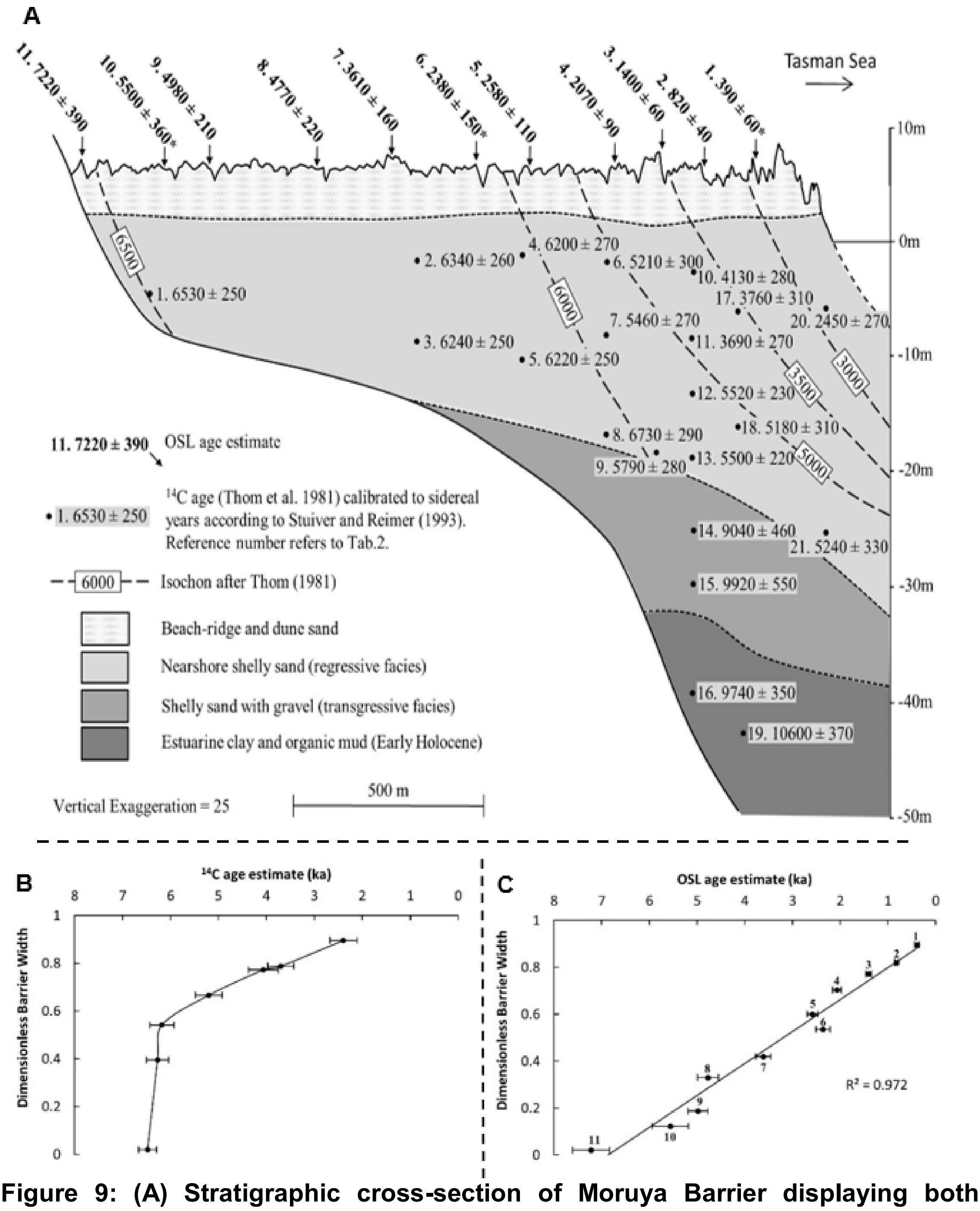

Figure 9: (A) Stratigraphic cross-section of Moruya Barrier displaying both radiocarbon and OSL chronologies. (B) Plot of ages versus barrier width using radiocarbon dates. (C) Plot of ages versus barrier width using OSL dates. Modified from Oliver et al., 2014b.

The supply of sand to the coast can dictate whether the shoreline will prograde or not. The prograded barrier near Moruya, NSW, is classic system representative of others studied in Australia and North America. These systems have long been considered to have built rapidly since ~6.5 ka until slowing or stabilising between 3 and 1 ka due to the depletion of sediment supply (e.g. Figure 9A: Bernard et al., 1962; Curray et al., 1969; Thom et al., 1978; Roy and Thom, 1981; Thom et al., 1981a&b; Shepard, 1990). Core transects through the north, central and south Moruya barrier determined differing rates of long-term sediment supply both through time and alongshore (Thom et al., 1981a: Figure 9&10). Preliminary work looked at the influence of accommodation space by creating a digital elevation model and producing volumetric slices based on isochrons from the three core cross-sections (Dougherty et al., 2012a: Figure 10). A time series of these volumetric slices shows similar longshore variations in progradation to that observed by Thom et al. (1981), due to the dependence on the same ^{14}C dating (Figure 10). Irregularity in the underlying basin geometry was used to explain these variation as well as complicated volumetric progradation rates (Dougherty et al., 2012a).

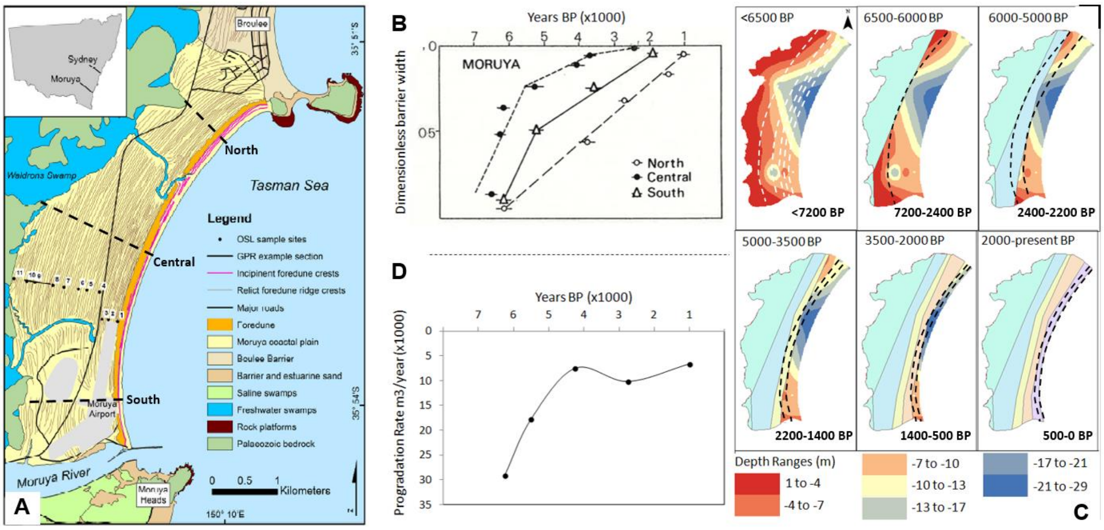

Figure 10: (A) Map of the Moruya barrier (from Oliver et al., 2014). (B) Progradation through time of the north, central and southern transects (Thom et al. 1981). (C) Preliminary schematic visualisation of progradation through time overlain on an elevation model of the transgressive sand sheet surface underlying the present day barrier. (D) Preliminary volumetric progradation rate in m3/y calculated from the time series shown in (C).

A recent study using OSL collected from across the central transect at documenting that the barrier prograded linearly for 4,000 years longer than that determined using radiocarbon (Figure 9: Oliver et al., 2014a&b). This constant rate of progradation and the linearity of the lateral extent of the beach ridges indicate that the total volume of sediment supplied to the coast must have increased steadily over time filling the embayment, seemingly unaltered by irregularities in accommodation space alongshore. Continued work used Light Detection And Ranging (LiDAR) to calculate the total volume of sand that has accumulated above Mean Sea Level (MSL) and the result indicates a relatively constant rate of 74,000 m^3/y (Oliver et al., 2014a). The distribution of this sediment along the accreting beach surface appears to be influenced by changes in the embayment length (Figure 11). Across-shore sediment accumulation must have recently increased, with respect to eolian sands above MSL, to build the anomalously large foredune ridge. Using the OSL rate of progradation these foredunes likely formed in the last few hundred years and rough volumes calculated using the areas (Figure 11D) and multiplying it by a 1m swath, it is evident that the rate of sediment supply has almost doubled from ~1.7 m^3/y (~11,600 m^3/~7000 years) to ~3.2 m^3/y (~640 m^3/~200 years). Collecting OSL samples from other classic barriers may also show they too prograded linearly and for longer than previously thought and that the ubiquitous large foredunes formed as a result of increased, rather than decreased, sediment supply.

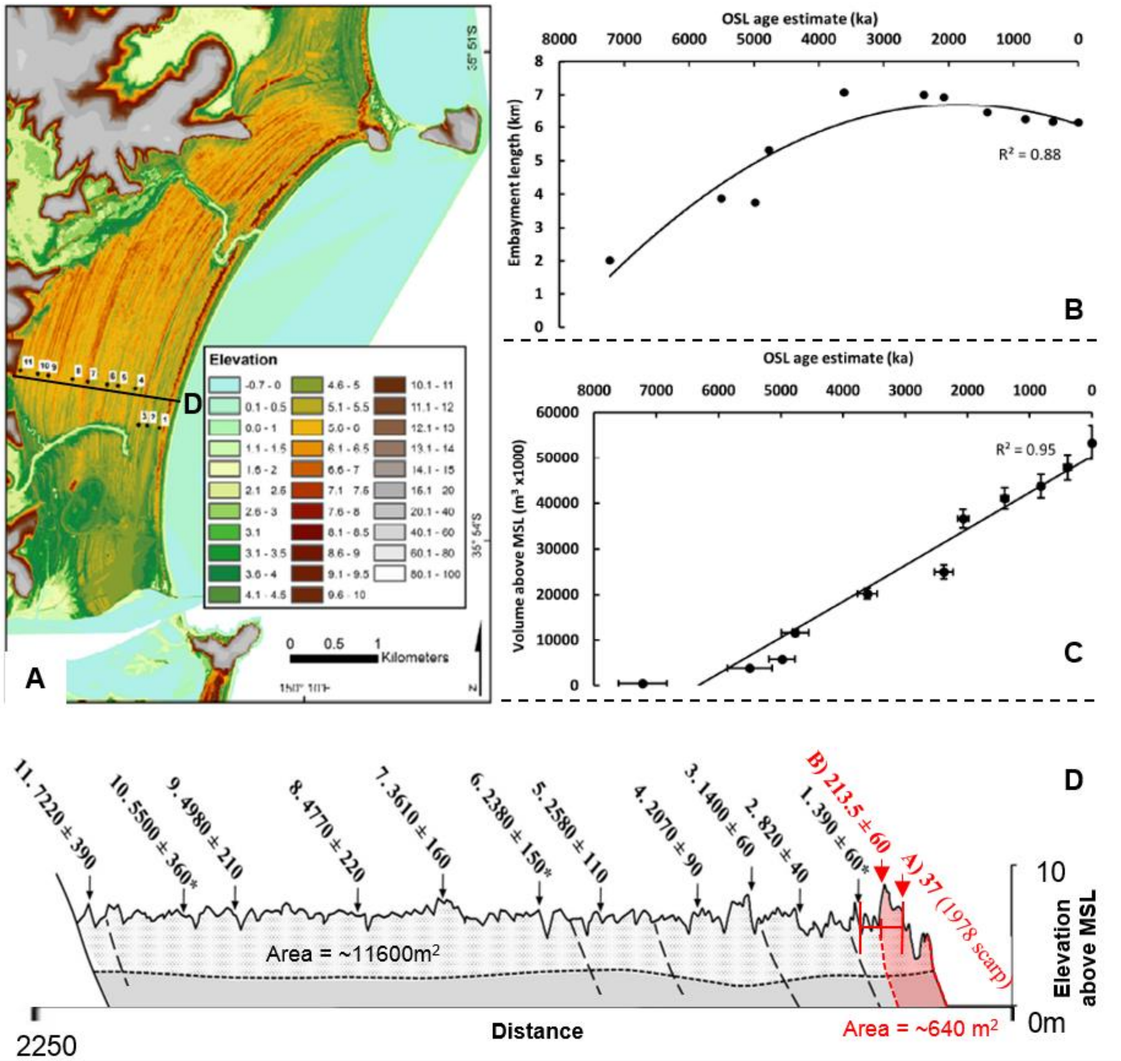

Figure 11: (A) LiDAR of Moruya barrier. (B) Plot of sediment volume delivered to the coast calculated with LIDAR and OSL. (C) Plot of embayment length over time. (D) Cross-section above MSL indicating difference in sediment accumulation across-shore.

Tuncurry is another well-studied prograded barrier in NSW, displaying the classic core and ^{14}C chronostratigraphy (e.g. Melville, 1984; Roy et al., 1994; Roy et al., 1997) despite GPR having been collected (Figure 12). Similar to Moruya, Tuncurry was thought to have prograded quickly (0.42 m/y) 6,000-15,000 years ago and then became relatively stationary. The isochrons used to construct this evolution, show a steepening of the beachfaces in seaward direction, but GPR shows that the older beachfaces in the rear of the barrier have a similar slope to those in the front (Figure 12C). Based on this, isochrons were redrawn using the geometry recorded along the present-day beach in the 1981 cross-section and used it to correlate ^{14}C dates located above 3.5 m, as this is similar to the depth of the GPR record and the seaward extent of the present-day beach profile (Figure 13). All of the points where the isochrons intersect the dune surface were digitised and the distances were plotted versus the age. Progradation of the recalibrated isochrons indicates a constant progradation over that past ~7000 years at a rate of ~0.28 m/y, similar to Moruya. The last 6,000 years of progradation closely mimics that modelled by Kinsela and Cowell (2011: Figure 14).

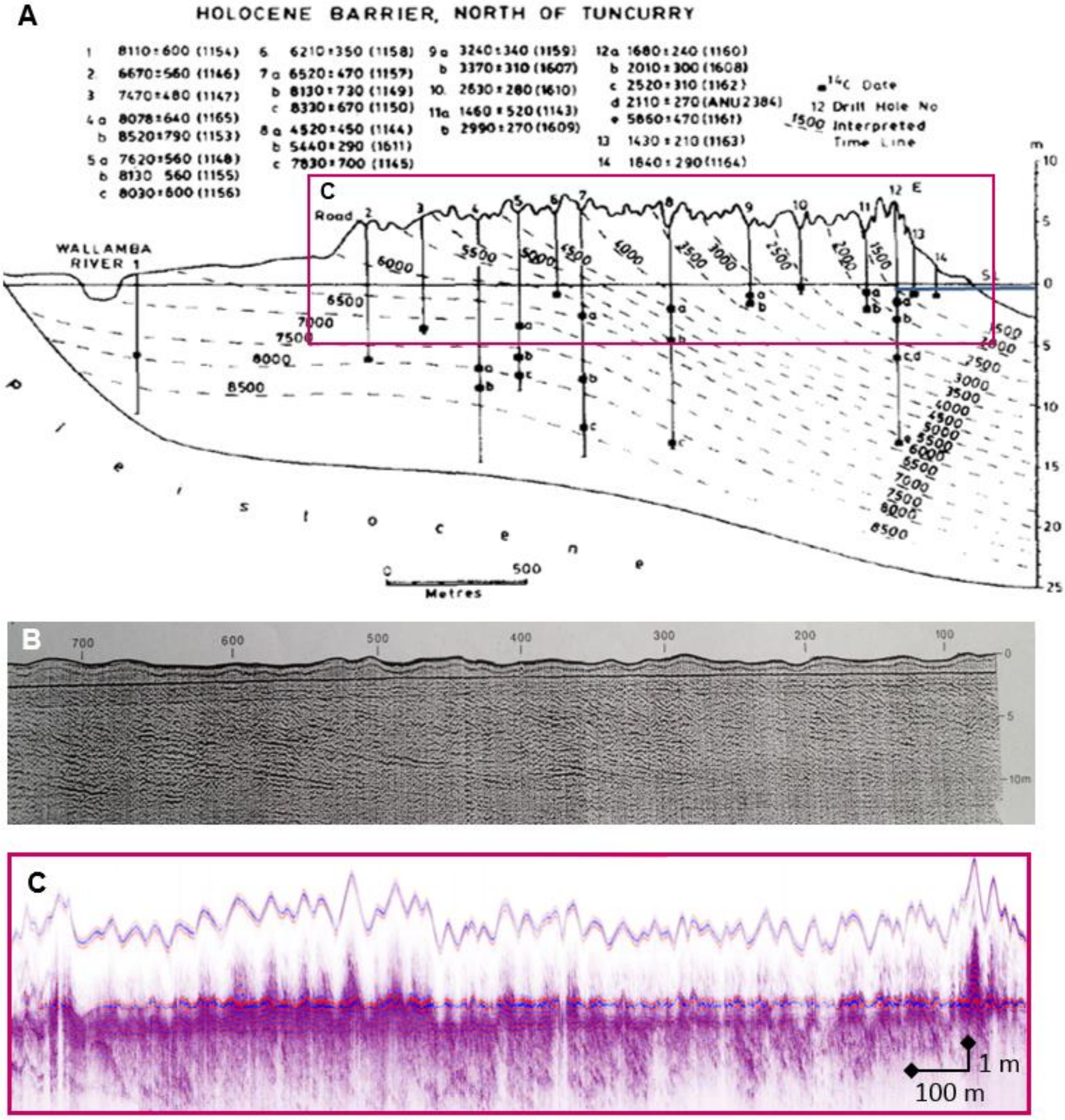

Figure 12: (A) Stratigraphic cross-section of Tuncurry Barrier with radiocarbon ages (Melville, 1984). (B) Analog GPR collected along a portion of Browns Track (Roy et al., 1997). (C) Digital GPR collected across the entire Tuncurry barrier.

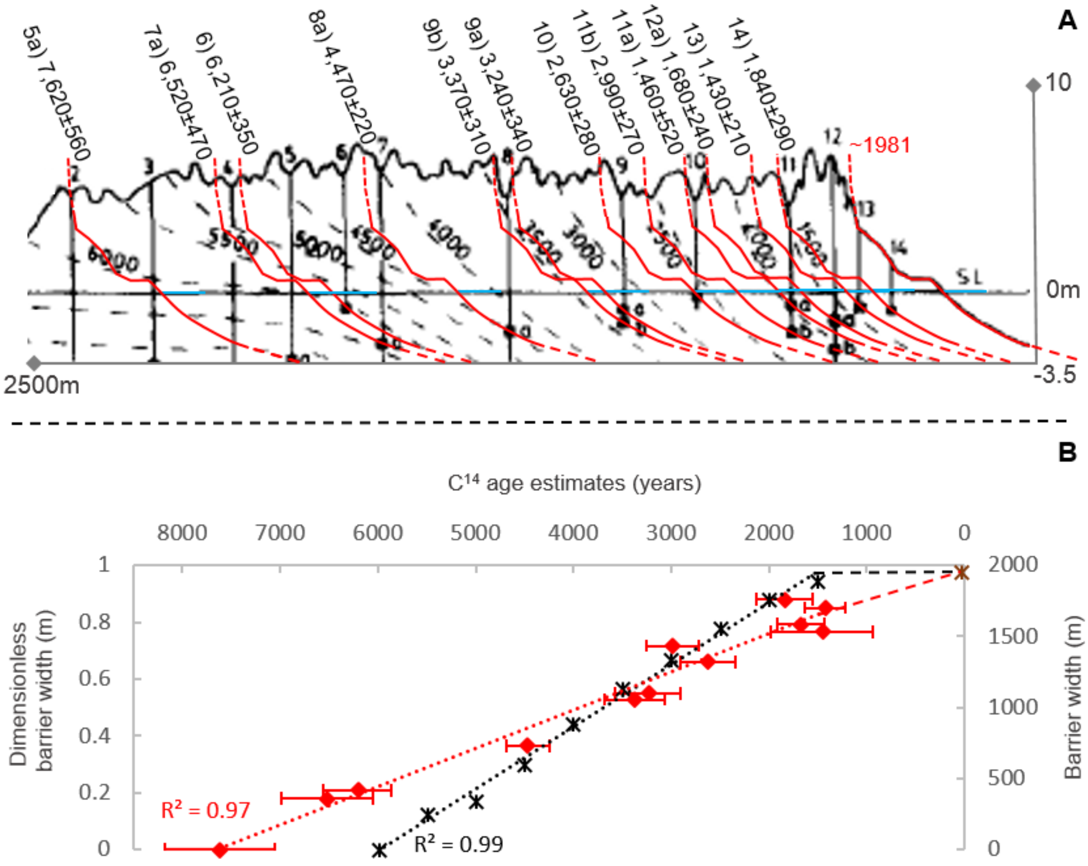

Figure 13: (A) Tuncurry shallow chronostratigraphy (Melville, 1984) with isochrons reconstructed using corresponding 'present-day' beachface geometry (in red). (B) Plot of progradation original (black) and reconstructed (red) isochrons.

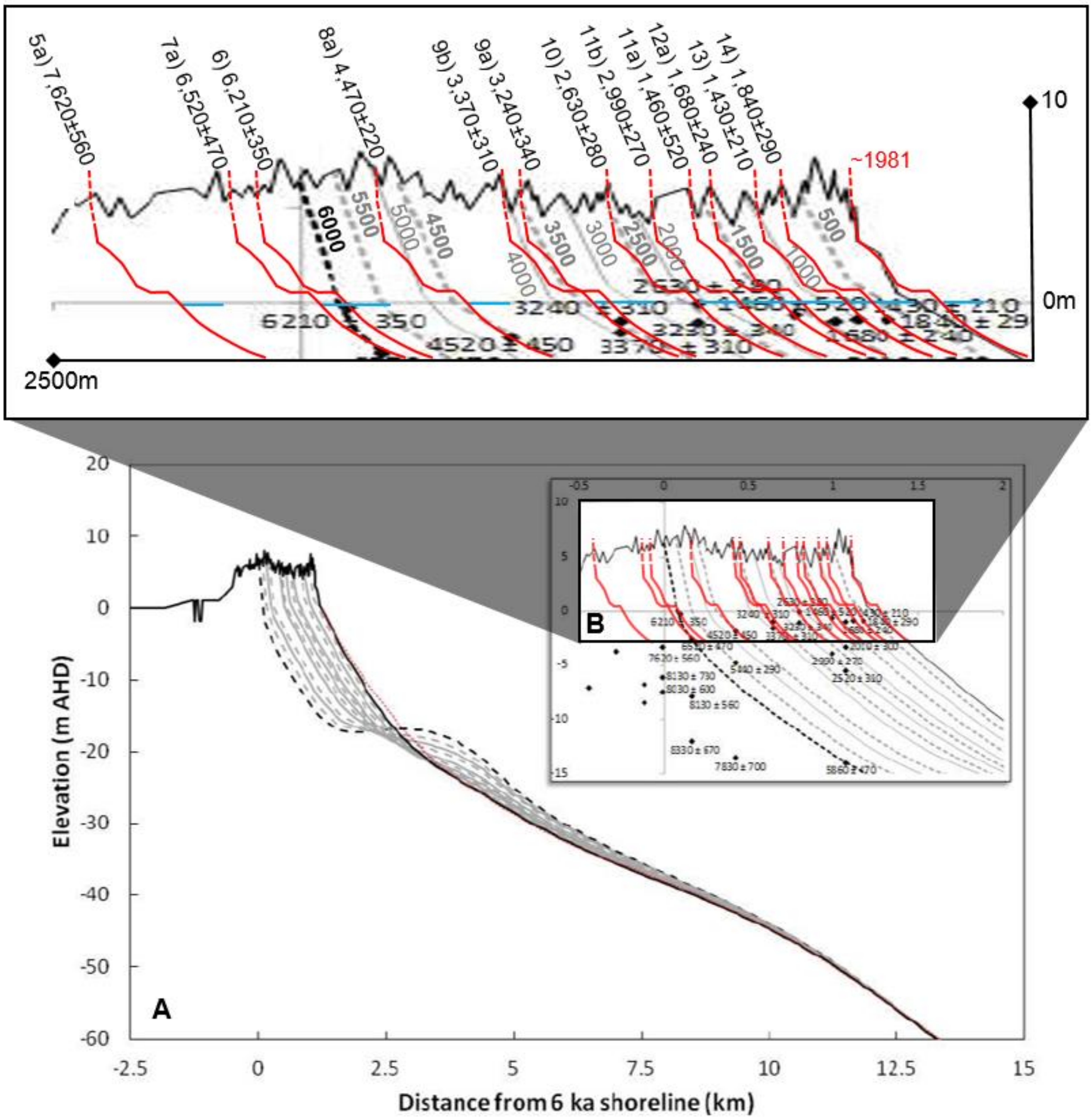

Figure 14: (A) Simulated evolution of Tuncurry barrier from 6,000 years ago to present (Kinsela and Cowell, 2011). (B) The reconstructed isochrons (Figure 13) were scaled and overlain to compare with the simulated isochrons.

Smaller-scale practical applications

Detection of buried features

Geophysics can remotely sense the location of subsurface objects and OSL could date the burial time. To demonstrate the utility of GPR to non-destructively locate a feature in a coastal setting, a riprap sea wall known to have been buried along Narrabeen beach is used (Figure 15). The GPR collected over the foredune imaged strong hyperbolic reflections within the data, interpreted to represent the sea wall (Wainwright et al., 2015). These characteristic signatures are produced when the radar signal diffracts or 'rings' around individual objects (Jol, 2009), here detecting the large rocks in the riprap. This

GPR also imaged the subsequent sediment accretion since the sea wall was last exposed in 1974. Had there not been documentation of when last this feature was exposed, a strategic OSL sample of the overlying sand could be used to determine an approximate time.

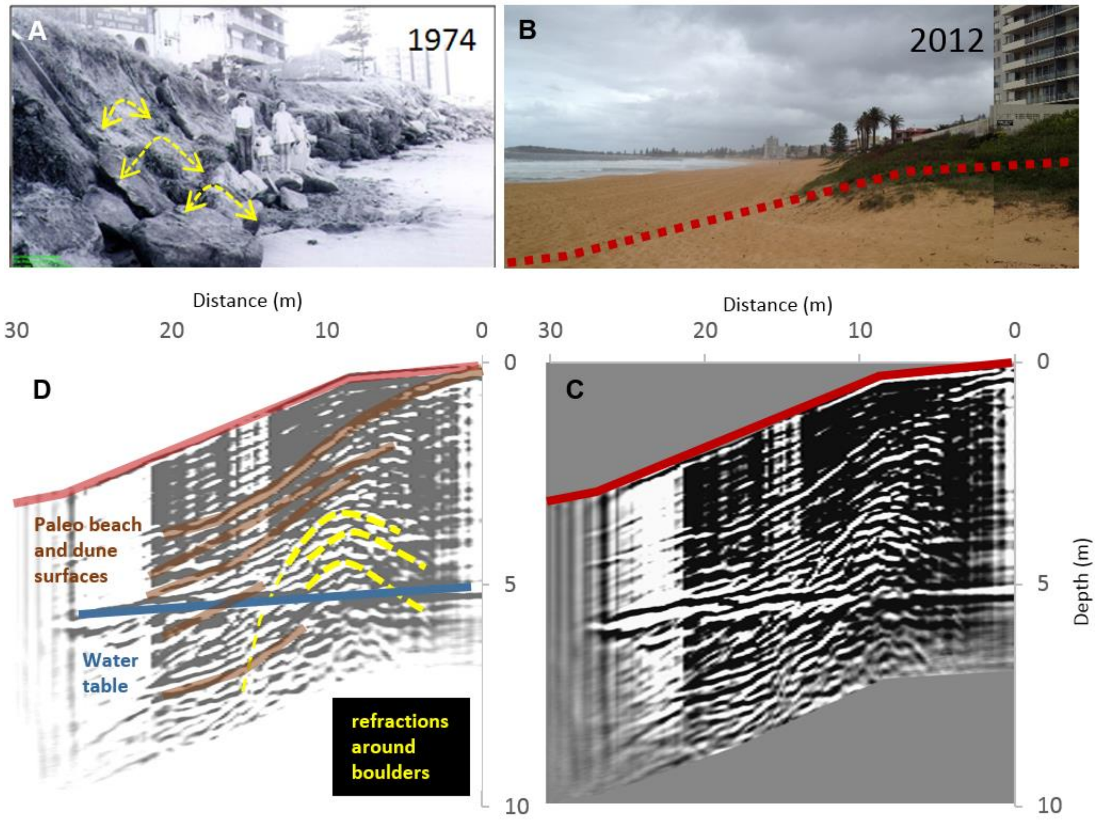

Figure 15: (A) Photograph of riprap/sea wall exposed by 1974 storm at Narrabeen. (B) Photograph of accreted beach in 2012, with GPR transect in red. (C) GPR data. (D) Annotated GPR showing hyperbola (yellow) over potential buried seawall and subsequent accretion with beach and dune stratigraphy (brown). Modified from Wainwright et al., 2015.

Reconstructing beach cut-and-recovery

Beach profiles are the best way to record short-term shoreline behaviour, but this data is restricted in location and duration to individual monitoring programs. GPR and OSL offer a method to recover a snapshot of any beach's 'sweep' zone, including the last major storm-cut and the subsequent net sediment accretion to the day of survey. Bengello Beach, NSW, is used to demonstrate this potential as it has the longest and most consistent beach profiling campaigns, spanning almost four decades (Thom and Hall, 1991; McLean and Shen, 2006; McLean et al., 2010). The GPR record collected seaward over the 1978 storm scarp imaged a strong reflection within the beach facies with a similar geometry and location as that recorded in nearby beach profile collected after the 1978 storm (Dougherty et al., 2012a&b:

Figure 16). The net volume of sediment accumulated above AHD in 2012 (calculated by multiplying the cross-sectional area by a 1 m, after Thom and Hall, 1991) is similar to the average volume measured by decades of beach profiles (160 m^3/m). Since this volume is the same as that eroded during the series of storms in the 1970s, then this data suggests that if a similar size erosion event occurred in 2012 the beach would have cut back to its 1978 location. This ability of GPR to reproduce cut-and-recovery data similar to profile records indicates the possibility to extract this information on beaches where no long term profile campaigns exists. Additionally, when the age of a large storm-cut beach profile is unknown, OSL can be used to determine the timing of the erosive event.

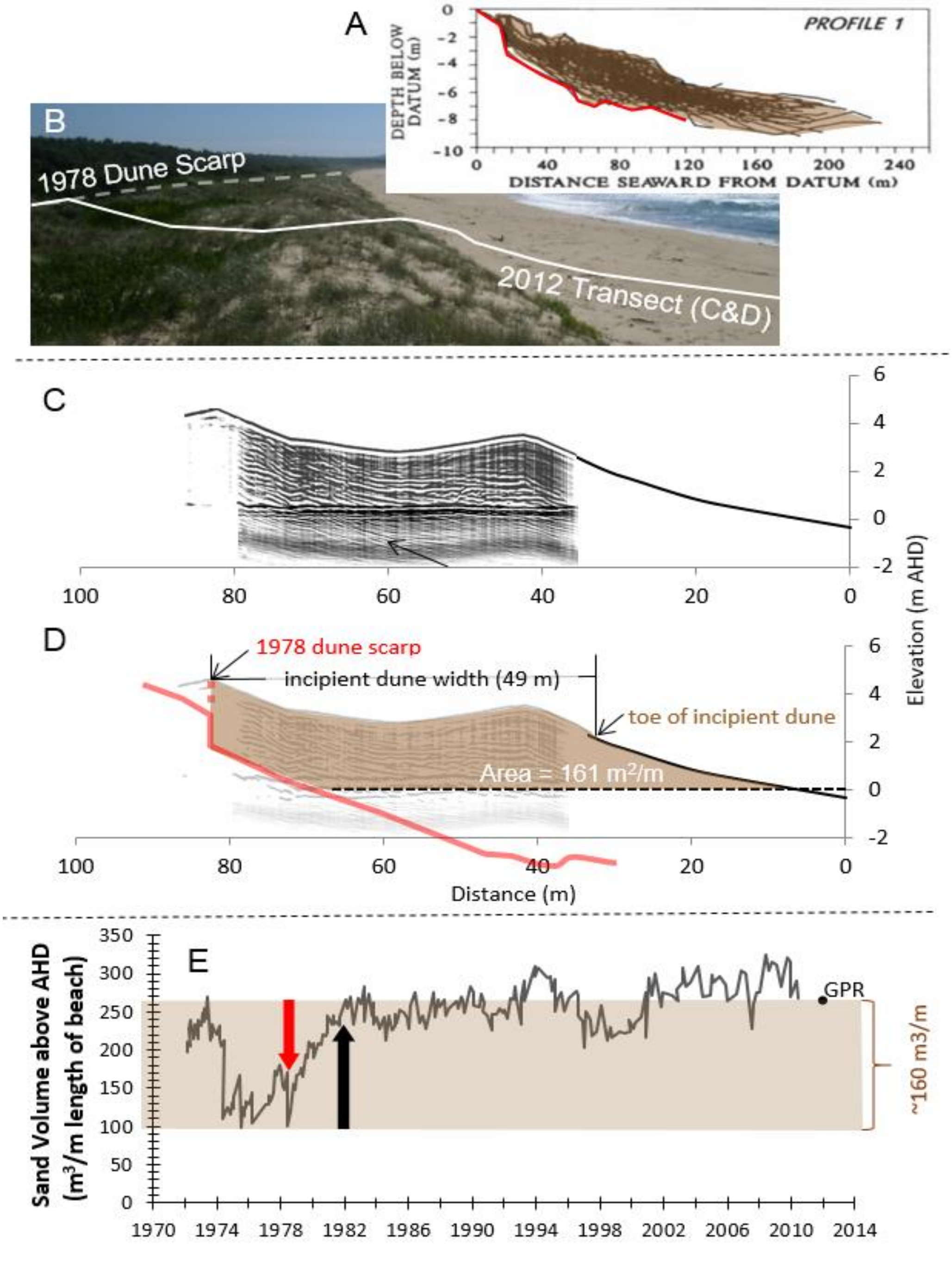

Figure 16: (A) 219 beach profiles, collected 1972-1987, recording the eroded morphology form the 1978 storm and volume of sand accumulated over 15 years. (B) Photograph of Bengello beach, near the location of Profile 1 (A), where GPR was collected in 2012. (C) GPR data. (D) GPR annotated with the location of 1978 dune/beachface and sediment accumulated until the survey day was calculated using the 161m^3/m area digitised. (E) Volume change through time as calculated from beach profile data. Modified from Thom and Hall, 1991; McLean and Shen, 2006; McLean et al., 2010; Dougherty et al., 2012a&b.

Conclusions

This paper demonstrates the potential of combining GPR and OSL on prograded barriers are at least fivefold:

1) Provide a record of storms over the Holocene.

2) Construct detailed sea-level curves.

3) Calculate sediment supply to the coast.

4) Non-invasively locate buried seawalls.

5) Extract a snapshot a beach's 'sweep' zone where no profiling surveys exist.

The practical and theoretical applications of this research can help predict how global warming will influence sea level, storms and sediment supply as well as how coastal barriers will respond to climate change. GPR and OSL have been collected from multiple prograded barriers in NSW and New Zealand to look for regional and trans-Tasman signatures.

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