In following with Climate of the Past's guidelines, this response will be structured such that each point will be addressed in numerical order following the sequence: a) comments from referee, b) author's response, and c) author's changes in manuscript.

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Changes addressing Chris Hein's Review:

ADRESSED General Revision #1:

a) Consider the addition of groundtruthing as a fourth approach, equally as important as LiDAR, OSL, and GPR.
b) While the idea of a grand slam is an appealing one, groundtruthing is not seen as a standalone technique per se. Rather coring or topographic profile collection (for example) as a means of groundtruthing remotely sensed data, is seen as an integral component of GPR and LiDAR methods. While LiDAR, GPR, and OSL can all be used individually or in various combination, it is not recommended that GPR or LiDAR is used without being groundtruthed (or at the very least state the omission and consider when interpreting the data). Coring or outcrop mapping used to ground-truth GPR and topographic profiling using levels, lasers, or GPS to ground-truth LiDAR are all techniques that can be used alone or in combination with other methods (e.g. air photograph analysis or radiocarbon dating) to study coastlines. Ultimately, our counter argument would be that groundtruthing of non-invasive subsurface data is not a critical fourth component to GOaL approach, but rather an essential element whenever remotely sensed high-resolution stratigraphic or topographic data is used (therefore embedded in GPR and LiDAR methods).
c) No changes are planned for incorporating ground-truthing as a fourth approach. However, the introduction paragraph to GOaL methodological approach (Section 2) has been significantly rewritten to emphasize the role of ground-truthing.

ADRESSED General Revision #2:

a) Recognize the limitations of certain field sites and conditions which may make any one of the three (or four) "hat trick" components not possible, or not the best approach for a given site.
b) It is recognized that the combination of GPR, OSL and LiDAR is not always the best approach or even possible for a given site. However, for those sites where these techniques are able to be used this paper aims to provide insight on how to optimize their utility. We are not insinuating, nor state within the paper, that this is an "ideal" approach for all sites. What is inherent, but seems to be made more explicit, is that the optimizing of this GOaL approach was conceived for sandy prograded barriers. Following on from the discussion of the previous comment the use of GPR, OSL, and LiDAR does not preclude the use of other methods and in some cases necessitates it. Of course where there is organic material for radiocarbon dating, use that instead of or with OSL.
c) The introductory paragraph to the GOaL methodological approach (Section 2) has been significantly rewritten to address these concerns.

ADRESSED General Revision #3:

a) Consider adding examples from additional global sites; this does not need to be in the discussion of the three "case studies" as those are meant to be focused on single papers.
b) This is a very good suggestion that does indeed broaden and strengthen the paper. In addition to some of references that were meant to be included, the response to this interactive discussion (both in the form of online comments and private emails) provided suggestions for other papers that will also be included. It is true that when drafting the

paper the idea was to use the three most recent examples that use GOaL specifically to study sea level, storms, and sediment supply as case studies. However, along the lines of Marc Hijma comment, it will be nice to reiterate some previous examples of successful studies mentioned earlier in the paper as reference when individually discussing study sites specifically on sea level, storms, and sediment supply.

c) Multiple additional references were included in the paper from sites spanning the globe.

ADRESSED General Revision #4:

a) Consider a more measured treatment of the Oliver et al (2017a,b) studies.
b) Since the submission of this manuscript to Climate of the Past, an extensive comment on Oliver et al. (2017a) has been published and a similarly detailed discussion paper on Oliver et al. (2017b) has been accepted with minor modifications (Dougherty, 2018a,b). These comment papers allow a nuanced conversation of the data and interpretations presented in each that was simply not possible nor appropriate for this technical note. This allows us to refer to these comment papers for a fuller discussion when identifying the potential pitfalls encountered when GPR, OSL and LiDAR are not used optimally. This technical not will focus specifically on how interpretations can be questioned when GPR data is not groundtruthed with cores as well as when rendering of LiDAR (and topographic profiles extracted from the remotely sensed data) masks or distracts from important aspects of the morphology. The importance of groundtruthing is agreed, as per the discussion above, and presnetaion publicly does matter if it is influencing interpretation (see discussion in Specific Comment #6 below). While it is uncomfortable to critique specific studies, it is necessary in order to have a rigorous scientific debate. Because of the critical nature of this aspect of the paper, it was important to us that it was published in a way that the authors of the Oliver et al. (2017a, b) papers could comment or correct anything that might be misleading. We are grateful for Climate of the Past's open access and interactive review process which allowed this option. Authors associated with both papers were made aware of this technical note addressing methods used in their papers before it was submitted and it is known that the lead author has viewed this Climate of the Past submission (as informed by ResearchGate).

3.2 Storms

To determine a storm record requires eroded paleo-beachfaces to be clearly identified within the stratigraphy. This requires coring of these storm layers and using these cores to groundtruth the GPR and make gain adjustments. Failure to do this can result in ambiguous interpretation of storm plaeo-beachfaces. A new example of GPR data will be added that shows GPR data with high gain applied masking the storm layers. This same data with the gain reduced according to an overlain core reveals obvious storm layers. This will demonstrate the potential to interpret an over exaggerated storm history for sites that do not core or adjust gain, such as Oliver et al. (2017b).

3.3 Sediment supply and coastal evolution

In order to discuss changes in evolution through time and not confuse these with alongshore variations, a single shore-perpendicular transect line from the oldest to the youngest part of the barrier is optimal. This GOaL paper advocates for using LiDAR to determine where the best location is to collect this transect. Then collect GPR along this transect and use this morphostratigraphy to target the best location to collect OSL. We agree with the reviewer that integrating two or more parallel lines improves the robustness as well as allowing a discussion about alongshore variation through time. However, this is not our point or the reason for the multiple lines drawn in Figure 7d. Rather these lines were extracted from the rerendered LiDAR to demonstrate how it can be used to determine the best location to extract the best transect to span the entire history. This process clearly shows that the western profile is the most complete. Comparing this one transect to those presented by Oliver et al. (2017a) identifies gaps within the morphologic data at points where the evolution shifts towards the beginning of barrier inception and in the most recent period. The LiDAR shows the accommodation space changes through time and identifies that anomalously large foredune ridges formed during this time. However, GPR and OSL were not collected for these areas of interest. The gaps in the topographic record, GPR stratigraphy and OSL chronology during these two points in time raises the question of whether the interpretation of halted progradation is due to ceased sediment supply or just a result of a lack of data. At the very least identifying that these gaps exist and considering the implication is crucial to any discussion about barrier evolution and the role of sediment supply. This does not negate sizable amount of data presented for the other area of the work that no doubt went into collecting it. Rather that following the simple order and suggestions presented in this GOaL methodology might have helped optimize this dataset by first targeting shifts in evolution using LiDAR morphology, detail how these sections of the barrier formed using detailed stratigraphy from GPR and then dating the timing of these changes using targeted OSL samples.

c) The two sections referring to the Oliver et al. (2017a,b) studies were redrafted so that specifics to the study sites are minimized and transferrable lessons for the best practice use of the GOaL techniques are emphasized (as suggested by the reviewer).

ADRESSED Specific Comments #1:

a) P6, L9 & Figure 2: this is focused on the utility of LiDAR, not the details of this study. However, it is not clear that the multiple sets of “prograded barrier islands” shown here were never a single island / beach-ridge plain. This is a great example of possible reworking of a non-continuous record, a limitation in reconstructing the evolutionary history of a progradational site, or the paleoenvironmental records contained within. This in fact may be a case for the use of subsurface data (GPR) to search for, e.g., landward-dipping beds at the landward side of each of those “islands” to try to infer if they formed as separate transgressive-regressive islands. LiDAR data here may in fact tell an incomplete story.
b) The main point of this section was to demonstrate how LiDAR can provide improved images of the morphology of coastal system and their surroundings to inform where to collect GPR. This approach was used at Rangitaiki Plains, but the GPR aspect was excluded so that LiDAR could be the focus. Based on this comment, it seems pertinent to add that this informed GPR collection. The combination of these data, along with previous studies of the area, was used to determine the evolution of this complex coastal system. The evidence for this series of prograded barrier islands is that the landward extent of each naturally transition into back-barrier deposits. These cohesive muds were more resistant to erosion and therefore preserved the morphology of the rear portions of these barrier islands as compared to the more easily erodible sandy beach and dune facies evidence by the reworking of the seaward side of these barrier islands. Beach-dune interface mapped in the GPR of these barriers show elevational offset of up to 5 m between sets of ridges. Their episodic formation is dated by volcanic ash and pumice layers deposited on these barrier islands and their associated back barrier environments (Selby and Pullar, 1971).
c) This discussion has been modified to clarify points raised above. Also an alternative LiDAR image with different rendering was added to Figure 2 in order to help to refocus this discussion on the utility of LiDAR to guide GPR collection and the importance of rendering/presentation on the identification of barrier features.

ADRESSED Specific Comments #2:

a) P8, L8-9: this statement would be stronger if supported with examples or details of how beachface mapping can be used to infer sea level, etc.
b) Nice suggestion.
c) References of examples were added to this sentence and an image of data that demonstrates beachface mapping was added to Figure 7(d,e,).

ADRESSED Specific Comments #3:

a) P8, L14: suggest being more specific. What about the change in reflection geometry indicates storms?
b) Noted that the use of “distinct geometries” is not very specific. In fact, storm-eroded beachfaces can be hard to distinguish on shape alone as evidenced in the Oliver et al. (2018b).
c) A sentence was added that states that storm steeper upper beachfaces with a strong reflection that makes it distinct form swell accreted paleo-beachface geometry. GPR data was also added to Figure 7 to demonstrate this.

ADRESSED Specific Comments #4:

a) P8, L19-26: If the authors are going to discuss these aspects of GPR processing and interpretation (including the necessity of ground-truthing, as discussed earlier), then it is also worth noting some additional key processing steps for proper GPR interpretation. For example, migration, ideally using field common-midpoint (CMP) surveys, to determine radar velocities.
b) It was very intentional not to specifically talk about processing steps, even very basic ones (as discussed in the GPR section). This is done for many reasons, one of which is that there are many different software packages, GPR brands and unit configurations (even within brands). Using the example above, some systems have transceivers and therefore cannot do common-midpoint survey; while some software packages process in terms of velocities and others use dielectric constants. We found it important to not get into specifies or advocate for any one approach. There is already a lot of literature out about processing and even recommended steps in coastal settings. What people will use is likely a product of the equipment they have access to. In each case the user should research papers that use the same configuration and software, then use the methods from papers that provide good examples as a base to start processing their data. The end goal is to present the data in a way that best represents the subsurface stratigraphy that it is imaging and highlight the specific aspect that is the focus of discussion. To this end, we feel that gain and groundtruthing are two crucial aspects that have not been emphasized enough and therefore highlight them here.
c) A paragraph has been added to the GPR section to explain as well as a couple of sentences to the paragraph about gain.

ADRESSED Specific Comments #5:

a) P10, L10: “calculations from the LiDAR data”. It may be worth noting that this would not have been possible without ample stratigraphic data from sediment cores, especially given the limited GPR penetration.
b) Yes to determine the total volume of barrier sands requires cores through the entire sequence. The references to calculations from the LiDAR data are specifically about the volume above MSL, similar to volume calculations for the envelope of change of modern shorelines form beach profile data. This is stated in the second mention on page 14, but oddly not the first on page 4. Thank you for drawing attention to this initial omission.
c) The clarification of ‘volume of barrier sediment supplied above mean sea level’ was added to the first mention of volume calculation on page 4.

ADRESSED Specific Comments #6:

a) P12, L15: “gain control is high in the GPR data”. That could just be the way in which the GPR data are shown in published form; that can be a challenge to get right. Presumably the GPR data were analyzed in high detail, and through careful tuning of gains to ensure best analysis resolution. Only those authors can speak to this. This same interpretation could be applied to criticisms of Oliver et al (2017a) noted on P14, L7-8 (LiDAR color scheme chosen for publication display).
b) Gain can be a tricky step to get right and really requires cores or some idea of what is being imaged in order to properly display the amplitude of change recorded in the GPR. Even without any groundtruthing to refer to, if the focus of the interpretation is that every beachface reflection represents a storm and ridges are formed by eolian processes, then at the very least the GPR should display the difference between beach and dune facies. We do not presume to know what the authors did with regard to the data, but can only speak to what is presented. What is known is that regardless of the detail of analysis or tuning of gains, ultimately the ‘interpreted’ data consists of every reflection being simply traced with no distinction of signal strength or barrier facies. With respect to the LiDAR, a similar response could be made that the presentation of the data should best reflect what the authors want the readers to focus on. While it is not known if other color schemes were trialed during analysis, the rendering chosen and topographic profiles extracted do not highlight increased accommodation space or the anomalously large sizes of the foredunes that formed during the specific time periods in question.
c) Changes made to Figure 7 to clarify the point about the importance of gain. In addition to trying to demonstrate this with the core, outcrop, and GPR in Figure 3, Figure 7 was amended to try a different approach to display the importance of gain adjustments. LiDAR with a different rendering has been added to Figure 2 to reiterate the importance of color scheme.

ADRESSED Technical Corrections #1:

a) P2, L20-21: the point concerning collaboration between scientists with specific expertise in each of the tools (some of which [e.g., GPR or pre-processed LiDAR data] are perhaps easy to use, but not easy to use well!) described in an important one.
b) This is a nice distinction that the ease of acquisition of these data, does not translate to ease of correct use (but the turn of phrase “easy to use, but not easy to use well!” is much better).
c) This point was added to the text and Hein personal communication 19 March 2018 was cited.

ADRESSED Technical Corrections #2:

a) Figure 5 caption: “prograded normally for a while”. This is unclear, unspecific, and qualitative. (the term “normally” is applied on P11, L7 as well, and does not seem to necessarily indicate “normal [sediment surplus driven] progradation”. Correct?). “drastic shift in evolution observed . . .” this is not clear from the data presented, nor is it clear what would qualify as a “drastic” change
b) This concept of how to term a barrier that is prograding in a consistent fashion, is something the authors discussed when it was initially referred to it as ‘classic’ progradation. We tried regular, uniform, ect. and agree the use of the word normal is not optimal. It is actually meant to indicate “normal [sediment surplus driven] progradation” that results in the tell-tale series of relic foredune ridges apparent in the air photograph. Within the last millennia the relic foredune ridges that formed between 1,700 and 1,000 yr BP were eroded and large transgressive dunes forms on the landward and seaward edges of the blowout. Over the last

1,000 years progradation also differs forming low-lying hummocky incipient dunes rather than larger distinct foredune ridges. In combination, this data defines a drastic shift in evolution over the last millennia as compared to previous ones.

c) The word 'normally' was change to 'uniformly' throughout.

ADRESSED Technical Corrections #3:

a) P11, L15: Costas et al 2016 is listed twice
b) Thanks for catching this Endnote user error
c) Deleted one

Changes addressing Zhixiong Shen's Review:

ADRESSED General Comment #1:

a) One advantage of combining Li-DAR topography and GPR not mentioned yet is that the former is very useful for elevation correction of the latter. However, some common pitfalls of the individual technique are not mentioned, which makes the strategy practically less useful to follow.

b) LiDAR is useful for rough topographic correction. Due to the fact that I use most of my data to try and infer sea level from heights of beachfaces and storms form their geometry, I like to use the most accurate topographic correction possible. To eliminate the uncertainties associated with LiDAR and extracting the exact transect line form the image that the GPR was collected along (usually the two data sets are acquired on different dates allowing possible discrepancies), I prefer the old school method of levelling or laser levelling in the actual elevations of the GPR transect line. This should be done at the time of collection and include a survey of the active beach and tie in any existing benchmarks. This is standard along with coring to ground-truth depth to water table on the day of GPR collection.

c) A sentence was added to the GPR section that states the utility of LiDAR to roughly topo correct GPR data, but that a proper survey should be conducted alongside GPR collection.

ADRESSED General Comment #2:

a) GPR data collection and interpretation depend not only on gain, but also on the frequency of radar, antenna shielding, spacing of traces, and speed of radar in sediments of different nature. I am not sure why the note specifically picked gain, but not others in the recommendation.

b) True there are many different set up and settings when it comes to collecting GPR. What is ultimately chosen depends greatly on the access to gear, the field conditions, the scientific question to be answered, etc. At this point there are plenty of papers and books about GPR that people can turn to in order to understand how GPR works and what settings are best for each particular study. The aim of this paper was to show the potential of optimizing the use of GPR in combination with OSL and LiDAR, not a' how-to' guide with specifics for acquiring and analysing each data set. Rather this paper works on the basis that readers have a standard knowledge of, and some experience with, these techniques. As advocated in the paper, it is important to lean from or collaborate with experts using each of these three methods as they are specific fields within geophysics, geochronology and remote sensing.

c) A paragraph has been added to the GPR section to explain as well as a couple of sentences to the paragraph about gain.

b) With respect to GPR, the units have become so affordable and user-friendly it has become relatively easy to access a machine, turn it on, and get data. While this is absolutely fantastic for the expansion of its use in many fields, there is a danger that without proper knowledge and training data can be collected incorrectly and/or misinterpreted. For the most part in the field of coastal research this is not the case, probably because it has been used in this field for so long with many people and papers to turn to. Therefore, most papers have the basics correct. The reason gain is singled out is for two reasons: 1) applying a high gain (as well as highlighting every reflection) is one very common occurrence in coastal data and 2) it is an incredibly important adjustment when trying to extract storm and sea level records from sandy barriers. I have increasingly noticed that along with the proliferation of GPR use, more papers and conference presentations don't have the gain adjusted so that the signal strength aptly reflects the contrast in the stratigraphy. I have seen high gain inhibit the identification and extraction of a sea level curve from otherwise good data and result in an exaggeration of the storm frequency and impact as demonstrated in Oliver et al. (2017b).

c) A paragraph has been added to the GPR section to explain as well as a couple of sentences to the paragraph about gain.

ADRESSED General Comment #3:

a) OSL age determination is affected by many assumptions about bleaching, distribution of radioactive sources in the sediment, water content variation, post depositional disturbance, disequilibrium in the uranium and thorium decay series, and cosmic radiation (often a very important component to the total radiation a beach sample received) change because of change of overlying sediment thickness. The choice of appropriate age model does not handle all these complications.

b) These are important considerations and will be assessed for incorporation within the manuscript.

c) A paragraph has been added and scope of the section shifted.

ADRESSED General Comment #4:

a) One more recommendation about OSL date is that the ages should be reported in a way to enable comparison across different publications. This is because OSL ages refer to the time before OSL measurement and the measurement time must be reported to ensure comparison. As an example of inappropriate reporting OSL data, I noted that the note used 'BP' as a unit for OSL data, which suggests to me that these OSL data refers to AD 1950 following the most common use of BP in the geochronology community. However, my sense is that I am reading the unit 'BP' in the note wrongly.

b) Another good point, this will be addressed in the final draft of the manuscript if accepted.

c) This has been included in the new paragraph.

ADRESSED Specific comments:

P4, L4: add 'can' before 'be utilized'

-reworded for clarity

P4, L10: add ’of’ before ’coastal’ toward the end of the line

-recommended change made

P6, L4: parenthesis for reference not correctly used

-good eye, changed

P6, L12-13: delete ’in the’ between the two lines

-again thank you for catching this, changed

P9, L11: replace ’bleaches’ by ’can bleach’, and ’any’ by ’light-sensitive’

- nice clarification, recommended change made

P9, L15: replace ’accumulation period’ by ’burial period’

-better, recommended change made

P11, L5-6: ’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’. Can this be shown in Fig. 5b?

-The figure caption has been rewritten to describe how it is shown in Fig. 5b.

P11, L14-15: repeating reference

-one deleted

P11, L20-21: ’Initially this complicated spit system did not appear as an ideal site to extract a sea level history’. What is the reason for this?

-The idea is that it looks more like longshore spit progradation, but the LiDAR displays a section of the barrier that shows foredune ridges identifying seaward progradation. However, after reading this comment, I think that this is not necessary and therefore this line has been deleted.

P14, L7: sentence toward the end does not seem to be complete

-completed

P16, L4: replace ’form’ by ’from’

-thanks for catching this dyslexic tendency, changed

P16, L5: replace ’intern’ by ’in turn’

-thanks, changed

Fig 1: the OSL data seem represented by circles filled by brown, but not open black circles as indicated in the caption.

-changed wording to clarify

Fig 2: legend in 2b is not legible

-figure has been modified to show that this legend is the same as the larger one legible in 2d

Fig 6: the thin dashed lines in 6b are not interpreted.

-the figure caption has been changed to include definition of these

Why are there two different y-scales in 6c?

-left is the elevation of the markers and the right is the elevation of the overlying dunes

What is the difference between berm markers and beach-dune markers? Are the latter beach/dune boundary?

-These are both in relation to the upper beach that was mapped and used as potential indicators of sea-level position within the barrier stratigraphy (i.e. beach backshore and upper foreshore).

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 a 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.~~:~~ These methods include: Light Detection and Ranging (LiDAR) to image~~es~~ the lateral extent of relict shoreline dune morphology in 3D; Ground Penetrating Radar (GPR) ~~data~~ to record~~s~~ paleo-dune, beach, and nearshore stratigraphy; Optically Stimulated Luminescence (OSL) to date~~es~~ ~~when~~ the deposition of sand grains ~~were deposited that form~~along 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 ~~-~~three detailed records of 1) storms, 2) sea level, and 3) sediment supply for that coastline. Obtaining all three for one barrier ~~-this~~ (a 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 collection and analysis that maximizes the potential of GOaL to contribute to climate change research ~~and~~ that can assist coastal communities in mitigating future impacts of global warming.

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 (e.g. Bernard et al., 1962; Curray et al., 1969; Schofield, 1985; 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 (e.g. 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~~eliminating extrapolation of radiocarbon ~~dates~~ ages using isochrons (Figure 1a). The utility of combining GPR, OSL and LiDAR on prograded barrier has been demonstrated by the success of previous studies (e.g. Clemmensen et al., 2014; Mallinson et al., 2008; Muru et al., 2018; Nooren et al., 2017; Timmons et al., 2010; Tõnisson et al., 2018). Foreseeing the future use and potential of these combined methods, this technical note outlines a systematic and semi-standardized structure for data collection and interpretation. The strategy is that with a large enough dataset of similarly studied prograded barrier around the world, local to global forcing on coastal evolution can be better deciphered (Shen, personal communication 5 March 2018).

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). However, as Hein (personal communication 19 March 2018) succinctly states, some of the tools like GPR or pre-processed LiDAR data are perhaps easy to use, but not easy to use well. These techniques are all specialty fields of science ~~on~~ in 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 and diligent about the interpretations as well as implications drawn from it.

Studies have shown that utilizing these approaches on prograded barriers, independently or in various combinations, can: (1) ~~quantify~~ decipher 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; Choi et al., 2013; Dougherty et al., 2015, 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 associated with the data to maximize the combination of GOaL on prograded systems.

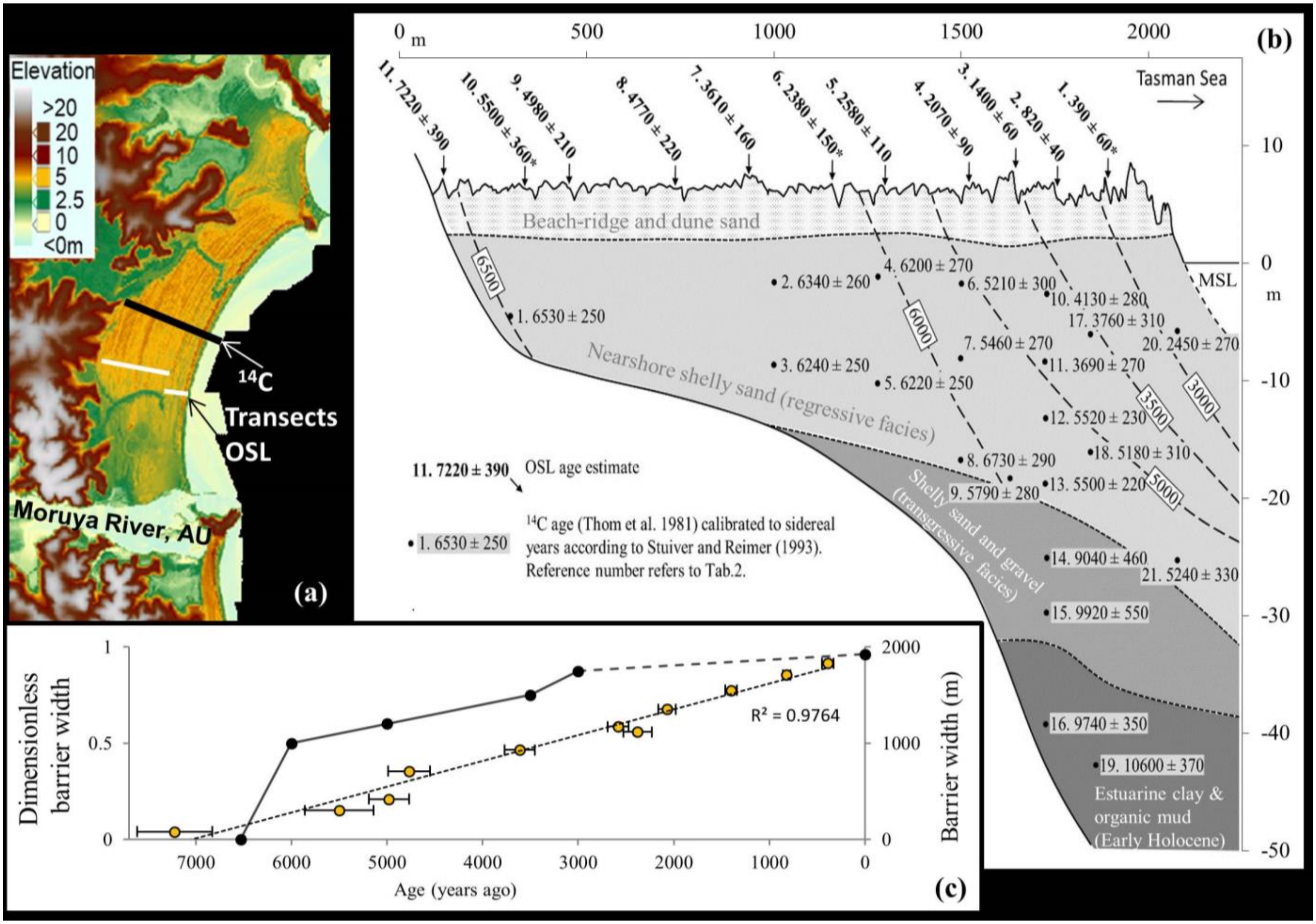


Figure 1. (a) LiDAR data of the prograded barrier system near Moruya, Australia, with the location of the transects where ^{14}C and OSL samples were collected. (b) Stratigraphic cross-section of Moruya Barrier displaying radiocarbon and OSL chronologies (Oliver et al., 2015; Thom et al., 1981). (c) Diagram of barrier width as a function of OSL (~~open~~ yellow dots with black circles) and radiocarbon (black ~~circles~~dots) 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).

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~~ they are recommended ~~that they~~ to 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. This technical note

~~This is not a How To guide for collecting each dataset, but rather expects some level of competency… Not a a practicle guide for using and combining this data to optimize…~~ is not a’ how-to’ guide with specifics for acquiring and analysing each data set. Rather this paper discusses the potential of combing these techniques and offers a practical approach to optimize the dataset. ~~Reiterate~~

~~This is not a How To guide for collecting each dataset, but rather expects some level of competency… Not a a practicle guide for using and combining this data to optimize…~~

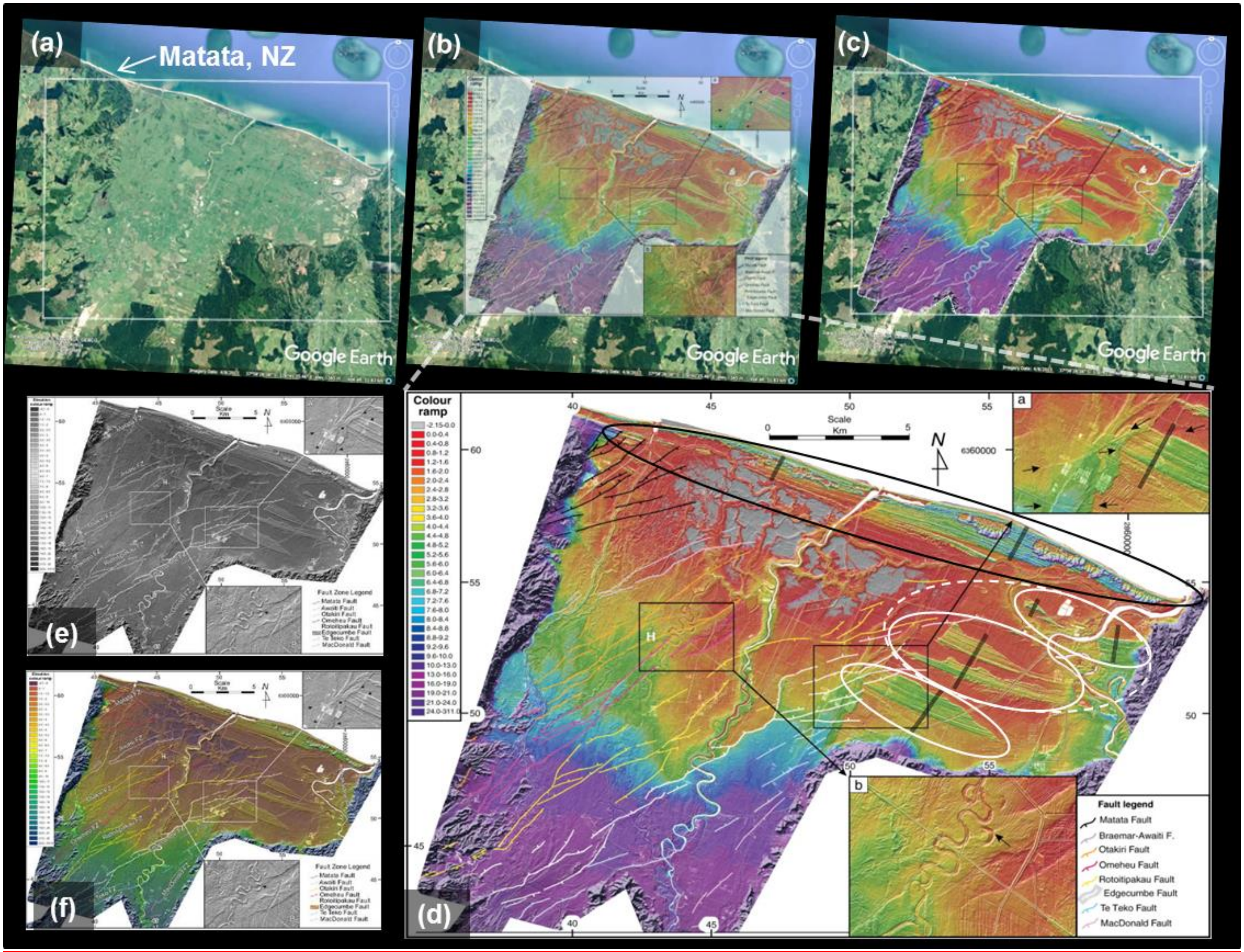
~~b) It was very intentional not to specifically talk about processing steps, even very basic ones (as discussed in the GPR section). This is done for many reasons, one of which is that there are many different software packages, GPR brands and unit configurations (even within brands). Using the example above, some systems have transceivers and therefore cannot do common-midpoint survey; while some software packages process in terms of velocities and others use dielectric constants. We found it important to not get into specifies or advocate for any one approach. There is already a lot of literature out about processing and even recommended steps in coastal settings. What people will use is likely a product of the equipment they have access to. In each case the user should research papers that use the same configuration and software, then use the methods from papers that provide good examples as a base to start processing their data. The end goal is to present the data in a way that best represents the subsurface stratigraphy that it is imaging and highlight the specific aspect that is the focus of discussion. To this end, we feel that gain and groundtruthing are two crucial aspects that have not been emphasized enough and therefore highlight them here.~~

This paper advocates that ~~A~~any of these high-resolution datasets, when collected and analysed correctly, improves our understanding of coastal evolution. However, these higher-tech approaches do no negate the use of more traditional techniques, like using radiocarbon dating where there is material suitable which is easier to collect then OSL as well as faster and cheaper to process. For example cheniers or coarse clastic beaches where various combinations of radiocarbon, OSL, GPR and LiDAR have been used to determine their evolution and a history storms or sea level (e.g. Billy et al., 2015; Hijma et al., 2017; Long et al., 2012; Hein et al., 2016; Morton et al., 2000; Neal et al., 2002; Weill et al., 2012). While the proposed GOaL approach proposed in this paper is geared toward the more prevalent sandy prograded barriers, it could easily be applied to (and compared with data from) these other types of coastal plains. In any environment, utilization of remote sensing techniques necessitates, rather than negates, the use of established methods (e.g. coring, auguring, outcrop mapping, and/or topographic profiling) necessary to ground-truth the data. Ultimately, these means of ground-truthing remotely sensed data is an integral component to (and should be embedded in) GPR as well as LiDAR methodologies; whether they are used independently or as part of the GOaL ~~approach..~~approach. The GOaL methodology will not be possible or ideal for all sites, however, for those where these techniques are able to be used this paper aims to provide insight on how to optimize their utility~~The idea of this approach, and associated general presentation tips, is~~ to ~~optimize~~ extracting paleoenvironmental records and decipher~~ing~~ 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. ~~Attaching~~Drones equipped with LiDAR are being explored as a lower cost option to acquire coastal data, but it is still expensive and requires experience (a pilots licenses in some airspace) to use (Klemas, 2015). ~~with drones is being explored for sites in regions where LiDAR has not been collected.~~ This section does discuss the complex details of how to collect or process LiDAR, but rather optimally utilizing professionally acquired and processed data. ~~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~~ as well as 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 obscured 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~~ the volumes of barrier sediment supplied above mean sea level (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~~: 1) target these areas modified by natural ~~or~~ and human processes to understand their impac~~t~~t or 2) 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~~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). Once the LiDAR is optimally rendered, this remotely sensed data needs to be ground-truthed to detect any errors in data acquisition or processing deficiencies (Gutierrez et al., 2001). This can be done in the field by checking the elevations using traditional survey equipment such as levels and total stations or Real Time Kinematic (RTK) GPS.


(a)
Matata, NZ
(b)
(c)
Google Earth
Colour ramp
Scale
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Fault legend
Matata Fault
Braemar-Awaiti F.
Otakiri Fault
Omeheu Fault
Rotoitipakau Fault
Edgecumbe Fault
Te Teko Fault
MacDonald Fault
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Fault Zone Legend

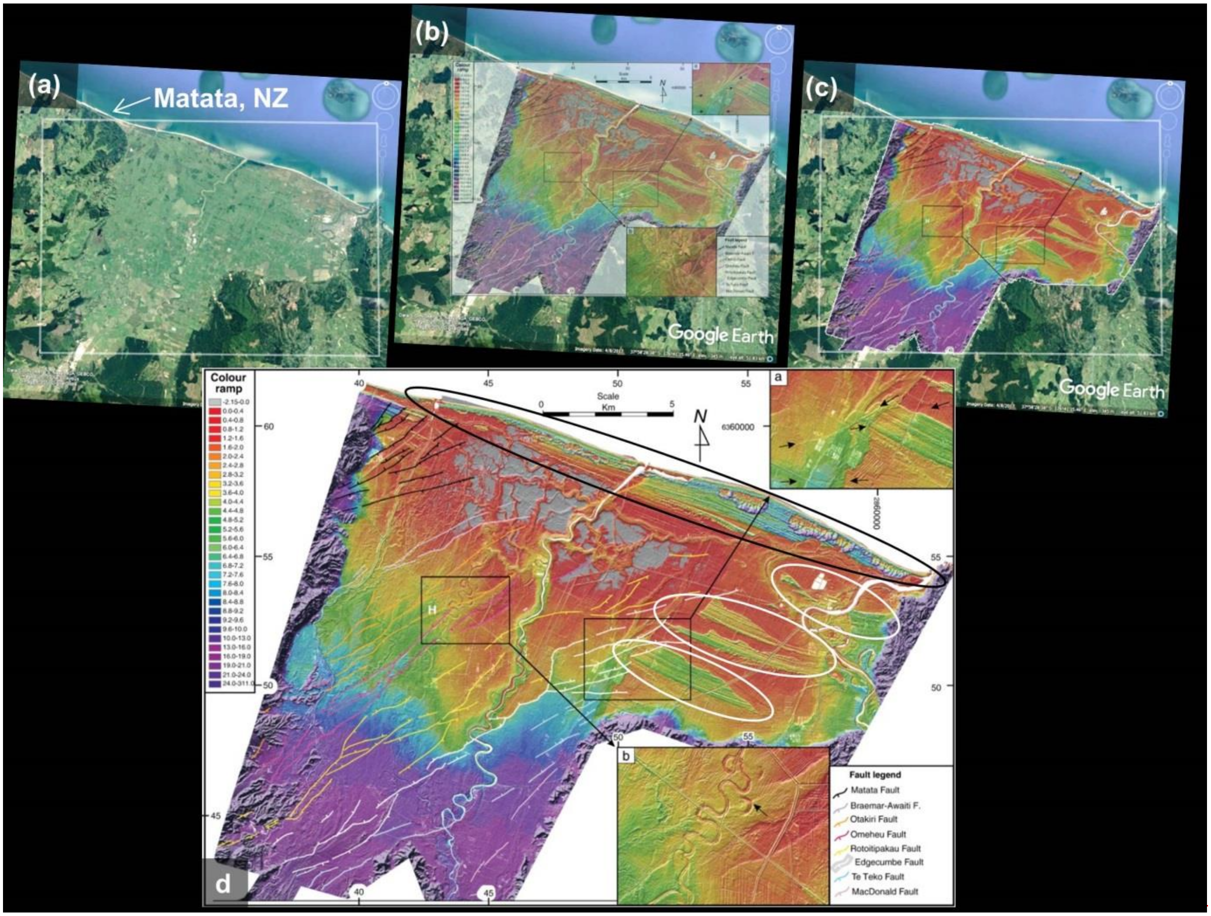


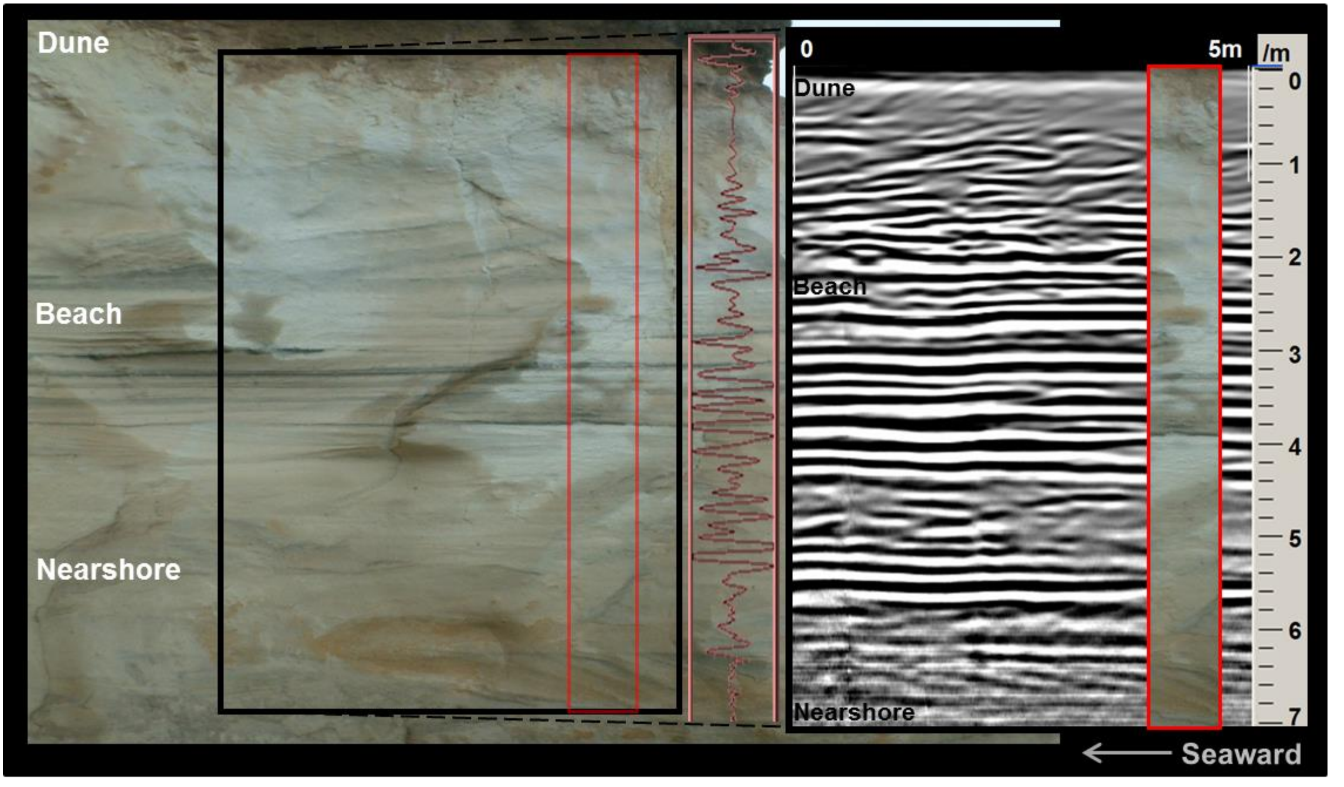
Figure 2. (a-c) Google Earth Image of Rangitaiki Plains, New Zealand, overlain with LiDAR shows complex infilling of this coastal embayment. (d) The ~~present-day~~modern coastline ~~is~~ displays a prograded barrier island (black oval). Faulting and river dynamics appear to have eroded the central and western portion of ~~a series of~~ older prograded barrier islands preserved in the eastern portion of the embayment (white ovals). Note difference in rendering of the LiDAR data and how the ~~color~~colour scheme chosen can either highlight the barrier structures or (b-~~c~~d) or blend them with the background (e-f). 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 as well as plan fieldwork. 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). The LiDAR collected by ~~(~~Begg and Mouslopoulou~~,~~ (2010) show that the infilling did not occur by uniform shoreline progradation, like at Moruya (Figure 1), but a rather complex evolution influenced by tectonic and riverine processes. ~~producing a unique set of prograded barrier islands.~~ This LiDAR imaged the modern prograded barrier island that formed after the area experienced ~5m of subsidence between 2.1 and 1.72ka ago (Begg and Mouslopoulou, 2010: circled in black in Figure 2d). The LiDAR data also identified remnants of prograded ~~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).~~ The detail revealed that the easily erodible beach and dune sands along the seaward side of these prograded sequences appear to have been modified. However, their landward extent does not appear eroded, especially the oldest two sequences that display the same natural transition to back-barrier deposits identified in the modern barrier island~~'s natural transition into back-barrier deposits~~ (documented by cores in Puller and Selby, 1971~~–~~). To test the hypothesis that these features formed similarly to the modern analogue, resulting in a unique set of prograded barrier islands, the LiDAR data was used to determine the best location to collect GPR transects (grey lines in Figure 2d). Toggling between overlain LiDAR and Google Earth images provided pre-field reconnaissance of obstacles (trees, houses, etc.) to consider logistics when targeting each specific profile. Given how rapidly and drastically coastal landscape changes, ~~being able to~~ selecting the ~~a~~ Google Earth image ~~collected~~ dated ~~around~~ closest to when the ~~the same time as the~~ LiDAR was collected is instrumental to providing good correlation in the overlay. It is also optimal to ~~use and~~ publish the LiDAR data augmented with aerial imagery when possible. This is useful for ~~analysing~~ the reader to analyse 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~~ should 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; Barboza et al., 2011~~; 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 variations 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).


Dune
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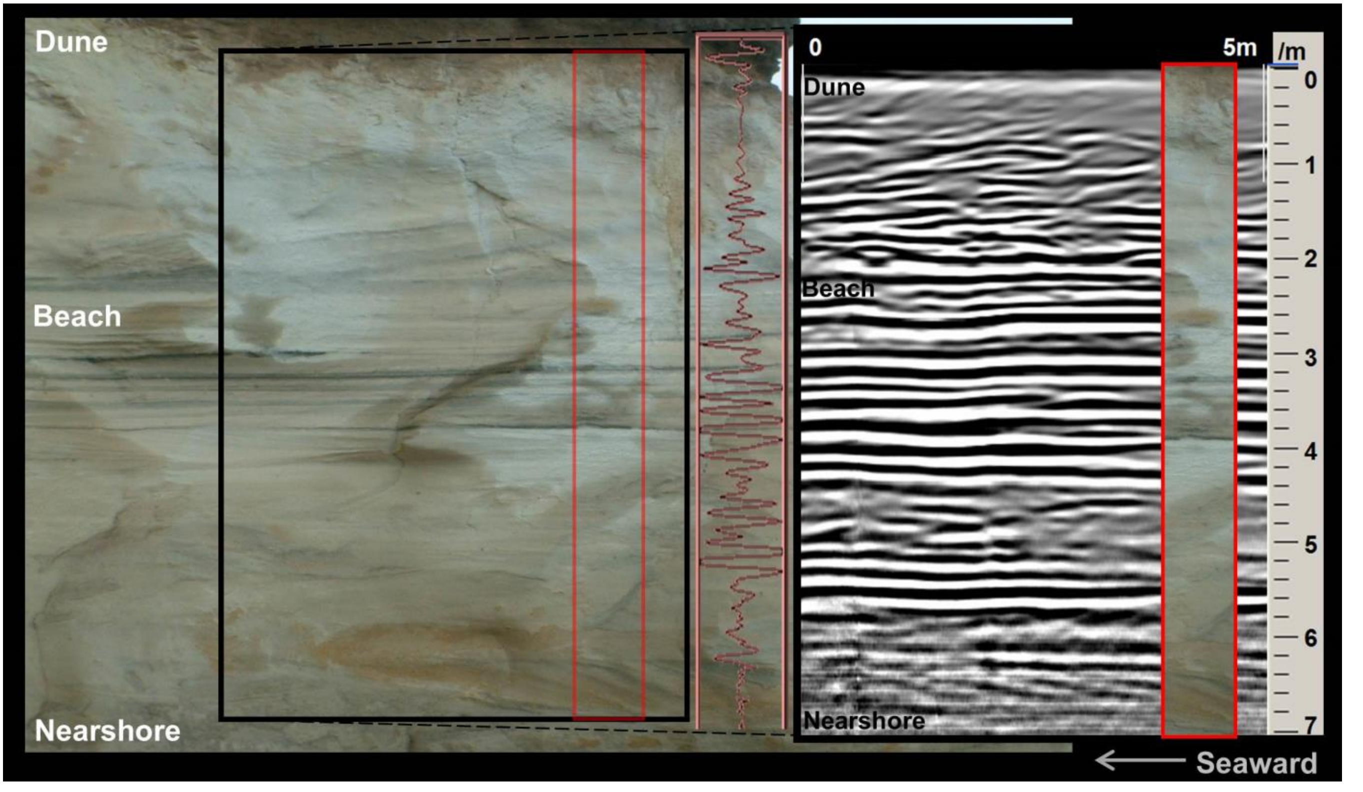


Figure 3. Left is a photograph of a scarp that cross-cuts a prograded Pleistocene barrier located near One Tree Point, New Zealand. This outcrop displays the small-scale stratigraphy of the barrier facies: dune, beach, and nearshore. Right is a transect of GPR data collected along the top of this outcrop 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).

Of the three GOaL techniques, GPR is the most easily accessible and affordable method for coastal geologist to collect and process data independently. The ability to buy or rent a GPR increased as their operation became more user friendly (e.g. from completely analogue systems with a stylus recorder, to partially digital systems using DOS ~~(Disk Operating Systems)~~ on a control unit or laptop computer, ~~and~~and now some are ~~are~~ complete with digital antennas ~~that~~ using~~e~~ Bluetooth communication run through simple Windows interfaces on tablets). Currently there are many brands and configurations of different ages in use as well as a variety of software packages that can be utilized to process their data. It is not within the scope of this paper to discuss all the differences in components, set-up configurations, settings, processing steps and terminology. This paper does not advocate for a particular unit, antenna, and software nor specific settings or a certain set of processing steps; as multiple variations produce similar high-resolution images of barrier stratigraphy when used correctly. Ultimately ~~what~~the type of gear ~~is~~ used for a certain project ~~will~~ likely depends on ~~the~~what ~~type of gear~~is available to the researchers. Novice users should utilize the extensive literature that exists on GPR and its use in coasts settings (e.g. Bristow and Jol, 2003; Buynevich et al., 2009). In addition to acquiring standard knowledge of GPR and the basics of processing, it is useful to research successful papers that use the same gear for specifics. It is also important to reiterate that when starting out it is best to collaborate or consult with someone who has experience with GPR, not just for acquisition and processing but especially interpreting the data. For use in GOaL, it is expected that there is a level of competency in GPR data collection, basic processing, and interpretation.

~~This paper does not advocate for any specific system~~

~~Therefore, the extensive literature that exists should be used to determine what settings and processing steps were used in successful studies using the same GPR system i Since the setup, operation, and terminology differ for the different GPR untis and software, In each case the user should research papers that use the same configuration and software, then use the methods from papers that provide good examples as a base to start collecting and processing their data.~~

~~At this point there are plenty of papers and books about GPR that people can turn to in order to understand how GPR works and what settings are best for each particular study.~~

~~There are many different set up and settings when it comes to collecting GPR.~~

~~It was very intentional not to specifically talk about processing steps, even very basic ones (as discussed in the GPR section).~~

~~Using the example above, some systems have transceivers and therefore cannot do common midpoint survey; while some software packages process in terms of velocities and others use dielectric constants. We found it important to not get into specifies or advocate for any one approach. There is already a lot of literature out about processing and even recommended steps in coastal settings.~~

~~b)~~

~~The end goal is to present the data in a way that best represents the subsurface stratigraphy that it is imaging and highlight the specific aspect that is the focus of discussion. To this end, we feel that gain and groundtruthing are two crucial aspects that have not been emphasized enough and therefore highlight them here.~~

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 ^{14}C 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~~ m depth) and in the crossbedding preserved as a bar migrated onshore in the nearshore (6-7~~ m~~ 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~~ 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 (e.g. van Heteren et al., 2000; Costas et al., 2016: Figure 7d), their geometry to produce storm records (e.g. Goslin and Clemmensen, 2017; Lindhorst et al., 2008: Figure 7e)~~, 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. Typically, erosion concentrates storm lag deposits on the steepened upper beachface and/or flattened lower beachface; which causes ~~Within the beach facies, storm lag deposits~~ high-amplitude reflections that are more prominent than the low-amplitude signature of the homogenous berm sands that accrete during intervening swell conditions. Mapping these distinct geophysical signatures throughout the barrier ~~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: Figure 7e). 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. van Heteren et al., 2000; Rodriguez and Meyer, 2006; Dougherty, 2014: Figure 7d). While it is noted that LiDAR can be used to roughly topographically correct GPR data, for the use of extracting sea level and storm records it is recommended that precise topographic profiles be surveyed in the field and tied directly to the GPR data.

~~*somewhere note the need to interpret the GPR not just trace every line…~~

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. Unlike other basic processing steps, there has been relatively little discussion about gain; but the fact that incorrectly gained data can impact interpretations warrants attention. The correct application of gain is not just important to accurately represent and interpret barrier stratigraphy, but critical to the extraction of sea level and storm records from it. ~~–~~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 (used as sea level proxy); yet alone individual beachfaces (not to mention eroded paleo-beachfaces preserving storm records). 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). As such, it is not recommended to highlight every line when interpreting GPR data (e.g. Figure 7a), but rather annotate specific facies stratigraphy interpreted from analysis of the signal strength and cores (e.g. Figure 6b). 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).

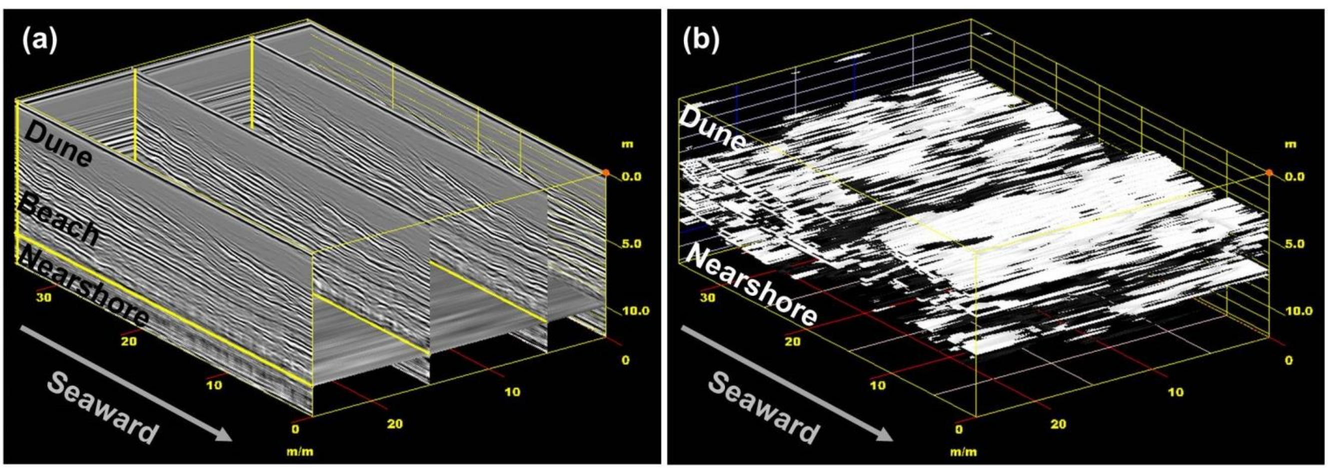


Figure 4. (a) Fence diagram showing some of the GPR transects collected in a grid configuration. (b) 3-D model of beachface stratigraphy constructed by isolating the most prominent reflections, shown in white, and interpolating between the transect lines. Figure modified from ~~(~~Dougherty ~~,~~ (2011).

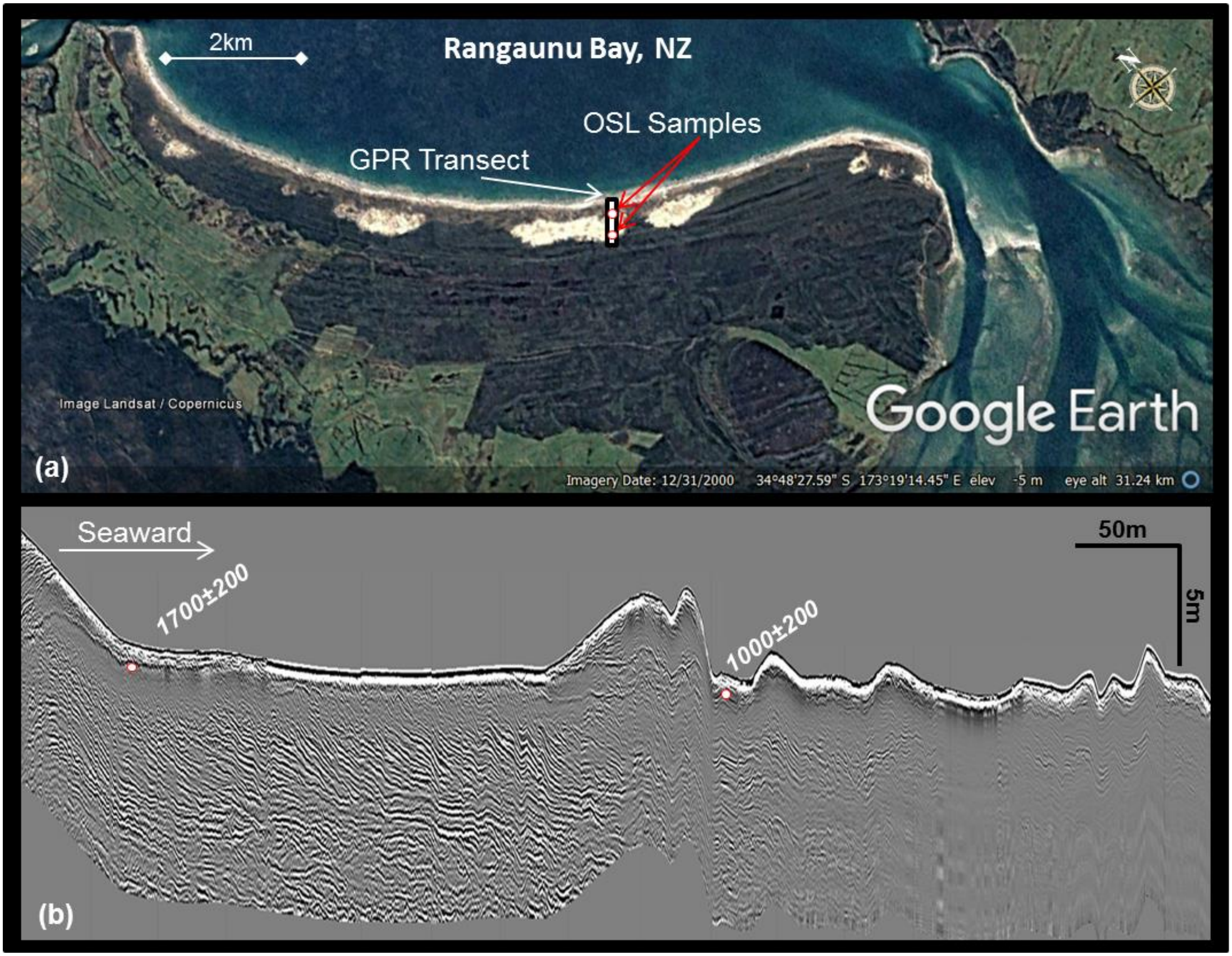
2.3 OSL

The final step is to apply a chronology to barrier formation ~~and~~ using 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~~ can bleach away light-sensitive ~~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 burial ~~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.

Collection of OSL samples in the field is relatively easy following various methods described in the literature or guidance from someone with experience; however the processing and analysis of samples requires a scientist trained in luminescence chronology (Bailey and Arnold, 2006; Huntley et al., 1985; Jacobs, 2008). Therefore, it is not within the scope of this paper to discuss how to process OSL samples (e.g. sample prep and mineral separation) or the complicated intricacies of analysis (e.g. assumptions like water content and burial history or considerations of experimental conditions and statistical models for each sample to be dated). Instead this section focuses on demonstrating the utility of OSL in barrier systems and how it can be optimized by using LiDAR and GPR to inform where samples are collected. Analysis of OSL sample is still expensive and time consuming (relative to radiocarbon), this combined with the reality that samples can be collected from anywhere within the barrier stratigraphy, demands that locations be targeted to best date the evolution or answer specific questions. Collection and analysis of LiDAR and GPR prior to OSL collection enables: 1) a thorough understanding the evolution to be constructed and questions with respect to the chronology formulated, 2) selection of the stratigraphic section to be dated, 3) location and sampling of the desired sediments using the LiDAR and GPR in the field. It can be important to know precisely what stratigraphic layer is sampled, which is why it is recommended that have the GPR in the field to locate and document the sample, especially if it is collected by vertical augur or core rather than an open trench. Another important aspect of utilizing OSL in GOaL, is reporting when the samples were measured in publications (Shen, personal communication 5 March 2018). Since the ages are refer to time before OSL measurement and there is a lag time between when the dates are published, it is significant to note this especially for younger ages to enable comparison between sites or even the same site dated at different times.

~~Before samples are collected, the evolution should be thoroughly understood from LiDAR and GPR data such that specific sample locations are targeted.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 samples 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.~~an idea

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). The OSL data revealed that the barrier has prograded at a constant rate throughout the Holocene (Figure 1c). Shell deposits within the beach facies, however, have been shown to provide similar ages to OSL dates acquired from associated beach and dune deposits (e.g. Murray-Wallace et al., 2002).


Rangaunu Bay, NZ
2km
OSL Samples
GPR Transect
Image Landsat / Copernicus
Google Earth
(a)
Imagery Date: 12/31/2000 34°48'27.59" S 173°19'14.45" E elev -5 m eye alt 31.24 km
Seaward
50m
5m
1700±200
1000±200
(b)

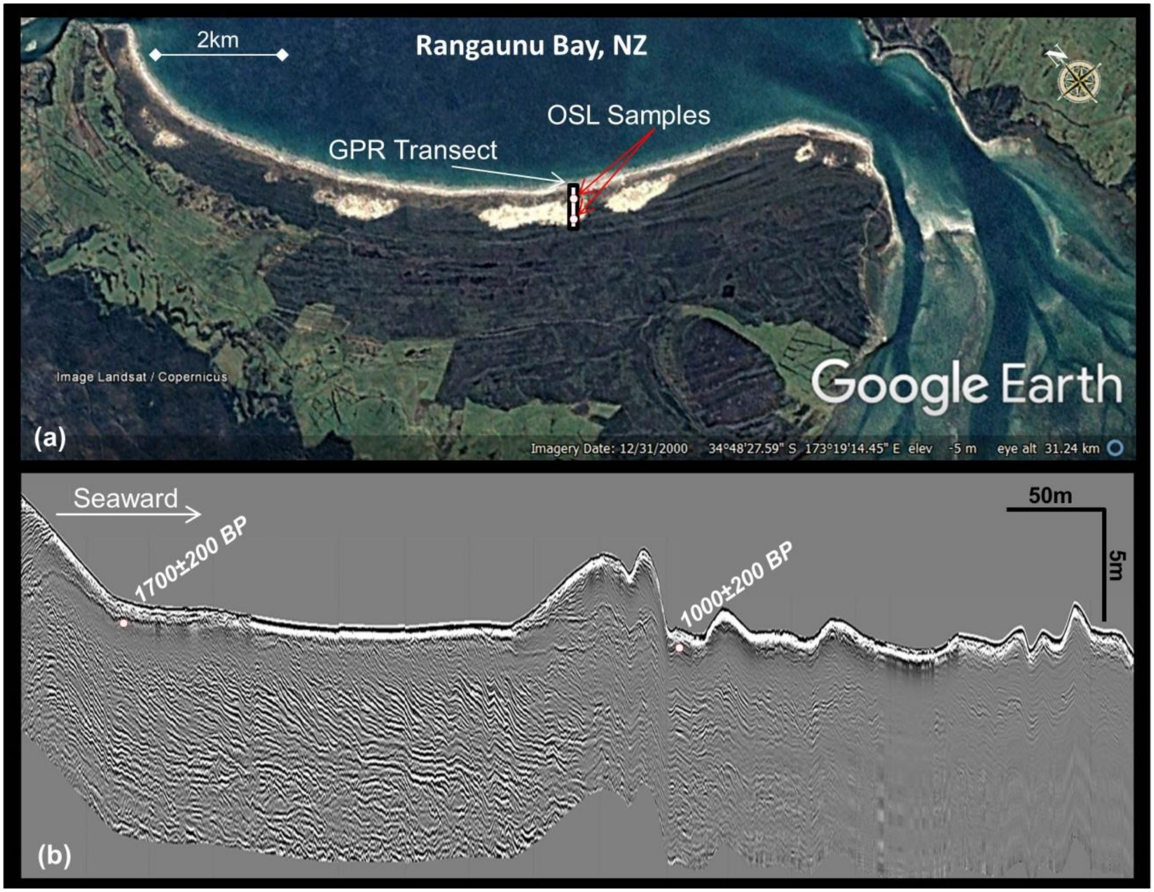


Figure 5. (a) Google Earth i~~I~~mage of East Beach, New Zealand, and the prograded barrier that it fronts. This aerial image shows the distinct change in morphology from the older vegetated foredune ridges to a large dune blowout fronted by low-lying irregular foredunes with sparse vegetation. This information was used to guide collection of the GPR to image the stratigraphy associated with these two changes in morphology (a-b). The GPR data revealed a major change in the stratigraphy from strong prograded beachface reflections to low-amplitude more chaotic reflections in the beachface. Both the morphology and stratigraphy was used to collect OSL samples to ~~, 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 (~1.7ka~~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~~~1.0ka). 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 shift 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 (Figure 5). The OSL samples were collected in 2004 and measured in 2005. ~~An OSL date of t~~The age of the last relict foredune preserved indicates that barrier prograded ~~normally~~ uniformly until at least 1,700 ~~yr BP~~years ago (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~~years ago (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)

Recently, 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~~ LiDAR of this complicated spit system ~~did not appear as an ideal site to extract a sea level history, but LiDAR~~ highlights ~~a classic~~the prograded section of the barrier targeted for GPR and OSL collection across the entire barrier, capturing a complete progradational history (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. This study, along with earlier work from North America (van Heteren et al., 2000; Rodriguez and Meyer, 2006), demonstrates~~ing~~ the potential of applying this method to regions where mid- to late- Holocene records are not as well documented and/or are debated (e.g. Dougherty, 2018)~~.~~. ~~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 complicated prograded barrier spit. Ultimately this information can be used to help forecast the evolution of this shoreline within the context of future climate change.~~

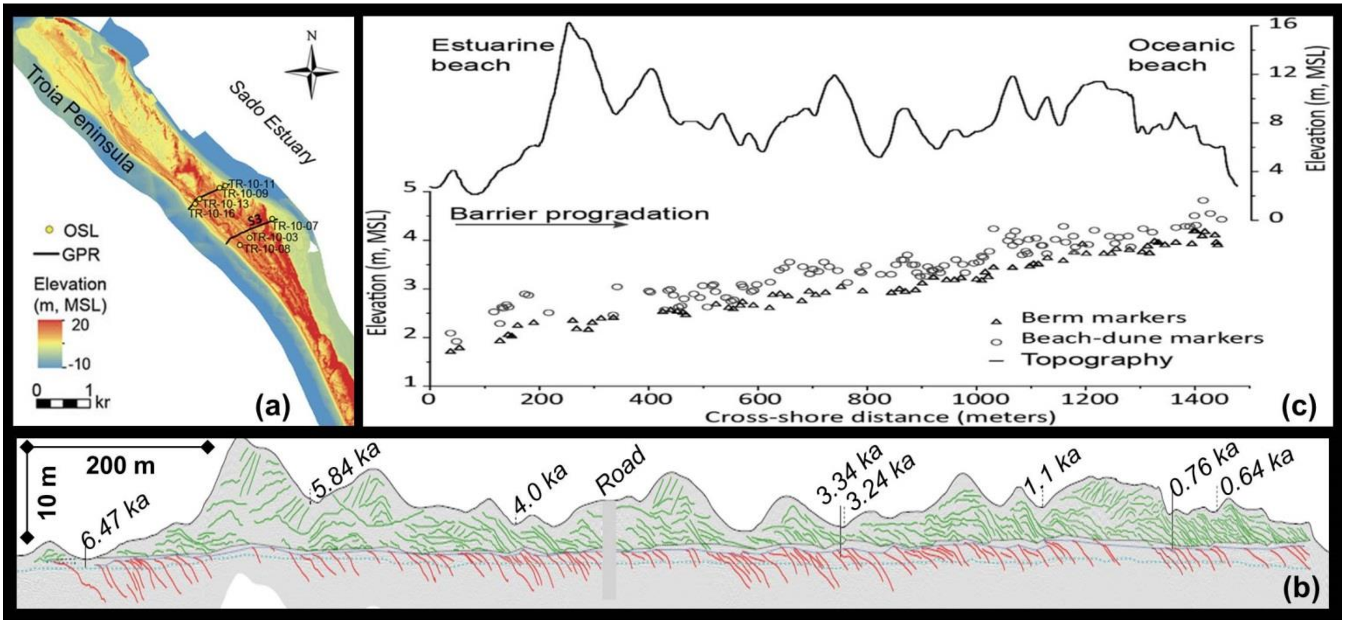
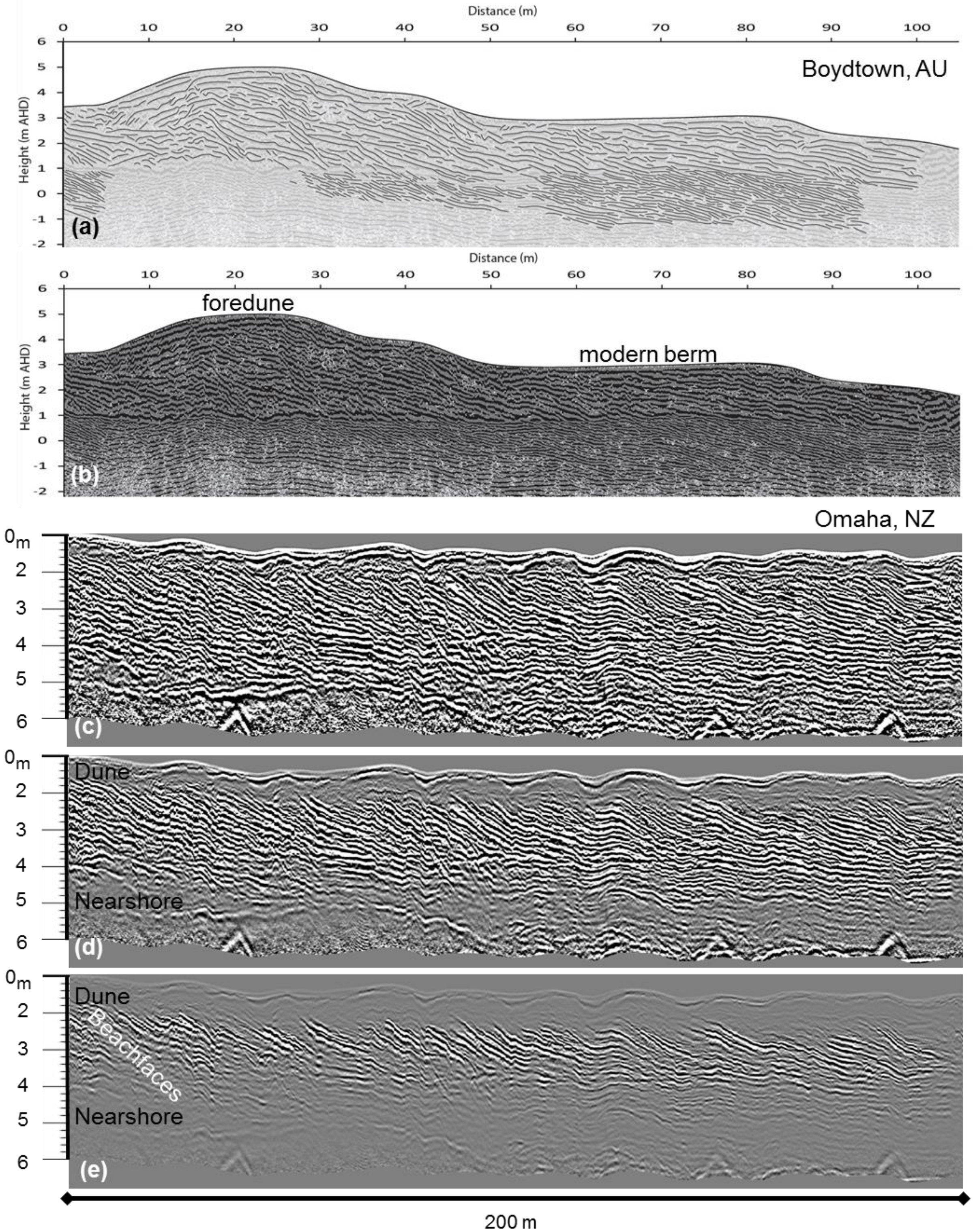


Figure 6. (a) LiDAR of Troia Peninsula, Portugal, showing locations of GPR and OSL transects. (b) GPR transect across the barrier ~~with~~ showing interpreted dune stratigraphy in green and beachfaces in red, with associated OSL ages. (c) Elevation plot of berm and beach-dune markers ~~(~~used as sea-level proxy~~)~~ (thin dashed lines above water table interpreted ~~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)~~ GPR data spanning millennia to the present-day berms were collected and 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 might overestimate the recurrence and impact of storms due ~~is likely skewed because~~ the high gain applied to ~~control is high in~~ the GPR data (e.g. Figure 7b~~c~~) as well as its ~~and~~ presentation highlighting~~the annotated data highlighted~~ every line (e.g. Figure 7a) instead of annotating interpreted facies or individual beachfaces (e.g. Figure 6b)~~amplitude peak with no regard for signal strength (e.g. Figure 7b)~~. ~~This~~ Both representations of the GPR data make~~s~~ it hard to distinguish large-scale facies boundaries (such as beach-dune interface used for sea level reconstructions), yet alone decipher ~~the beach and dune facies as well as~~ storm-eroded ~~and~~ from swell-accreted paleo-beachfaces (as demonstrated in Figure 7c-e). ~~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).~~ For example, the GPR data of the modern berm (that by its nature was constructed during swell conditions), displays similar beachface stratigraphy as GPR from below the relict beach/foredune ridges considered to only record high-energy storm conditions. Coring or augering to ground-truth what is causing these strong reflections would have shown the difference between dune and beach facies that are both represented by similar high-amplitude signatures ~~(Tamura et al.)~~. Additionally, these cores would have determined which of these ~~that not all~~ strong beachfaces reflections were caused by~~were a result of~~ erosional lag deposits (e.g. heavy-mineral, coarse-grained, and/or shell hash). Ideally, to extract a regional storm record prograded barriers: 1) LiDAR is used to determine the straightest and most continuous transect through each barrier, 2) GPR data collected across the barrier are processed and gain adjusted to highlight the strongest reflections in the beach facies as well as ground-truth to determine the paleo-beachfaces comprise storm lag deposits (e.g. Dougherty, 2014; Dougherty, 2018), and 3) finally the GPR is used to locate eroded paleo-beachfaces and acquire an OSL sample from an associated post-storm recovery deposit of the most prominent reflections (e.g. Buynevich, 2007). A discussion including these and other studies on proxy records of Holocene storm events in coastal barrier systems are nicely reviewed by Goslin and Clemmensen (2017)~~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.~~



Distance (m)
0 10 20 30 40 50 60 70 80 90 100
Height (m AHD)
6 5 4 3 2 1 0 -1 -2
Boydtown, AU
(a)
Distance (m)
0 10 20 30 40 50 60 70 80 90 100
Height (m AHD)
foredune
modern berm
(b)
Omaha, NZ
0m 2 3 4 5 6
(c)
0m 2 3 4 5 6
Dune
Nearshore
(d)
0m 2 3 4 5 6
Dune
Beachfaces
Nearshore
(e)
200 m

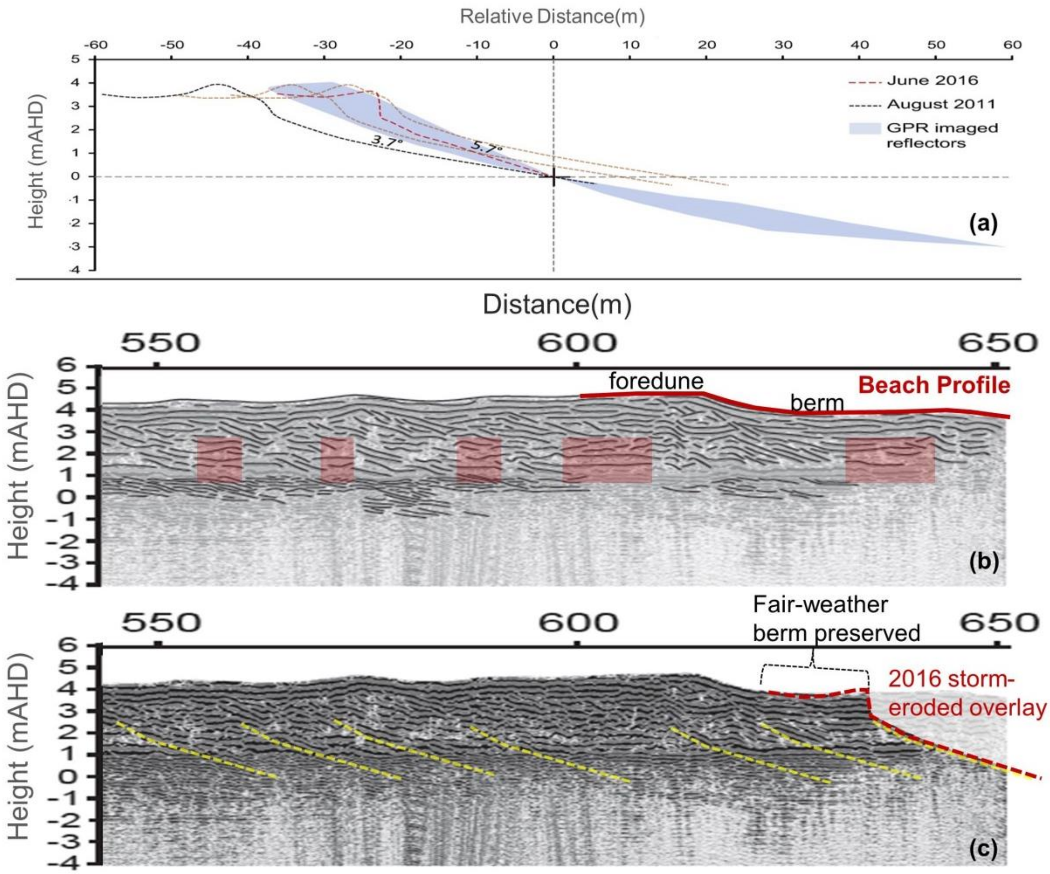


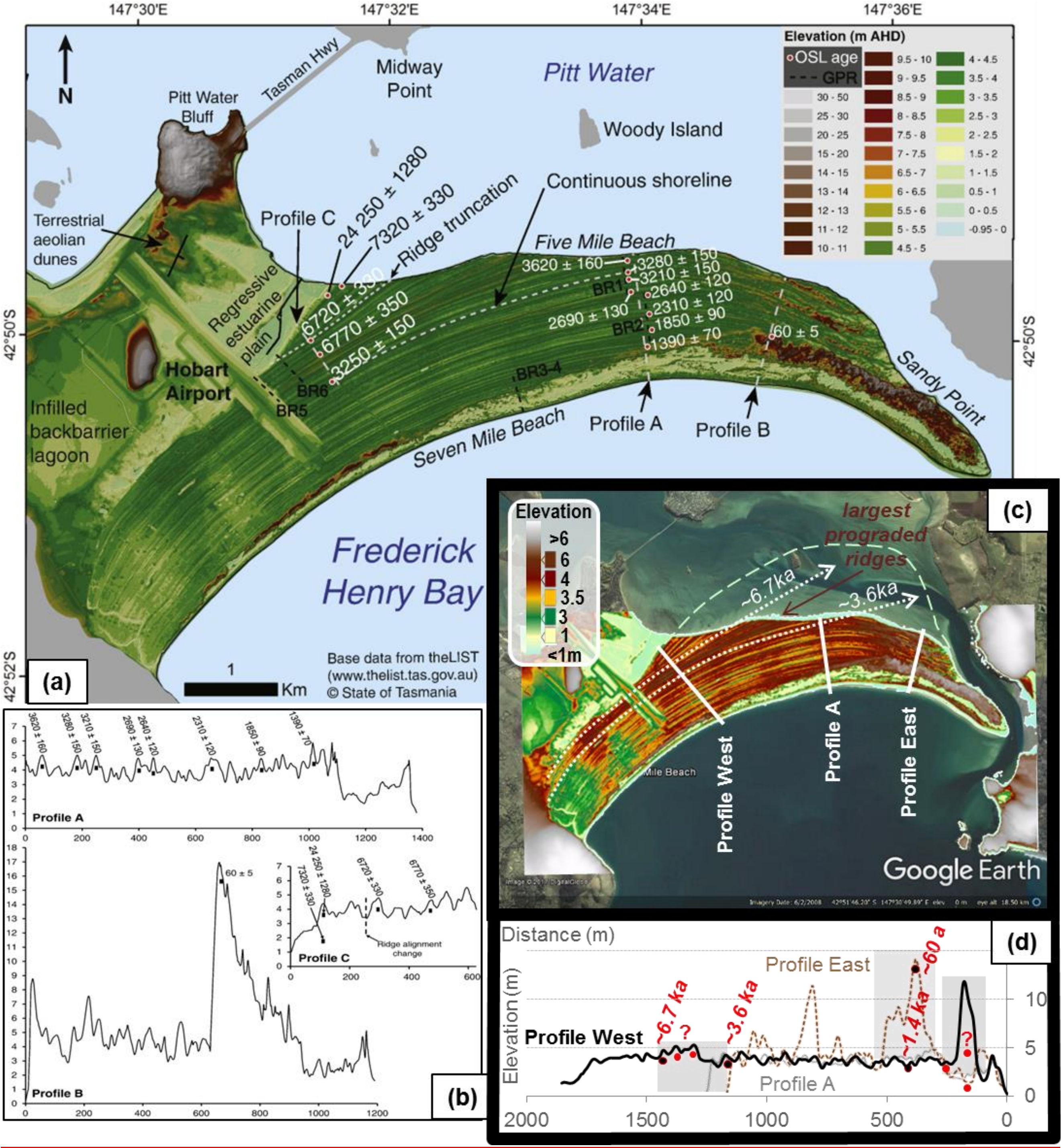
Figure 7. (a) An example of the ~~Topographic profiles of recent swell-accreted (black) and storm-eroded (red) beach geometry plotted with the range of topographic profiles extracted from the GPR (blue area) in~~ “interpreted” GPR presented in **Oliver et al. (2017b).** ~~Since the swell-accreted profile 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)** The uninterpreted ~~Interpreted GPR profile of the seaward-most portion the barrier, representing data presented in Oliver et al. (2017b)~~processed GPR data from the supplementary material showing such a high gain applied that it is hard to distinguish dune from beach facies, yet alone storm-eroded paleo-beachfaces from the swell-accreted berm stratigraphy. (c) GPR data from a prograded barrier in New Zealand (Dougherty, 2014) with a similar high gain applied. ~~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).~~ (d~~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.~~The same GPR data as (c) but with the gain adjusted so that the more homogenous dune sand is accurately represented as a low-amplitude signal, compared to the alternating layers associated with paleo-beachfaces under varying wave energies. Note this represents the best gain to map the beach-dune interface across the barrier as a proxy for sea level. (e) The same GPR as (c-d), but with the gain decreased such that the strongest reflections are highlighted, and once ground-truthed as high-energy lag deposits, can be used to ~~determine~~construct a storm record. Figure modified from Oliver et al. (2017b) and Dougherty (accepted).

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). The GOaL data was used to ~~Oliver et al. (2017a) concluded~~conclude that changes in ~~a lack of~~ sediment supply ~~caused~~ caused two pauses in progradation during~~two periods of paused progradation between~~ ~6.5-3.5ka ago and ~~6,000 and 3,000 years ago as well as over the past~~ 500a ago-present~~ years~~ (Figure 8a,b) ~~(Figure 8a and b)~~. However, gaps in the morphology, stratigraphy, and chronology coincide with these timeframes; raising the question of whether these interpreted hiatuses resulted from a lack of data ~~these two time periods lack OSL dates and GPR data impacting this hypothesis~~ (Figure 8d). The ~~gaps~~breaks 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~~ obscures features in the morphology that~~do not clearly~~ distinguish ~~major~~ changes in the evolution, ~~-~~such as the largest foredune ridges formed as the barrier prograded a minimum of 200m between ~6.5 and 3.5ka ago~~over~~ (Figure 8a~~A and B~~). To demonstrate the contrast in presentation ~~Augmenting a Google Earth image with~~ 5~~ m~~ m LiDAR, (freely accessible from Geoscience Australia at ~~(~~http://www.ga.gov.au/elvis/) was augmented with a Google Earth image (Figure 8c). This highlights not just the elevation of these larger ridges, but ~~,~~reveals that these features bifurcate to the east (indicating even greater progradation in this part of the barrier) and extend laterally to the west filling an abrupt increase in accommodation space (Figure 8c). ~~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~~ The discontinuous topographic profiles presented in Oliver et al. (2017a) not only mask the increased elevation of these prominent relict foredune ridges; but completely omits the anomalously large foredune that that formed along southeast half of the barrier over the past 500 years (Figure 8b,d). While no GPR was collected for this foredune or the one in the north, evidence of transgression exists as ~~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 is unconformabley deposited on top of the 1,400-year old low-lying foredune ~~ridge~~ (Figure 8c and d). This is an example of how despite the impressive amount of data that result from combing GOaL, significant features or gaps in data can be overlooked. Where it is not feasible to collect parts of the dataset, this absence of data should be acknowledged, addressed, and considered when discussing interpretations or conclusions as well as the certainty with which they are asserted.

Changing the display of existing LiDAR and ~~-~~extracting continuous topographic profiles from it identified gaps in the data that challenge the ~~the~~Oliver et al. (2017) conclusion that sediment supply paused with evidence that: 1) progradation likely slowed rather than stopped ~6.5-3.5ka ago and 2) transitioned to transgression in the last 500 years where it is unlikely to resume prograding during accelerated sea-level rise (Dougherty, 2018). Applying the three-step methodology presented in this paper can optimize the GOaL dataset at Seven Mile. This would not only fill the gap in knowledge with respect to barrier formation and sediment supply, but could provide insight on the unresolved sea level record in Tasmania as well as how its history impacted evolution. An ideal implementation of GOaL approach at Seven Mile is as follows: 1) Use LiDAR to identify a transect spanning the entire Holocene record that captures shifts in evolution (western profile in Figure 8c,d) and utilize areal imagery to locate the nearby road and airstrip that both provide access across the entire barrier. 2) Collect a continuous shore-normal GPR profile spanning the barrier; with additional data acquired specifically to document the anomalous morphology documenting a shift in evolution. Then ground-truth the GPR and LiDAR data using cores/augers or outcrop mapping on the eroded backside of the barrier, sediment samples, and topographic profiles. 3) Utilize the LiDAR and GPR to plan OSL sample locations that target timing of changes expressed in the morphostratigraphy and captures rates of progradation. Integrate the ~~The~~ dataset ~~can be integrated~~ for analysis after all the components have been ~~Once the data is collected,~~ processed and~~, and~~ rendered~~ the data set is then analysed~~. Use the digital elevation model from combined LiDAR and OSL data to calculate the volume of barrier sand above mean sea level to determine sediment budget over time (e.g. Dougherty et al., 2015). Combine GPR and OSL data to construct a sea level curve following published methods (e.g. van Heteren et al., 2000; Dougherty, 2014; Costas et al., 2017). ~~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, evaluate barrier formation to determine the nature of shifts in evolution through time and consider with respect to~~ring~~ any ~~past changes~~ changes identified~~with respect to~~ in ~~factors such as~~ sediment supply or sea ~~-~~level~~, storms and sediment supply~~. ~~can then provide insight on past shifts in evolution~~with the potential to ~~and the future erosion of the beach as it is impacted by climate change.~~



Pitt Water
Midway Point
Tasman Hwy
Pitt Water Bluff
Woody Island
Terrestrial aeolian dunes
Profile C
Regressive estuarine plain
Ridge truncation
Continuous shoreline
Five Mile Beach
Hobart Airport
Infilled backbarrier lagoon
Seven Mile Beach
Profile A
Profile B
Sandy Point
Frederick Henry Bay
Base data from theLIST (www.thelist.tas.gov.au) © State of Tasmania
Elevation (m AHD)
OSL age
GPR
(a)
(b)
(c)
(d)
largest prograded ridges
~6.7ka
~3.6ka
Profile West
Profile East
Google Earth
Distance (m)
Elevation (m)
~60 a
~1.4 ka

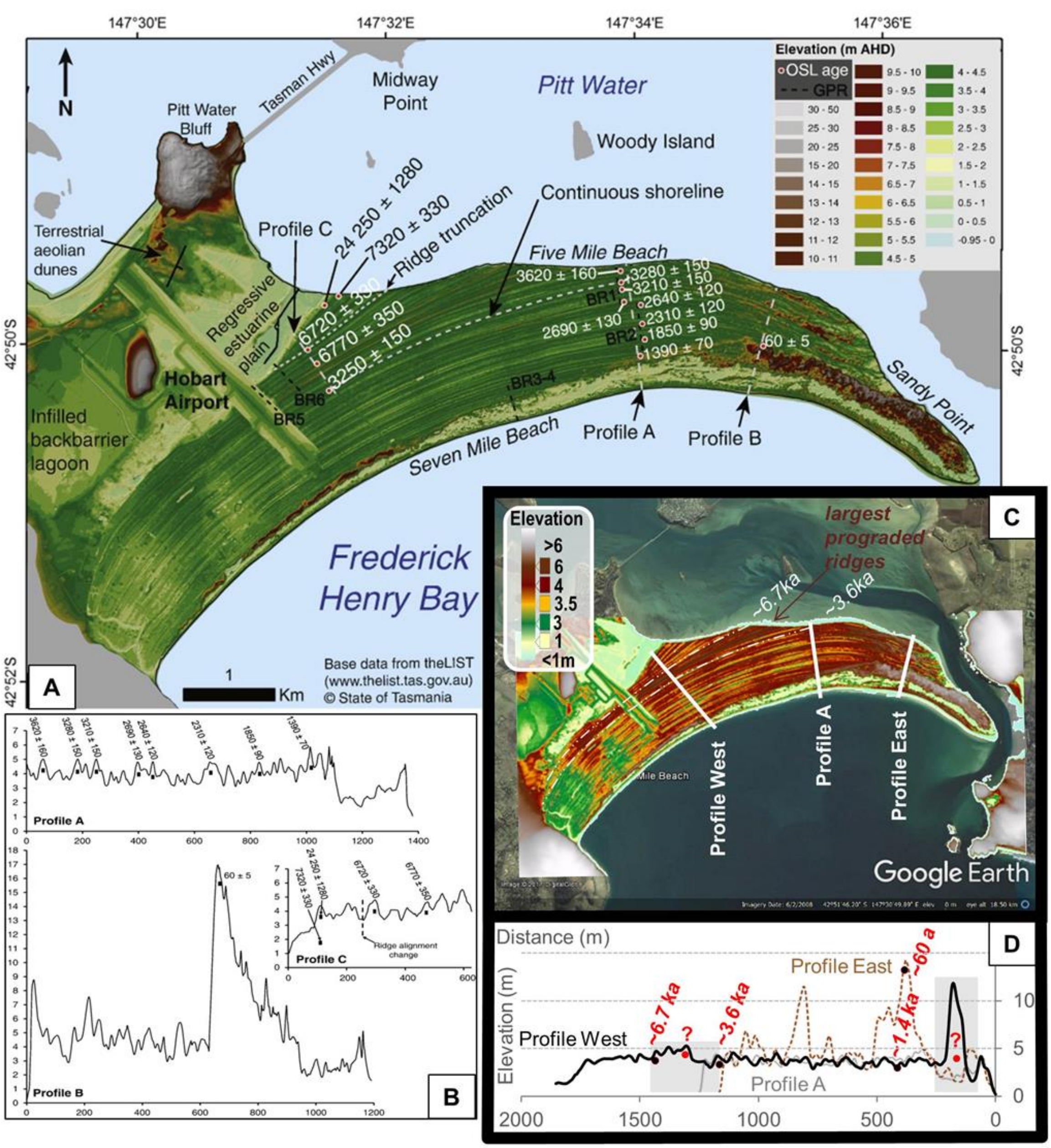


Figure 8. Morphology and chronology of Seven Mile Barrier, Tasmania, Australia. (a) LiDAR data showing the location of topographic profiles ~~(shown~~ in (b) and GPR ~~transects as~~transects as well as OSL ages ~~(~~in years~~)~~ from Oliver et al. (2017a). (c) Google Earth image augmented with 5 ~~m~~ m LiDAR (Geoscience Australia; http://www.ga.gov.au/elvis/). This combined image shows the potential size of the barrier prior to erosion (dashed green line) and ~~showing~~ the lateral extent of the largest set of prograded foredune ridges which formed between ~6.7~~,700~~ and 3.6ka~~,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 ~6.7~~,700~~ and 3~~.,~~6ka ~~00 years~~ ago and the extraordinary height of the ~~present-day~~ foredune that formed in the last 500 years, which is missing in (b). ~~lacking OSL and GPR.~~ Profile East overlay indicates relatively recent barrier transgressive evident from the large 60-year old dune ~~unconformabely~~unconformably deposited above the ~1,400-year~~,40~~ old ~~0-yr old~~ low-lying ~~ridge~~foredune.

Note the gaps in data that coincided with interpreted pauses in progradation by Oliver et al. (2017a), with grey boxes indicating an absence of GPR data and red dots indicate a lack of OSL ages~~ lacking OSL and GPR~~. Also note the vertical age discrepancy in Profile C in (b) and how GPR could help to understand these age models. Figure modified from Oliver et al. (2017a) and Dougherty (2018).

3 Concluding remarks

Utilizing GOaL on prograded barriers provides insights on coastal evolution over spatial and temporal scales spanning ~~form~~ from 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 in tuern 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) utilize LiDAR and GPR to gain a comprehensive understanding of the evolution and target the specific features needed to be dated to provide a complete chronology~~identify exactly what facies within the stratigraphy is dated and choose the most appropriate age model~~. 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 and 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.

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