Clim. Past Discuss., https://doi.org/10.5194/cp-2018-4
Manuscript under review for journal Clim. Past
Discussion started: 30 January 2018

Climate of the Past
Discussions
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Technical note: Optimizing the utility of combined GPR, OSL, and LiDAR (GOaL) to extract paleoenvironmental records and decipher shoreline evolution

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Abstract. Records of past sea levels, storms, and their impacts on coastline are crucial in forecasting future changes resulting from anthropogenic global warming. Coastal barriers that have prograded over the Holocene preserve within their accreting sands history of storm erosion and changes in sea level. High-resolution geophysics, geochronology, and remote sensing techniques offer an optimal way to extract these records and decipher shoreline evolution: Light Detection and Ranging (LiDAR) images the lateral extent of relict shoreline dune morphology; Ground Penetrating Radar (GPR) data records paleo-dune, beach and nearshore stratigraphy; Optically Stimulated Luminescence (OSL) dates when sand grains were deposited that form these shorelines. Utilization of these technological advances has recently become more prevalent in coastal research. The resolution and sensitivity of these methods offer unique insights on coastal environments and their relationship to past climate change. However, discrepancies in analysis and presentation of the data can result in erroneous interpretations. When utilized correctly on prograded barriers these methods (independently or in various combinations) have produced storm records, constructed sea-level curves, quantified sediment budgets, and deciphered coastal evolution. Therefore, combining the application of GPR, OSL, and LiDAR (GOaL) on one prograded barrier has the potential to generate detailed records of storms, sea level, and sediment supply for that coastline. Obtaining this GOaL hat-trick can provide valuable insights into how these three factors influenced past and future barrier evolution. Here we argue that systematically achieving GOaL hat-tricks on some of the 300+ prograded barriers worldwide would allow us to disentangle local patterns of sediment supply from regional effects of storms or global changes in sea level, allowing direct comparison to climate proxy records. To fully realize this aim requires standardization of methods to optimize results. The impetus for this initiative is to establish a framework for consistent data analysis that maximizes the potential of GOaL to contribute to climate change research and assist coastal communities in mitigating future impacts of global warming.

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1 Introduction

Global warming is causing seas to rise and is forecasted to intensify storms, but the degree of these increases as well as their impacts on vulnerable sandy coastlines is uncertain (IPCC, 2013). Paleo-environmental records of sea level and storms as well as the evolution of shorelines throughout the Holocene can provide insight into future impacts. Coastlines that have positive sediment budget, and space available to accommodate it, have built seaward through time forming strandplains comprising a series of foredune/beach ridges (Figure 1a). These accreted coastal sands preserve a history of sea level change, storm impacts and sediment supply within their stratigraphy. The resulting coastal systems are called prograded barriers and they have been studied for over a half century to decipher their evolution and extract paleoenvironmental records (Bernard et al., 1962; Curray et al., 1969; Thom et al., 1981). Over the past few decades, more traditional methods have been augmented by state-of-the-art remote sensing, geophysical and geochronological techniques (Dougherty et al., 2016; Tamura, 2012). For instance, two-dimensional topographic surveys of dune ridges (Figure 1a) were expanded laterally by 3D digital terrain models produced using Light Detection and Ranging (LiDAR) (e.g Gutierrez et al., 2001). Generalized stratigraphic cross-sections interpolated between cores (Figure 1a) have been filled in with detailed dune, beach, and nearshore structures from high-resolution Ground Penetrating Radar (GPR) (e.g. van Heteren et al., 1998). Finally, Optically Stimulated Luminescence (OSL) directly dates when beach and dune sand was deposited (e.g. Jacobs, 2008), which eliminated extrapolation of radiocarbon dates using isochrons (Figure 1a).

There has been a steady uptake in the utilization of these geophysical, geochronological, and remotely sensed data since the decades when the applications were first introduced. Recently, however, there has been notable proliferation in their use associated with the ease in which this data is able to be acquired (as Lidar becomes more available, GPR more user friendly, and OSL more accessible). These techniques are all specialty fields of science on their own right and collaboration between experts in these different disciplines can avoid common pitfalls. This is important not just to ensure that the data is as precise and accurate as possible, but also that the results (or lack thereof) are presented in such a way to not mislead interpretations. This is not always straightforward with these types of high-resolution data sets as the detail and volume can mask or overwhelm significant aspects/features; analogous to obscuring both the forest (barrier evolution) and the trees (individual beachfaces). Therefore, it is important to be intentional with the questions being addressed using the data, as well as diligent about the interpretations and implications drawn from it.

Studies have shown that utilizing these approaches on prograded barriers, independently or in various combinations, can: (1) quantify frequency-intensity of storm records (e.g. Buynevich et al., 2007; Dougherty, 2014; Nott and Hayne, 2001), (2) construct sea-level curves (e.g. Nielsen et al., 2017; Rodriguez and Meyer, 2006; van Heteren et al., 2000), (3) quantify sediment budgets (Bristow and Pucillo, 2006; Dougherty et al., 2015; van Heteren et al., 1996), and (4) decipher coastal evolution (e.g. Barboza et al., 2009; Costas and FitzGerald, 2011; Hein et al., 2016). Combining GPR, OSL, and LiDAR (GOaL) on certain systems offers the possibility to determine a history of storms, sea level, sediment supply, and their impact on shoreline evolution. Given the increased prevalence of these techniques and the existence of 300+ prograded barriers located around the world (Scheffers et al., 2012), a systematic application of GOaL to decipher coastal evolution can also detect local patterns of sediment supply, regional records of storms or global changes in sea level. The larger-scale records have the potential to be used like and combined with other climate proxy records. The possibilities necessitate standardizing important parts of this methodological approach to optimize results. The aim of this article is threefold: (1) present a basic introduction to the capabilities of GOaL individually, (2) provide a simple strategy that logically utilizes information from each technique to optimize the resulting GOaL data set, and (3) highlight the possibilities and pitfalls to maximize the combination of GOaL on prograded systems.

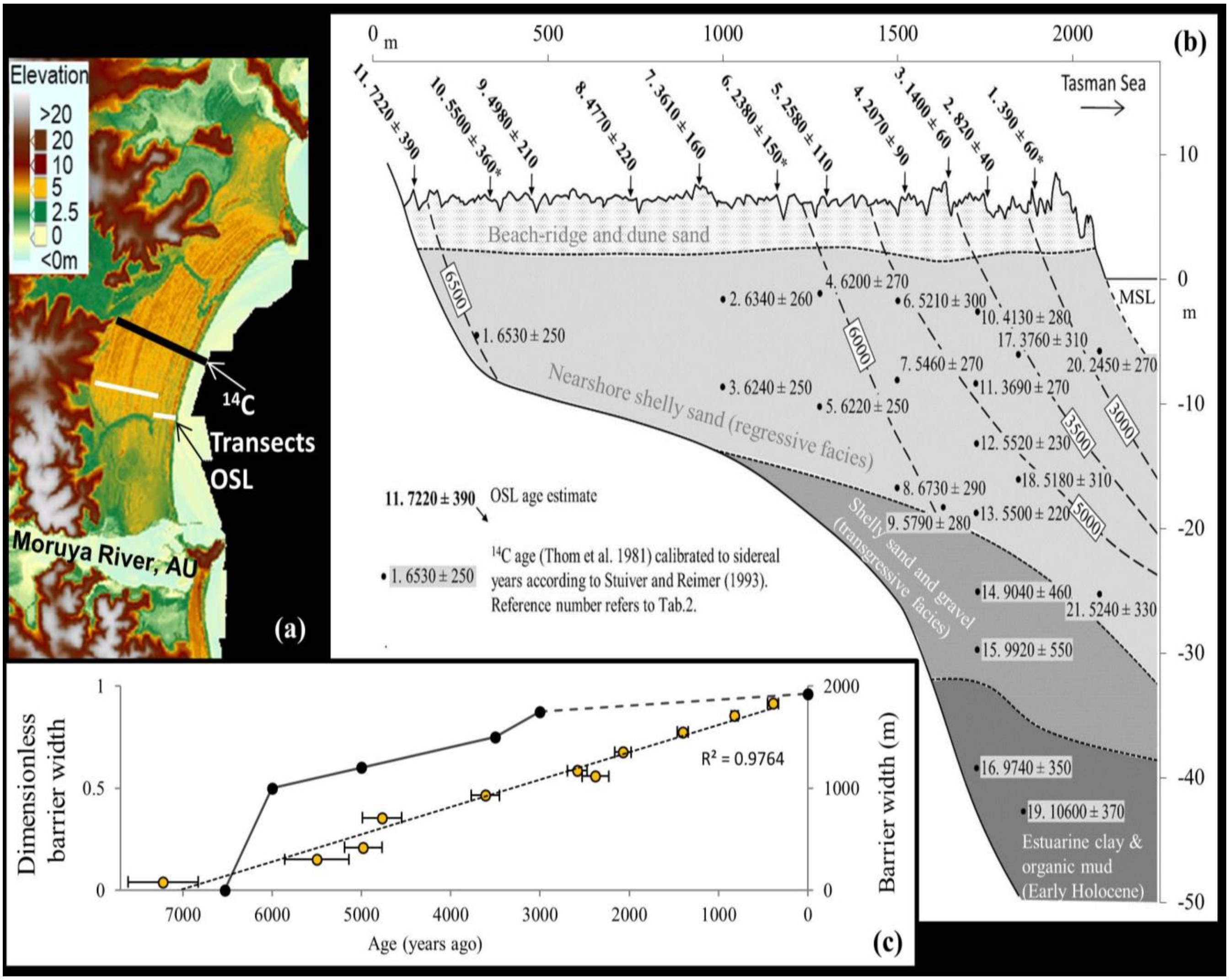

Figure 1. (a) LiDAR data of the prograded barrier system near Moruya, Australia, with the location of the transects where 14C and OSL samples were collected. (b) Stratigraphic cross-section of Moruya Barrier displaying radiocarbon and OSL chronologies (Oliver et al., 2015; Thom et al., 1981). (c) Diagram of barrier width as a function of OSL (open black circles) and radiocarbon (black circles) ages. The new OSL chronology shows that progradation has been much more linear than was previously thought using radiocarbon. Figure modified from Dougherty et al. (2016) and Oliver et al. (2015).

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2 GOaL methodological approach

With each GOaL technique producing such high-resolution data, how it is collected and presented can affect the results or interpretations. This section explains a simple methodological approach to maximize the volume and detail of GOaL from prograded barriers. These methods are introduced in the order that is recommended that they be utilized, with a brief statement of the logic for applying each technique in the three-step methodology. Specifics of the different techniques, instrumentation, or settings/parameters are not discussed. There is already a large body of literature about these different methods and their utilization in coastal settings referenced within each section. The type of equipment or method used is usually reliant on what is available and ideal settings are site specific. Furthermore, coastal researchers often rely on other experts in the field of remote sensing, geophysics and geochronology to collect the data or even utilize previously published results. Any of these high-resolution data, when collected and analysed correctly, improves our understanding coastal evolution. The idea of this approach, and associated general presentation tips, is to optimize extracting paleoenvironmental records and deciphering impacts of storms, sea level, and sediment supply versus accommodation space. Results from published studies are used to demonstrate the capabilities of GOaL independently, as well as the advantages of combing them in the suggested order.

2.1 LiDAR

Documenting barrier morphology and coastal setting is a vital first step to understanding shoreline evolution. Airborne LiDAR uses scanning laser altimetry as a survey method of obtaining topographic information for coastal dunes and intertidal areas above low water mark (Figure 2). Aircraft mounted sensors combine Global Positioning Systems (GPS) and laser range finder to remotely map the surface of the earth over areas tens to hundreds of kilometres in extent with a horizontal resolution of 1 meter or less and a vertical accuracy of 0.10-to-0.15m. The detailed information about the elevation of the land surface and vegetation is acquired by emitting laser pulses which reflect off objects and produce a backscatter recorded by the sensor. In addition to a ‘travel time’ for each pulse and subsequent return signal, an intensity of reflectance is also often measured and used to identify vegetation canopy versus ground surfaces. LIDAR surveys (as with most remote sensing techniques) needs to be ground-truthed to detect any errors in data acquisition or processing deficiencies (Gutierrez et al., 2001). This can be done by checking the elevations using traditional surveys or Real Time Kinematic (RTK) GPS.

Traditionally air photographs, satellite images, and topographic profiles were used to assess coastal systems and plan fieldwork. The advent of platforms like Google Maps, Google Earth, NASA Worldview and NASA Word Wind provide free imagery collected over time, bolstered the amount of data available (Figure 2). LiDAR penetrates the vegetation that often obscure details of the morphology in aerial imagery and removes this obstruction during processing. Digital terrain models created form LiDAR data refine the morphology detecting subtle dune topography. This data set can be used to extract topographic profiles and calculate sediment volumes (Dougherty et al., 2015; Dougherty et al., 2012; Oliver et al., 2014). The classic prograded barrier system located near Moruya, Australia, offers an example of the detail and lateral extent mapped in LiDAR (Figure 1a) as compared to the original two-dimensional topographic profile (Figure 1b). This LiDAR captures the uniform shoreline progradation represented by the series of beach/foredune ridges (yellow with high crest in red, Figure 1a) as well as interactions from inlets, tidal creeks and open ocean (green and off-white colours, Figure 1a). This barrier morphology can be used to either: target these areas modified by natural or human processes to understand their impact or avoid them to isolate the influence of storms, sea level, and sediment supply versus accommodation space. The display or rendering chosen to analyse and present LiDAR data can impact interpretations. Since coastal systems are relatively low-lying features, the elevation scale range and colour scheme chosen should to at least define the barrier from intertidal areas (done using cool and warm colours in Figure 1a). In more complicated systems the display should be such that important changes in the surrounding geologic setting or within the dune morphology are easily discernible.

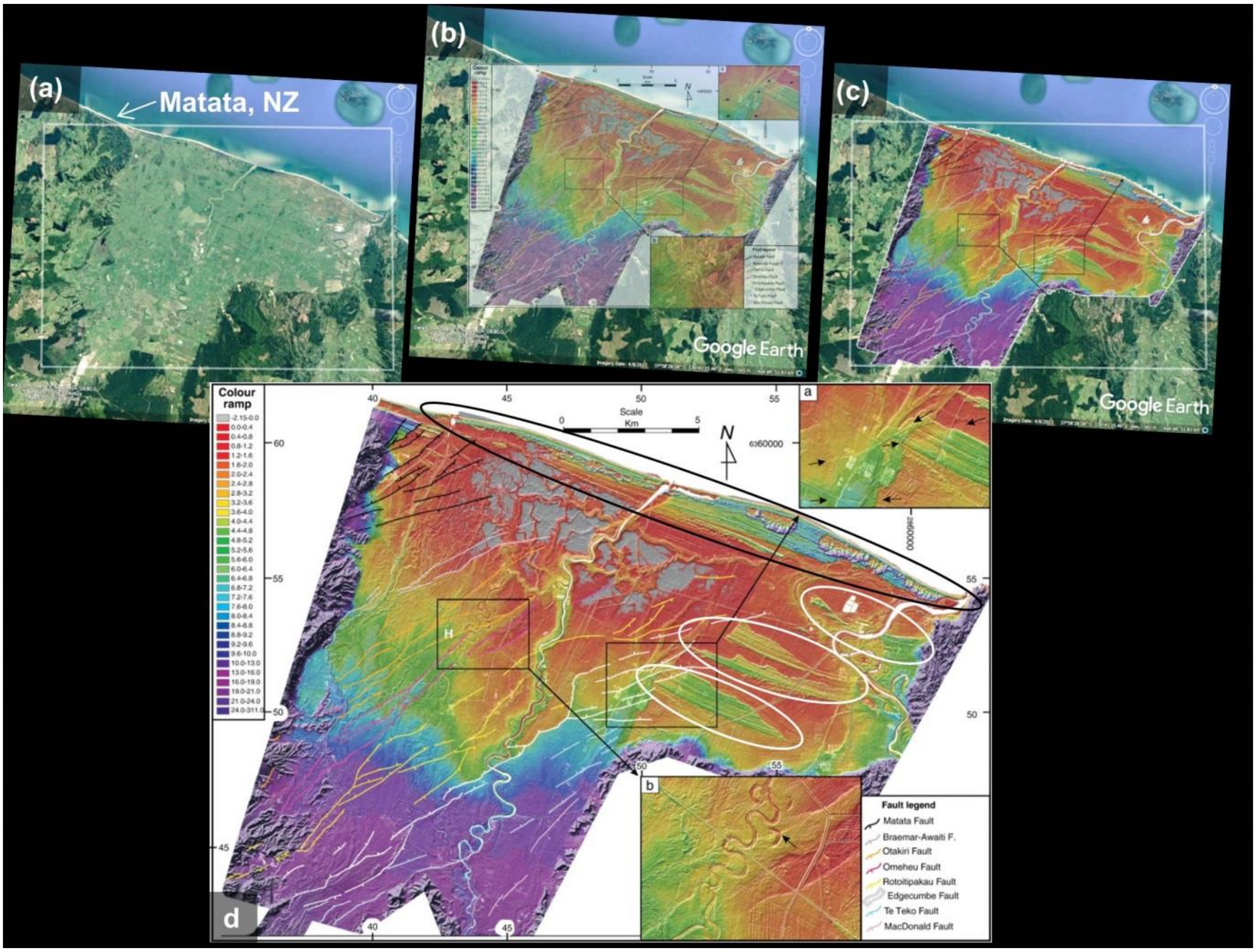

Figure 2. (a-c) Google Earth Image of Rangitaiki Plains, New Zealand, overlain with LiDAR shows complex infilling of this coastal embayment. (d) The present-day coastline is a prograded barrier island (black oval). Faulting and river dynamics have eroded the central and western portion of a series of older prograded barrier islands preserved in the eastern portion of the embayment (white ovals). LiDAR modified from (Begg and Mouslopoulou, 2010).

Augmenting air photos or satellite images with LiDAR provides a more complete understanding of the geologic setting to contextualise and understand coastal evolution. A Google Earth image of the Rangitaiki Plains in New Zealand displays a filled coastal embayment that has a prominent series of foredune ridges behind the present-day shoreline (Figure 2). LiDAR collected by (Begg and Mouslopoulou, 2010) show that the infilling did not occur by uniform shoreline progradation, like at Moruya, but a rather complex evolution producing a unique set of prograded barrier islands. The LiDAR data guided research on the remnants of the four relict barrier islands displaying classic foredune ridge sequences preserved in the eastern section of the embayment (white circles in Figure 2d). Each sequence likely formed across the entire embayment, similar to the present-day prograded barrier island (black circle in Figure 2d). However, subsequently they became modified by tectonics and river dynamics that completely eroded the central to western portion of the barrier islands (see insets a and b in Figure 2d). Given how rapidly and drastically coastal landscape changes, being able to select a Google Earth image collected around the same time as the LiDAR is instrumental to providing good correlation in the overlay. It is optimal to use and publish LiDAR data augmented with aerial imagery. This is useful for analysing barrier morphology in the in relation to shallow subaerial offshore, inlet, estuary sediment deposits, and/or human modification that is sometimes not captured in the LiDAR.

2.2 GPR

Once the surface morphology is analysed, the next step to determine how a barrier formed is to study the history preserved in the shallow subsurface. The LiDAR data can be used to inform where best to acquire detailed stratigraphy using geophysics. Ground-Penetrating Radar (GPR) is a high-resolution geophysical technique can image dune, beach and nearshore facies with decimetre resolution over kilometres of coast (e.g. Buynevich et al., 2009; Jol et al., 1996). To achieve subsurface imaging, GPR emits short pulses of electromagnetic energy (microwave radiation) into the ground (Jol et al., 1996). These transmitted high-frequency radio waves are sensitive to the electrical conduction properties of the material being penetrated (dielectric permittivity) and differences in permittivites cause them to be reflected or refracted or scattered back to the surface. A receiving antenna records variation in the return signal, detecting changes in material properties of subsurface structures and facies by travel-time within the waveform. Individual waveforms display changes within the subsurface by recording a wave-amplitude spike at a stratigraphic boundary surface. Collecting GPR along a transect line stacks individual wave traces laterally such that low wave-amplitude signals represents homogenous sediments and increase in amplitude is associated with greater contrast in sediment characteristics (e.g. change in water content, mineralogy, grain-size, sorting, etc.). The variation in waveform detects changes that occur at stratigraphic boundaries, as peaks of high-amplitude merge to form strong reflection surfaces. It also detects more subtle changes within the facies, with lower amplitude peaks forming medium to weak reflections (Figure 3).

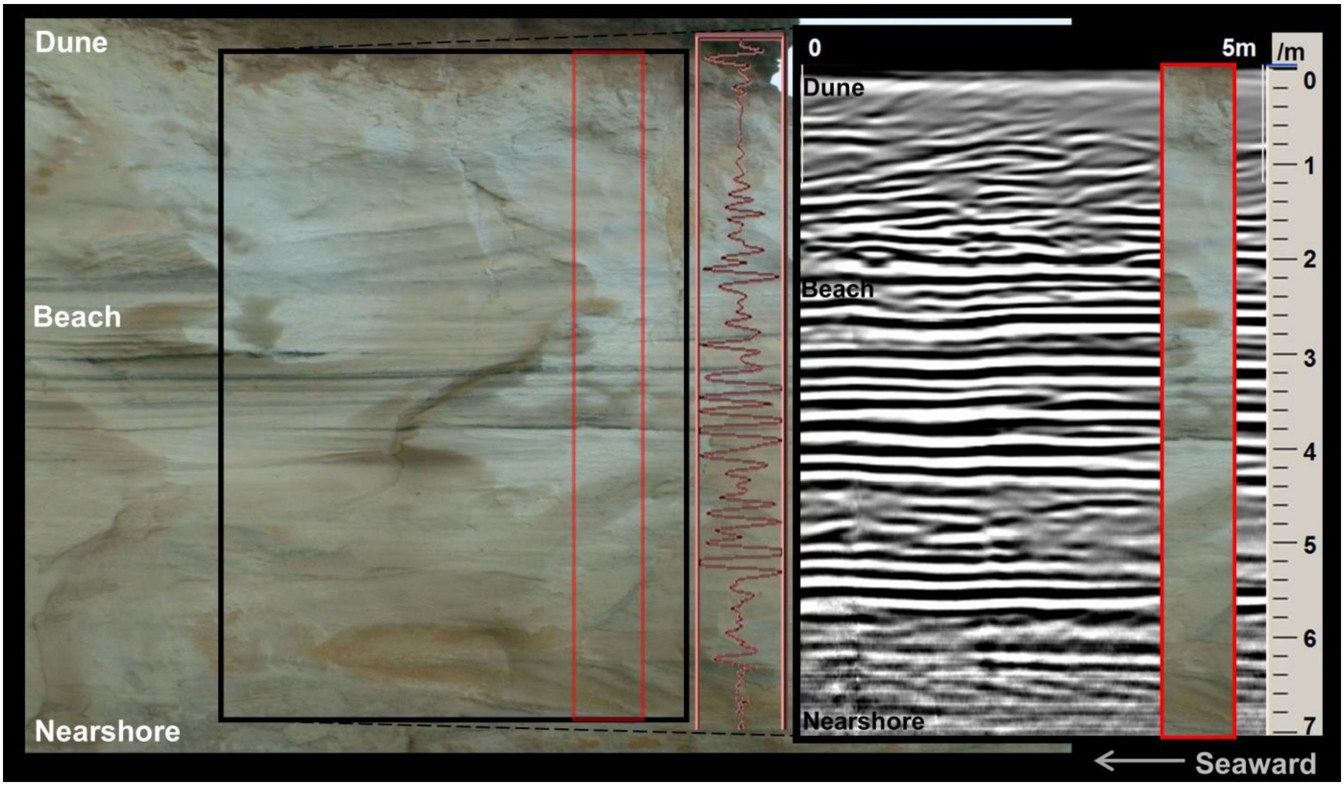

Figure 3. Left is a photograph of a scarp that cross-cuts a prograded Pleistocene barrier located near One Tree Point, New Zealand. This outcrop displays the small-scale stratigraphy of the barrier facies: dune, beach, and nearshore. Right is a transect of GPR data collected along the top of this outcrop that accurately maps the sedimentary beds exposed records the internal barrier structure in detail. Between the GPR data and the corresponding section of the outcrop, is a single waveform. This overlay is to exemplify how the wave-amplitude spikes correspond to changes in the stratigraphy and laterally form the strong or weak reflections in the geophysical data. The section of the outcrop photo (outlined in red) is overlain on the GPR data to demonstrate the need to ground-truth the geophysical data with cores to determine what is causing the reflection. Note that all of these overlays are approximate as GPR had to be collected a small distance from the cliff to minimize edge effects within the geophysical data. Figure modified from Dougherty and Nichol (2007).

Initial cross-sectional models of prograded barriers display generalized shallow stratigraphy with largescale subsurface facies boundaries interpolated from drill core data and isochrons extrapolated from 14C age samples (e.g. Bernard et al., 1962; Curray et al., 1969; Thom et al., 1978: Figure 1b). The electromagnetic properties of sandy barriers are ideal for producing excellent GPR images because of the high resistivity of the sediment opposing the flow of electrical current (Leatherman, 1987). Collecting GPR across entire prograded barriers can extract high-resolution stratigraphic records providing a continuous cross-sectional view of barrier architecture that detects small-scale features and large-scale facies boundaries previously unrecognised in point source core data (e.g. Fitzgerald et al., 1992; Jol et al., 1996; van Heteren et al., 1998) A unique outcrop of a Pleistocene prograded barrier in One Tree Point, New Zealand, illustrates the sensitivity of GPR in detecting stratigraphy (Dougherty and Nichol, 2007: Figure 3). The geophysical record shows how the heavy mineral beachfaces create the strongest reflections between 2 and 5 m. Medium-strength reflections are detecting the more diffuse heavy-mineral concentrations within the dune sequence (0-2 m depth) and in the crossbedding preserved as a bar migrated onshore in the nearshore (6-7 m depth). The weak, reflection-free areas in the dune and nearshore represent homogenous deposits. However, GPR uncovers structure in the fine-grained, well-stored, quartz dune sand at the top that would have been otherwise invisible to the naked eye.

Ground Penetrating Radar can detect differences such as compaction and/or water content allowing stratigraphy to be more obvious in the geophysical records. For example, the prominent reflections between 5 and 6 m identify the transition in sands between beach and nearshore facies that is otherwise not detectible without grain-size analysis (Figure 3). The ability of GPR to detect individual beachfaces as well as their boundaries with dune and nearshore facies enables them to be mapped throughout a prograded barrier. Mapping the beachfaces through time allows their elevation to be used as a sea level proxy, their geometry to produce storm records, and their spacing to infer sediment supply. Because GPR is sensitive to subtle changes in the subsurface, the record must be ground-truthed using cores, augers, or outcrops, in order to verify barrier facies and boundaries (e.g. Costas and FitzGerald, 2011; Hein et al., 2013; Hein et al., 2016). Additionally, topographic profiles of the present-day beach and sediment samples from each facies should be collected, preferably capturing both storm and swell geometry and sedimentology. Within the beach facies, storm lag deposits are displayed more prominently than the intervening swell accretion, this contrast, combined with distinct geometries, enables storm records to be extracted (Buynevich et al., 2007; Buynevich et al., 2004; Dougherty et al., 2004). As a whole, the high to medium amplitude beachface signatures standout compared to the weak or reflections-free signals in the dune and nearshore facies (Figure 4). This contrast allows beachface elevation to be used as a proxy for sea level (e.g. Dougherty, 2014; Rodriguez and Meyer, 2006; van Heteren et al., 2000).

In order to delineate barrier facies as well as individual beachfaces it is fundamental to ensure that the amplitude of the waveform peak relates to the contrast within the stratigraphy (e.g. strongest reflections are the storm-eroded beachfaces and weakest is homogeneous dune sands). The waveform amplitudes can be adjusted using what is referred to as a gain control. Gain represents the value by which the scaled waveform data is multiplied to get the output data. It is important to adjust the gain according to the core/auger/outcrop data as low gain makes all reflections weak and high gain makes all reflections strong. This lack of contrast makes it hard to distinguish different barrier facies boundaries yet alone individual beachfaces. It is also important to keep in mind that individual changes in the subsurface result in double peaks within the waveform, which is presented in the GPR record as prominent coupled lines (demonstrated in Figure 3 as white and black or black and white, depending on normal or reverse polarity). This means that not all lines on a GPR record represent changes in the subsurface (e.g. Figure 3). Three-dimensional grid modelling can be used to visualise how good gain control can distinguish barrier facies boundaries (Figure 4a) and isolate beachfaces by interpolating the highest amplitude reflections between a series of shore perpendicular transects (Figure 4b). The use of 3-D models is not necessary for extracting sea level and storm records, but could be useful in studying shoreline rotation (Harley et al., 2011; Short and Trembanis, 2004) or smaller-scale and more irregular features such as beach cusps (Coco et al., 1999; Masselink et al., 1997).

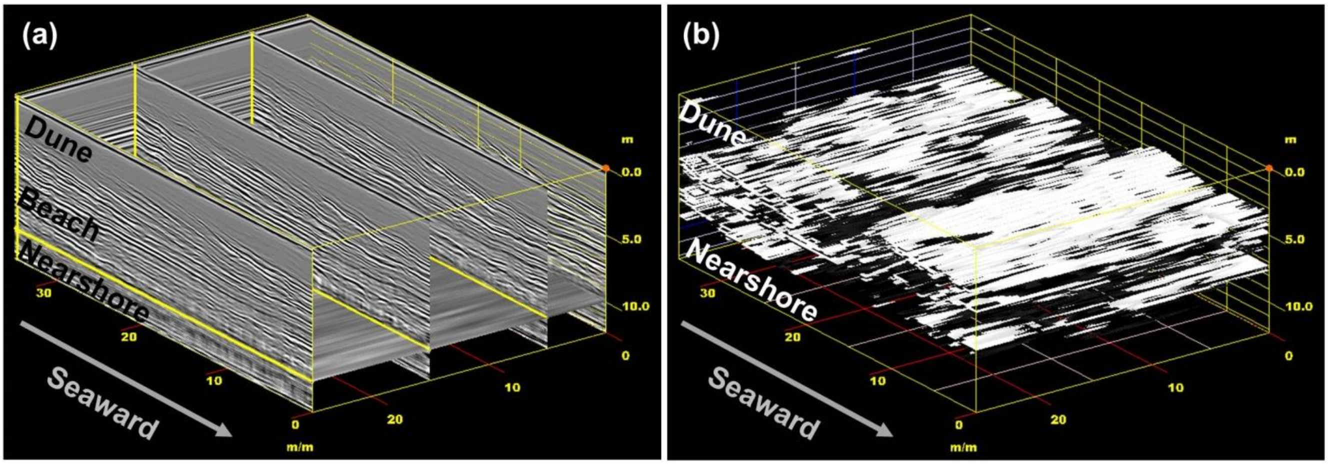

Figure 4. (a) Fence diagram showing some of the GPR transects collected in a grid configuration. (b) 3-D model of beachface stratigraphy constructed by isolating the most prominent reflections, shown in white, and interpolating between the transect lines. Figure modified from (Dougherty, 2011).

2.3 OSL

The final step is to apply a chronology to barrier formation and the detailed morphostratigraphy. Adding a temporal component to coastal formation is important to understand shoreline evolution over timescales that operate on longer-terms than that documented historically. 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, are 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. OSL chronology can provide the resolution necessary to decipher decadal-, centennial-, and millennial- scale patterns of coastal behaviour necessary to reconstruct sea-level curves, determine storm frequencies, and calculate sediment supply/progradation rates. In order to maximise this chronology, it is important to know precisely what stratigraphic layer is sampled and to choose the most proper dating schemes, which may be sample specific; the reliability of the OSL dating results depends on how the experimental conditions and statistical models are properly considered for each sample to be dated. For instance, the materials to be dated, preheat temperatures, age models (particularly when it comes to single grain dating; Bailey and Arnold, 2006) etc., should be carefully determined.

Originally, dating coastal barrier formation was dependent on sourcing scarce organic matter (often involving deep coring) and extrapolating the conventional radiocarbon ages to the surface using isochrons (e.g. Figure 1a). Since OSL chronology determines the time elapsed since mineral grains were buried, this technique dates when paleo-beachfaces and relict foredunes were forming. Dating of coastal systems using OSL has been very successful on a global scale (e.g. Jacobs, 2008). Quartz is both a principle mineral used in luminescence dating and abundant in coastal barriers. Therefore, LiDAR and GPR can be used to target specific stratigraphic layers in a strategic manner for sampling. This approach has shown to more accurately date beach and dune formation than inferred ages from proximal shell, wood or peat deposits, especially when those samples are from deep nearshore or offshore deposits (Murray-Wallace et al., 2002; Oliver et al., 2015). Oliver et al., 2015 offers an example comparing radiocarbon and luminescence ages at the Moruya barrier. Because this study focused on comparing chronologies, LiDAR and GPR data were not presented in Oliver et al. (2015), but both techniques were used to target specific stratigraphic layers for OSL dating (Figure 1c). The results revised the longstanding theory, based on radiocarbon dates, that the barrier prograded at two different rates before halting 3,000 years ago due to diminished sediment supply (Roy and Thom, 1981). With OSL data revealing that the barrier prograded at a constant rate (0.28m/yr) for 7,000 years (Figure 1c) and calculations from the LiDAR data documenting a steady supply of sediment (4,700 m3/y) above MSL (Dougherty et al., 2015; Oliver et al., 2014).

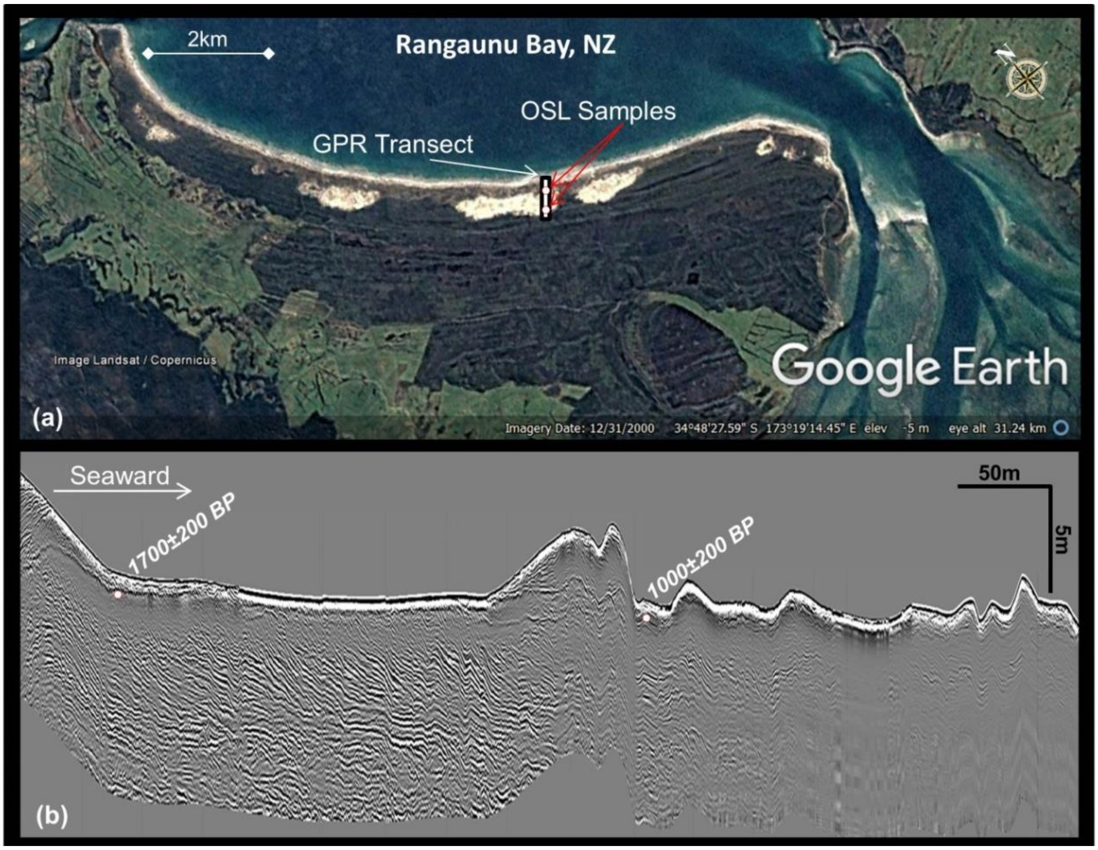

Figure 5. (a) Google Earth Image of East Beach, New Zealand, and the prograded barrier that it fronts, with the location of the GPR and OSL collected to study the recent shift in barrier progradation. (b) The stratigraphy imaged in the GPR data shows that while the morphology has been disturbed over this youngest portion of the barrier, the beachfaces prograded normally for a while. OSL was used date the youngest intact relict foredune ridge (1,700 yr BP) and the timing of the drastic shift in evolution observed in both the dune morphology and beach facies stratigraphy (1,000 yr BP). Note GPR is particularly useful to study nearshore dynamics in the stratigraphy at this site, since its location in the high-energy breaker zone makes this region difficult to access and monitor. Figure modified from Dougherty (2011).

Morphostratigraphy from aerial imagery, LiDAR and GPR is useful in determining where best to collect OSL samples, whether it is to date significant shifts in barrier evolution (Figure 5) or avoid them to extract a complete Holocene chronology, as was the case with Moruya (Figure 1). East Beach Barrier in New Zealand demonstrates how surface and subsurface data guided OSL to better understand a recent transition from uniform progradation to a more complex evolution (Figure 5a: Dougherty, 2011). In order to decipher the timing of this shift, the aerial imagery was used to target the changes in morphology and GPR to locate corresponding differences in the underlying stratigraphy. An OSL date of the last relict foredune preserved indicates that barrier prograded normally until at least 1,700 yr BP (Figure 5b). After this time, a large dune blowout formed modifying any previously existing morphology. The distinct shift in both the stratigraphy and morphology dated, produced an age of ~1,000 yr BP (Figure 5b). This younger age is important to understand the change in evolution within the context of the regional setting. In the last millennium three major events could have impacted the coastline: (1) the arrival of Maori people (Wilmshurst et al., 2008), (2) sea-level stopped dropping from a mid-Holocene highstand (Dougherty and Dickson, 2012), and (3) a large tsunami struck the area (Nichol et al., 2004).

3 GOaL hat-trick (Combined GOaL examples)

Over roughly a year, three studies have utilized GOaL on prograded systems to: 1. reconstruct sea level (Coastas et al., 2016 (Costas et al., 2016), 2. determine the impact of storms (Oliver et al., 2017b), and 3. decipher barrier evolution and sediment supply (Oliver et al., 2017a). These studies are used here as a framework to discuss the significance of GOaL and potential pitfalls. Where necessary, recommendations are offered in order to improve robustness of interpretations.

3.1 Sea level

Costas et al. (2016) provides an excellent example of how GOaL can be used to reconstruct Holocene sea-level from Troia Peninsula, Portugal. Initially this complicated spit system did not appear as an ideal site to extract a sea level history, but LiDAR highlights a classic prograded section targeted for GPR and OSL (Figure 6a). The presentation in the supplemental material of both raw (not shown) and interpreted GPR data (Figure 6b) across the entire barrier, is ideal for the reader to see the beach and berm elevational markers used as a sea-level proxy. Complete transects are often not collected for logistical reasons, and when collected often only parts are published. However, it is best to collect a single transect line that spans the barrier as to capture a complete Holocene history. It is also very informative to indicate the location of OSL samples on the GPR, regardless of whether it is displayed on the entire record or selected detailed sections. This allows the specific stratigraphic section dated to be identified. Topographic profiles of the modern beach and cores were used to ground-truth the GPR such that the berm/beach-dune contact could be interpreted as a proxy for sea-level (Figure 6b), efficiently summarized in Figure 6c. Results showed good agreement with known sea-level curves in southwest Europe, demonstrating the potential of applying this method to regions where mid- to late- Holocene records are not as well documented and/or are debated. Additionally, this GOaL data set could also be used to determine a storm and sediment supply record over the Holocene as well as decipher the influence of these factors on the formation of this prograded barrier spit complex. Ultimately this information can be used to help forecast the evolution of this shoreline within the context of future climate change.

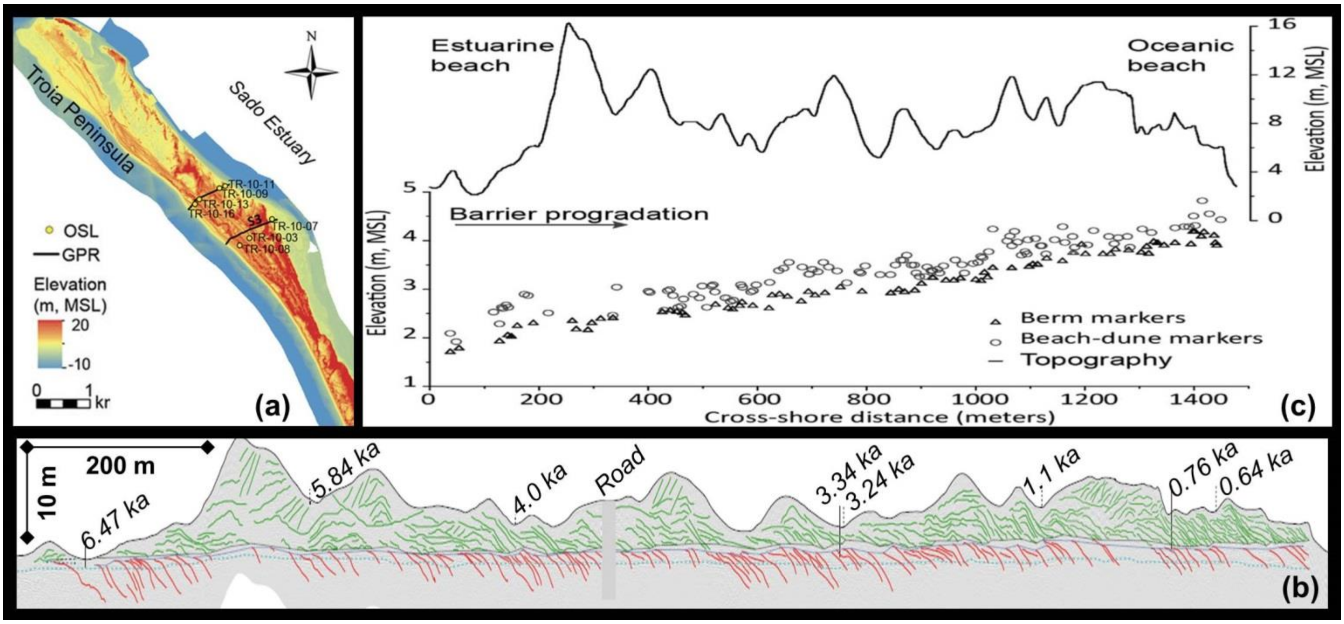

Figure 6. (a) LiDAR of Troia Peninsula, Portugal, showing locations of GPR and OSL transects. (b) GPR transect across the barrier with interpreted dune stratigraphy in green and beachfaces in red, with associated OSL ages. (c) Elevation plot of berm and beach-dune markers (used as sea-level proxy) imaged in the subsurface with GPR and displayed with corresponding overlying dune morphology; efficiently summarizing supplemental material data (b). Figure modified from Costas et al. (2016).

3.2 Storms

Oliver et al. (2017b) used GOaL on two proximal prograded barriers (Wonboyn and Boydtown) along the southeast coast of Australia. The crux of the study focused using topographic profiles of the present-day beach spanning days to years to interpret shoreline evolution over centuries to millennia. Beach profile data capturing a storm-eroded and swell-accreted geometry were used to interpret the GPR data (e.g. Figure 7a). Oliver et al. (2017b) concluded that all of the paleo-beachfaces in the geophysical record were stacked post-storm profiles with no berm stratigraphy preserved. However, this interpretation is likely skewed because the gain control is high in the GPR data (e.g. Figure 7c) and the annotated data highlighted every amplitude peak with no regard for signal strength (e.g. Figure 7b). This makes it hard to distinguish the beach and dune facies as well as storm-eroded and swell-accreted beachfaces. Despite this, flat-lying berm stratigraphy, imaged by the GPR collected across the present-day beach, can be seen throughout the barriers and illustrates its preservation (e.g. Figure 7b and c). Coring or augering to ground-truth the strong reflections would have shown the difference between dune and beach facies that are both represented by similar high-amplitude signatures (Tamura et al. 2017). Additionally, these cores would have determined that not all strong beachfaces reflections were a result of erosional lag deposits (e.g. heavy-mineral, coarse-grained, and/or shell hash). There is indeed storm eroded paleo-beachface reflections preserved throughout the stratigraphy, but not in the frequency implied in this study, as they are separated by berm structures (e.g. Figure 7c). Consequently, Oliver et al. (2017b) overestimate the recurrence and impact of storms, without discussing variation in intensity/magnitude. Neither of the sites studied are optimal for extracting a Holocene storm record (or sea-level curve) as Wonboyn has vegetation that inhibits the collection of GPR across the entire barrier and Boydtown has a tidal creek running across the middle, eroding and modifying part of the record.

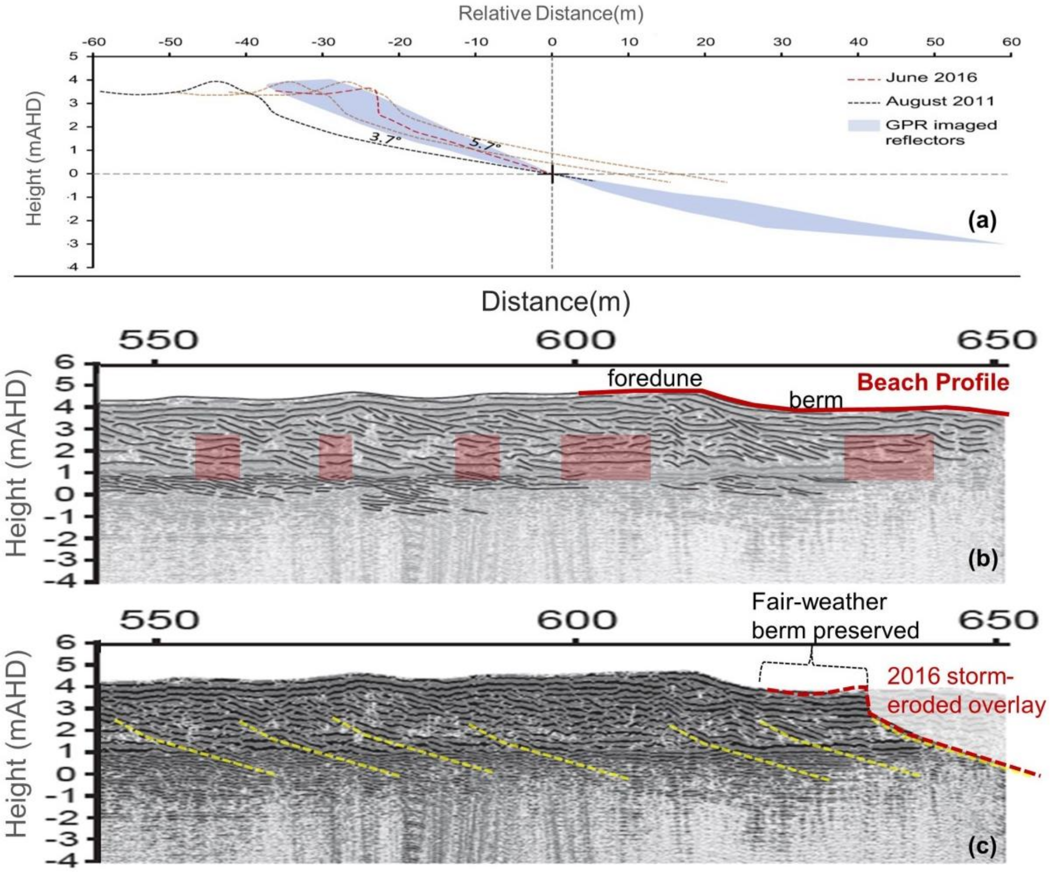

Figure 7. (a) Topographic profiles of recent swell-accreted (black) and storm-eroded (red) beach geometry plotted with the range of topographic profiles extracted from the GPR (blue area) in Oliver et al. (2017b). Since the swell-accreted profile falls outside of the blue area, Oliver et al. (2017b) interpreted that only storm-eroded beachfaces were recorded in the GPR. However, it is how these profiles are plotted (normalizing the distance (0m) relative to the intersection with AHD) that inhibits overlap due to unnatural spacing of the beachface topographies. Moving the swell-accreted profile along the x-axis and closely stacking it next to the storm-eroded profile (as demonstrated by brown dashed lines), shows that the upper beachface falls well within the blue envelope. (b) Interpreted GPR profile of the seaward-most portion the barrier, representing data presented in Oliver et al. (2017b). Note the flat-lying reflections beneath the present-day berm (on the right) are similar to other flat-lying reflections preserved landward throughout the GPR (highlighted by red boxes). (c) Processed GPR from Oliver et al. (2017b) supplementary data showing such a high gain applied that it is hard to distinguish dune from beach facies, yet alone storm and swell beachfaces. Overlay of the 2016 storm-eroded profile (red dashed line) was used to identify strong reflections with similar geometry (yellow dashed lines) showing paleo-beachfaces representing high-energy events. These storm-eroded beachfaces are spaced by lower-amplitude, flat-lying reflections that represent swell-accreted berm stratigraphy, proving that not only storm-eroded beachfaces are preserved in the GPR.

Clim. Past Discuss., https://doi.org/10.5194/cp-2018-4
Manuscript under review for journal Clim. Past
Discussion started: 30 January 2018

3.3 Sediment supply and barrier evolution

Oliver et al. (2017a) uses GOaL to decipher the complex progradation of Seven Mile Barrier in Tasmania, Australia (Figure 8a). Oliver et al. (2017a) concluded that a lack of sediment supply caused two periods of paused progradation between 6,000 and 3,000 years ago as well as over the past 500 years (Figure 8a and b). However, these two time periods lack OSL dates and GPR data impacting this hypothesis (Figure 8d). The gaps in the chronology and stratigraphy leading to this conclusion may have resulted from the rendering of the LiDAR as well as how topographic profiles were extracted from it. The green colour scheme and discontinuous profiles do not clearly distinguish major changes in the evolution over (Figure 8A and B). Augmenting a Google Earth image with 5 m LiDAR, freely accessible from Geoscience Australia (http://www.ga.gov.au/elvis/), reveals the existence of the largest set of prograded foredune ridges formed between 6,000 and 3,000 years ago (enclosed in black dashed line in Figure 8c). A topographic profile across the entire Holocene barrier illustrates the prominent ridges and seaward swale, which combined represent over 200 m of progradation (western profile Figure 8d). Additionally, the LiDAR show these features bifurcate to the east (indicating greater progradation in this part of the barrier) and extends laterally to the west (Figure 8c). This barrier progradation and expansion as well as foredune aggradation indicate that sediment supply did not halt during this time period (Dougherty, in press).

Multiple shore-perpendicular continuous profiles extracted from the LiDAR capture the spatial complexity of the barrier evolution over time (Figure 8d). The western profile, that spans the Holocene, clearly displays the recent shift depicted by the present-day foredune that is more than three times taller than any relict ridge formed over millennia. Oliver et al. (2017a) also concluded that this recent shift in evolution, resulting in the large foredune, represents a pause in progradation due to a reduction in sediment availability. However, it appears that progradation has not temporarily stopped, but rather transitioned to transgression as evidenced by the large 60-year old foredune unconformabley deposited on top of the 1,400-year old low-lying foredune ridge (Dougherty, in press: Figure 8c and d). In the current state of sea-level rise, this barrier is not likely to resume progradation, but rather erode and continue transgressing. Collecting GPR and OSL data across the entire Holocene barrier (as well as ground-truthing all of the GPR with cores and topographic profiles of the present-day beach) can not only fill the gap in knowledge about how and when the large foredune formed but also produce records of past sea level and storms. Digital elevation models from the LiDAR can also be used to better understand the volume of barrier sediment supplied above mean sea level. Finally, considering past changes with respect to factors such as sea-level, storms and sediment supply can then provide insight on past shifts in evolution and the future erosion of the beach as it is impacted by climate change.

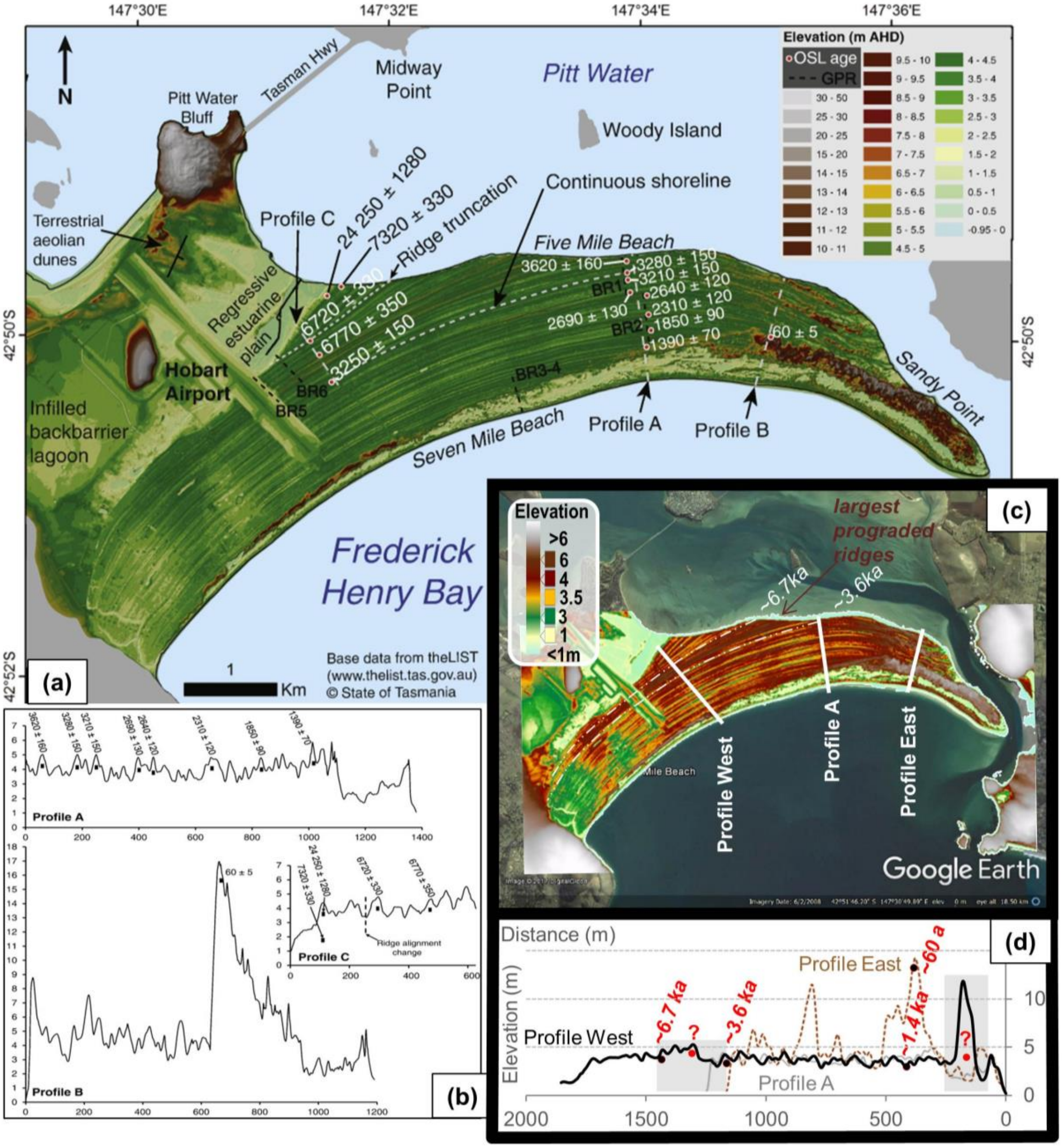

Figure 8. Morphology and chronology of Seven Mile Barrier, Tasmania, Australia. (a) LiDAR data showing the location of topographic profiles (shown in b) and GPR transects as well as OSL ages (in years) from Oliver et al. (2017a). (c) Google Earth image augmented with 5 m LiDAR (Geoscience Australia; http://www.ga.gov.au/elvis/) showing the lateral extent of the largest set of prograded foredune ridges which formed between ~6,700 and 3,600 years ago (darkest reddish brown ridges within the white dashed lines). (d) Topographic profile across the east and west portion of the barrier (location in c) overlain on Profile A from Oliver et al. (2017a). Profile West transects the entire Holocene barrier displaying the largest prograded ridges between ~6,700 and 3,600 years ago and the extraordinary height of the present-day foredune lacking OSL and GPR. Profile East overlay indicates relatively recent barrier transgressive evident from the large 60-year old dune unconformabely deposited above the ~1,400-yr old low-lying ridge. Also note the vertical age discrepancy in Profile C in (b) and how GPR could help to understand these age models.

3 Concluding remarks

Utilizing GOaL on prograded barriers provides insights on coastal evolution over spatial and temporal scales spanning form the present-day beach to paleo-beachfaces formed over millennia. LiDAR produces 3D images of the barrier morphology informing where best to collect 2-3D GPR records of dune, beach and nearshore stratigraphy, which intern informs which specific stratigraphic layers should be targeted for OSL dating. In addition to following the simple order to this methodological approach, a few general recommendations can maximize building and interpreting these GOaL datasets: 1) diligence in rendering LiDAR data and overlay with aerial imagery, 2) use appropriate gain control on GPR data and ground-truth, and 3) identify exactly what facies within the stratigraphy is dated and choose the most appropriate age model for the sample. Executing GOaL optimally on a prograded barrier has the potential to generate detailed records of storms, sea level, and sediment supply for that coastline. Obtaining this unprecedented GOaL hat-trick can provide valuable insights into how these three factors influenced past and future barrier evolution. With 300+ prograded barriers worldwide (Scheffers et al., 2012), achieving this GOaL hat-trick systematically on different systems can also detect local patterns of sediment supply, regional records of storms or global changes in sea level. The prevalence of these coastal deposits combined with the increased accessibility of GOaL techniques, affords the possibility to establish this method such that it can be utilized like, and compared with, other climate proxy data. Ultimately, this research will continue to contribute to theoretical research on coastal evolution and climate change; which in turn will inform practical applications to best mitigate the impacts of global warming on vulnerable communities and infrastructure.

Acknowledgements

We would like to thank Duncan FitzGerald and Ilya Buynevich for sharing their knowledge and enthusiasm for GPR and coastal science. Many thanks to: Peter Annan of Sensors and Software for helping me customize GPR specifically for this research during a three day Pulse Ekko course in Canada, Mads Toft of Mala GPR Australia for insights gained while trying to get UOW’s unit fixed, GBG Australia for offering replacement units and geophysical advice, as well as everyone at Geophysical Survey Systems, Inc. (GSSI) in New Hampshire for their collaboration and support over the past 20 years. Much appreciation to John Begg, Navin Juyal, and Vikrant Jain (in New Zealand) as well as Seoyoung Heo, Christina Neudorf, Luke Gliganic, Daniela Mueller, Thomas Doyle, Heidi Brown, and Zenobia Jacobs (in Australia) for sharing their expertise in LiDAR and OSL. This manuscript was supported by GeoInsights Consulting.

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