Pitman Sebastian (Orcid ID: 0000-0002-3726-4427)

Title:

Storm response of a mixed sand gravel beach ridge plain under falling relative sea levels: A stratigraphic investigation using ground penetrating radar

Authors:

Sebastian J. Pitman[a*], Harry M. Jol[b], James Shulmeister[c], Deirdre E. Hart[a]

Affiliations:

a. Department of Geography, University of Canterbury, Christchurch 8041, New Zealand.
b. Department of Geography & Anthropology, University of Wisconsin-Eau Claire, Eau Claire, WI 54702-4004, USA.
c. School of Earth and Environmental Sciences, University of Queensland, St Lucia, QLD, 4072, Australia.

*Corresponding author: sebastian.pitman@canterbury.ac.nz

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Abstract:

Beach ridge stratigraphy can provide an important record of both sustained coastal progradation and responses to events such as extreme storms, as well as evidence of earthquake induced sediment pulses. This study is a stratigraphic investigation of the late Holocene mixed sand gravel (MSG) beach ridge plain on the Canterbury coast, New Zealand. The subsurface was imaged along a 370 m shore-normal transect using 100 and 200 MHz ground penetrating radar (GPR) antennae, and cored to sample sediment textures. Results show that, seaward of a back-barrier lagoon, the Pegasus Bay beach ridge plain prograded almost uniformly, under conditions of relatively stable sea level. Nearshore sediment supply appears to have created a sustained sediment surplus, perhaps as a result of post-seismic sediment pulses, resulting in a flat, morphologically featureless beach ridge plain. Evidence of a high magnitude storm provides an exception, with an estimated event return period in excess of 100 years. Evidence from the GPR sequence combined with modern process observations from MSG beaches indicates that a paleo storm initially created a washover fan into the back-barrier lagoon, with a large amount of sediment simultaneously moved off the beach face into the nearshore. This erosion event resulted in a topographic depression still evident today. In the subsequent recovery period, sediment was reworked by swash onto the beach as a sequence of berm deposit laminations, creating an elevated beach ridge that also has a modern-day topographic signature. As sediment supply returned to normal, and under conditions of falling sea level, a beach ridge progradation sequence accumulated seaward of the storm feature out to the modern-day beach as a large flat, uniform progradation plain. This study highlights the importance of extreme storm events and earthquake pulses on MSG coastlines in triggering high volume beach ridge formation during the subsequent recovery period.

Keywords: Pegasus Bay; regressive barrier; wave-built facies; post storm recovery; beach progradation

Introduction:

Beach ridges are linear, shore-parallel, progradational accumulations of sediment primarily deposited by wave action (Hesp, 1999; Otvos, 2000). They can form under the influence of calm waves from constructive swash processes, overtopping during energetic storms, or more commonly through a combination of both processes (Taylor and Stone, 1996). Under conditions where sediment supply is large and/or relative sea level is falling or stabilizing, and the nearshore is shallow with a gentle gradient, it is common for multiple beach ridges to coalesce into large beach ridge plains (Hesp, 1999; Billy *et al.*, 2014). Beach ridge formation is common in gravel environments (Kirk, 1980; Shulmeister and Kirk, 1993), where ridge formation requires moderate to high energy wave conditions in order to rework significant amounts of heavy sediment into ridges above the high tide level (Scheffers *et al.*, 2012). Although wave action is the dominant process agent responsible for the formation of beach ridge plains, the availability of finer sediments may result in a secondary, surface morphology whereby sediments are reworked by aeolian processes into foredune ridges atop the beach ridges (Hesp, 1999). This aeolian reworking process has been observed on relict mixed sand gravel (MSG) progradational plains (e.g. Shulmeister and Kirk, 1996).

Sandy beach ridges have been widely considered in the coastal literature (see Taylor and Stone, 1996), but MSG ridges have received comparatively little attention despite their abundant distribution on high latitude, paraglacial (Billy *et al.*, 2014) and fluvio-glacial (Shulmeister and Kirk, 1996) coasts. This echoes the relative dearth of research on MSG beaches globally, since the seminal observations of Kirk (1980). The situation has in part been due to complexities of measuring processes on such a steep and often energetic beach type (Blenkinsopp *et al.*, 2011), though the emergence of remote sensing techniques provides new opportunities for studying these environments (Pitman, 2014). The increasing availability and capability, coupled with reducing costs, of ground penetrating radar (GPR) systems has allowed rapid, non-invasive investigation of stratigraphy in a range of coastal environments (Neal *et al.*, 2002; Buynevich *et al.*, 2008). For MSG environments, GPR is particularly effective at detecting sharp transitions between deposits of differing grain sizes or mineralogies, including those associated with high-energy events such as coastal storm deposits (Buynevich *et al.*, 2008).

Understanding the internal architecture of features such as beach and foredune ridges provides some insight into the past geomorphic environmental conditions under which they were formed (Hesp and Short, 1999; Jol *et al.*, 2003; Buynevich *et al.*, 2008). The application of GPR techniques to beach ridges has provided more evidence that overtopping processes during storms can be an effective mechanism of building up the height of the ridge formation (Clemmensen and Nielsen, 2010). GPR studies show that coarse clastic ridges, such as those on composite and MSG beaches, generally dip seawards at moderate angles of between 3° (Billy *et al.*, 2014) to 12° (Neal *et al.*, 2002), and the combination of GPR with coring and dating techniques enables the estimation of ridge plain progradation rates (Engels and Roberts, 2005).

This paper describes the morphostratigraphy of a prograded MSG beach ridge system overlain by a sandy veneer, on the Pacific-facing east coast of New Zealand's South Island. This beach ridge study is unique in that the basal antecedent topography is that of a gravelly Pleistocene alluvium plain derived from the Southern Alps, which was subsequently eroded, reworked and prograded during the Holocene transgression and subsequent stillstand (Shulmeister and Kirk, 1993).

Study Area:

The Canterbury Plains, located on the east coast of New Zealand's South Island (Figure 1a), consist of gravelly alluvium derived from erosion of the quartzo-feldspathic metasediments (graywackes and argillites) of the Southern Alps, and were laid down over the Pleistocene (Shulmeister and Kirk, 1996). The Plains are dissected by the Banks Peninsula volcanic complex, with MSG shorelines eroding rapidly (0 to 5 $m.y^{-1}$, averaging 0.3 $m.y^{-1}$) along the 240 km Canterbury Bight south of the peninsula (Hart *et al.*, 2008). North of the peninsula a Holocene dune and swale progradation sequence, comprising of sand and silt interspersed by river gravels (Figure 1b), occupies the surface of the plain in southern Pegasus Bay (Blake, 1968). Sea levels in this region are thought to have stabilised around their current level c.6,500 years before present (Figure 2), during a mid-Holocene highstand (Clement *et al.*, 2016). At the time of European colonisation of the area around two centuries ago, much of the coastal reaches of the Canterbury Holocene plain were comprised of an interlinked series of river-mouth lagoons, inter-fan coastal lakes, and swampy wetlands, fringed by coarse clastic beaches and barrier beaches (Kirk and Lauder, 2000).

The contemporary beaches of Pegasus Bay are relatively stable and sandy in the south, which is sheltered from southerly swells by the peninsula, grading to erosional and composite and then MSG along the more exposed northern third of the bay. Our study site sits towards the southern extent of the Pegasus Bay MSG beaches, 1 km north of the small braided Kowai River and 10 km north of the slightly larger Ashley River (Figure 1). The site lies 23 km north of the current position of the larger braided Waimakariri River and beyond the extent of its Pleistocene fan. The site has also experienced c.15 m of shoreline erosion over the last 22 years (Figure 3). There has been significant investigation of the evolution of this northern part of the Pegasus Bay coastal plain through case studies using morphological mapping and sediment coring (Shulmeister and Kirk, 1993, 1996, 1997), but no attempts have been made to image transects of the subsurface stratigraphy.

Pegasus Bay has a globally unusual tidal regime in that the perigean-apogean variations are more pronounced here than spring-neap cycles (Byun and Hart, 2015), with an average tidal range of c.2 m. Waves generally propagate from the south or southeast, with long term average significant wave heights of 2 m and a mean wave period of 6.5 secs (Author analysis of wave buoy data). These waves refract around Banks Peninsula, creating a reverse eddy that helps drive net southward sediment transport along the coastline of southern Pegasus Bay, nourishing New Brighton Spit. Sand from the Waimakariri River in central Pegasus Bay dominates the sheltered southern bay's sediment budget, with this large braided river's substantial gravel bedload component currently trapped within its low gradient, lower plains reaches, from where it is artificially extracted to prevent channel aggradation and river avulsion that characterised the river's previous behaviour. The Ashley River is a sediment transport direction hinge point, with northerly locations experiencing northwards sediment transport. The largest storm events to affect the Pegasus Bay coastline are generated by north-easterly winds associated with localised sea breezes or low pressure systems tracking down the eastern NZ coastline (Stephenson and Shulmeister, 1999), though in the northern part of the bay, southerlies may have more impact due to the shelter afforded by the headland outcrops in the north as well as the reduced sheltering from Banks Peninsula compared to in the south.

Methods:

A GPR profile was measured along a shore-normal beach access track at the study site (Figure 1c), perpendicular to the general direction of progradation of the plain. The profile extended from the shoreline mean high water spring tide (MHWS) level in the east, for a distance of 370 m inland. Data collection was achieved over two days, with an initial test profile extending 130 m from the MHWS mark on 6 Jun 2018, which was subsequently extended by 240 m on 2 Jul 2018. There was 21 mm of rainfall in the 7 days preceding the first survey, and no recorded rainfall in the 7 days prior to the second survey. Small patches of surface water were visible near the transect line during the first survey, but not on the transect itself. The results suggest these were isolated puddles, and not indicative of raised groundwater, with no detectable adverse effect on data acquisition. The study site was dry during the second survey.

The profiles were shot using a Sensors & Software pulseEKKO GPR system with both 100 and 200 MHz antennae. For 100 MHz operation, an antennae separation of 1 m with 0.25 m step size was used, whereas 200 MHz operations utilised a 0.5 m separation with 0.1 m step size. Antennae separation refers to the fixed distance between transmitter and receiver and is a parameter that controls depth resolution, with poorer resolution as separation increases (Jol and Bristow, 2003). Step size refers to the interval along a transect at which measurements were taken, and therefore dictates horizontal resolution. Recommended step size varies with antenna frequency, and the step sizes used here were selected to approximate the Nyquist sampling interval, which represents one-quarter of the distance of the wave length in the ground, in order to accurately resolve sub-meter sedimentary structures (Bristow, 2009). Common midpoint surveys (Annan, 2009) collected in the field were analyzed to determine a near surface velocity of 0.09 m/ns which was used to calculate depth. Topography along the

GPR line was collected using a laser level to geometrically adjust the resulting transect. The digital profile was processed using pusleEKKO software and applied an automatic gain control, dewow filter, trace-to-trace and down-trace averaging to the wiggle trace plot (Cassidy, 2009). Automatic gain control is a method of amplifying features at depth in the trace, although this gain operates indiscriminately on both signal and noise. Dewow processing is the application of a basic running average filter to remove the initial DC signal component in the trace (Cassidy, 2009). Trace-to-trace and down-trace averaging involves the application of simple 2D spatial and temporal filters, respectively (Neal, 2004). These filters are applied to remove high frequency noise from the signal and highlight subsurface stratigraphy.

The pulseEKKO GPR system provides real time images of the subsurface structure, which allows for coring targets to be identified in the field. This resulted in three sites being identified for hand coring, to establish the structure of the initial 1 – 2 m of the subsurface. An extensive truck-mounted coring operation has previously been conducted in the area just south of the Kowai River (Shulmeister and Kirk, 1993), such that the hand cores extracted as part of the current study could be used to test if a similar stratigraphic structure was present at our study site. The earlier truck mounted coring exercise proved tricky since the open-work nature of the gravels made core recovery difficult, but a clear distinction was able to be drawn between shallow shoreface beds, thicker marine sands and gravels from the nearshore, and an underlying gravel and sand lag layer from the mid-Holocene transgression.

Results:

GPR transects along the Holocene progradation plain north of the Kowai River were used to determine the stratigraphy of the deposits. Five stratigraphic units were distinguished from interpretation of both the 100 MHz (Figure 4a) and 200 MHz (Figure 4b) transects, with the area broadly characterised by sequential MSG beach ridges, prograded eastwards towards the coast (Figure 4c). Across the entire surface of the transect lies a thin (c.1 m) veneer of fine sandy sediment (U1). At 100 and 200 MHz frequency, the air and ground wave in the GPR return slightly obscures this surface layer (Figure 4), but its presence was confirmed visually and through coring (Figure 5). Along the most landward part of the GPR transect (i.e. from 0 to >100 m), the U1 surface is primarily comprised of coarse sand, with a surface layer of soil in the vicinity of a small stream. Along the length of the transect this U1 layer was at times interrupted by thin lenses of MSG deposits, and in all cases was underlain by a layer of large gravel clasts, impenetrable by hand coring (Figure 5). The depth of the U1 to underlying gravel interface varied from 1 to 1.25 m below the surface, with the deepest sections evident at the most offshore extent of the transect, coincident with the back of the modern day foredune. This layer was associated with a transition from linear horizontal bedding of fine sand sediments (U1) towards seaward-dipping gravels (U2), or horizontal (U3) lagoonal bedding as revealed by the GPR (Figure 4). At depth, a basal unit (U4) was evident, with slight landward dipping beds. This is potentially evidence of an erosional truncation surface representative of the shoreline eroding backwards towards the Pleistocene cliff (Figure 1), prior to the Holocene transgression. Along the GPR transect the ground surface sloped gradually upwards towards the coast, rising 2.6 m in elevation between its landward end to a maximum atop the modern foredune and beach complex (U5), before dipping seaward again across the contemporary beach. However, most of this surface slope is accounted for by changes in thickness of the sand veneer (U1) and the active dune (U5), with underlying gravel units (U2 and U3) displaying a near horizontal interface with the surface layer.

The dominant subsurface feature occurring between 100 and 325 m along the transect is the series of progradational beach faces (U2) that dip seawards, typically at angles of around 7° (Figure 4c). Overlain by the U1 fine sediment layer, these U2 beach faces appear to end at depths of 4 to 5 m in a near horizontal subsurface. This apparent horizontal sublayer might represent the saltwater table beneath the plain, acting to attenuate the GPR signal, as opposed to an actual change in sediment deposit layering. There are occasional significant erosive scarps present in the dataset (Figure 6a), characterised by a sigmoidal form that truncates the landward beach ridges, and dips seaward at steeper angles (c. 11°). Nearest the surface, overwash deposits associated with these large events have also been preserved (Figure 6b). The steep erosive face is continuous to depths in excess of 4 m, after which it appears to downlap onto a basal unit. In the seaward direction, beach recovery is evident in subsequent onlapping, lower gradient (c. 3°) ridges. The storm event is also sufficient to leave a surface signature in that the area directly above the top of the scarp slope shows a noticeable dip in elevation/swale, and the surface above the area of beach recovery shows increased ridge growth. There are two such significant events preserved in the stratigraphic record, located within U2 at 125 m and 250 m along the profile (Figure 4).

Unit U3 is an isolated area of hummocky reflections, varying between near horizontal planar cross to trough crossed beds. The signal underneath U3 is rapidly attenuated, other than one anomaly (A1) associated with interference from overhead power cables (Figure 4c). U4 is the only unit that shows predominantly landward sloping bedding that uplaps into the well-formed beach ridge features of U2.

The surface layer over the active foredune (U5) shows two sand veneers (U1), which are not found elsewhere on the beach ridge plain. The stratigraphy shows significant foreslope accretion, but little to no evidence of vertical aggradation or rear-slope accretion (Figure 7). The dune signal truncates the clear beach ridge signal on the landward side, and shows evidence of probable wave reworking on the coastal side.

Discussion:

Site Overview

The stratigraphic record along this transect north of the Kowai River is dominated by a sequence of paleo-beach faces, which generally dip seawards at angles of around 7°, and a landward dipping deflation surface similar to Type 1 beach ridges described by Carter (1986). Coring during this study indicates that the ridges are composed of MSG sediments, which reflects the composition of the modern day beach. Additionally, the gradient of the paleo beach faces (7°) is comparable to that of the modern day beach (Figure 3), and well within the normal range of contemporary mixed sediment beaches (Jennings and Shulmeister, 2002). The comprehensive coring programme of Shulmeister and Kirk (1993) confirmed a thick (c. 5 m) sedimentary unit consisting of matrix-supported to openwork rounded gravel, with abundant shelly material, which is coincident to the depths at which we observe beach ridge stratigraphy. Furthermore, Shulmeister and Kirk (1993) also identified consistent overwash records, consisting of 0.2 to 0.3 m thick bands of coarse discs in a sand matrix, overlaying 0.5 m of coarse sand and fine gravel, similar to those observed in this study (Figure 5). Shulmeister and Kirk (1993) were able to identify a marine sand unit at depths between 8 and 12 m in their site, alongshore from the current study location. Their sample yielded an age of 4138 ± 71 yrs BP, and was interpreted as a sandy aggradation of the nearshore prior to emplacement of regressional ridges. The recent work of Clement et al. (2016) shows that over the last 4000 years, sea levels in Canterbury (Figure 2) have been steadily falling as a result of ocean siphoning (Mitrova and Peltier, 1991). Therefore, the paleo-beach faces outlined in the current study (U2), which are shallower than this previously identified marine sand unit, can be interpreted as forming under isostatic sea level fall.

The beach ridges in this study are unusual in that there is very little surface signature of the prograding ridge plain, unlike other well documented examples (Engels and Roberts, 2005; Clemmensen and Nielsen, 2010; Billy *et al.*, 2014; Montes *et al.*, 2018) where large ridges and swales with wavelengths of c.100 m are described. Landward of the study area there is a large sand dune ridge measuring > 200 m front to back, and standing 6 – 8 m high (Figure 1c). Furthermore, pronounced ridge and swale topography is evident between the sand dune and the Pleistocene cliff (Figure 1c), as well as south of the Kowai River on the Holocene progradation plain, described in a previous investigation by Shulmeister and Kirk (1993), and attributed to prolonged periods (10^2 – 10^3 years) of stable shoreline position. The large sand dune ridge slightly shoreward of the study area (Figure 1c) is remarkably conspicuous within the context of the wider area, and demarcates the onshore extent of the progradation plain described here.

A static sea level explains the formation of a barrier feature at the location of the sand dune ridge, but does not fully explain the well-developed sand dunes in an area otherwise dominated by gravels. One possible explanation for both the extreme sand dune growth and the subsequent featureless progradation of gravel beach faces is that it resulted from tectonic activity. It is expected that rapid sedimentation at the coast would follow the catastrophic failure of a large regional fault such as the Hope or Porter's Pass Faults. Failures of the Alpine Fault have been observed to create rapid dune development and progradation on the west coast of New Zealand in locations that do not experience rapid dune growth under normal conditions (Wells and Goff, 2007; Goff, 2008; Nobes *et al*. 2016). Rapid fluvial transfer of fine materials from the Southern Alps to the east coast through rivers such as the Waimakariri has also been proposed (McFadgen and Goff, 2007). The immediate impact of such an event would be rapid dune formation following the input of finer material to the coastal zone. Following the rapid throughput of finer materials, a high volume of bedload (gravels) dislodged by the earthquake moves through the system, and impacts at the coast are evident over the next 100-200 years (Goff, 2008). This sequence of morphological evolution following a large scale Alpine Fault failure is consistent with the topographic evolution of the current study site, whereby a conspicuous single ridge of large dunes has formed, followed by a progradational beach ridge sequence as an excess of coarser gravel sediments are able to make their way through the system. This infers that the progradational sequence would be rapid, resulting in the lack of surface expression that we observe at our site. This is similar to a study by Shepherd (1991) which showed the formation of much smaller dune ridges than would typically be expected, and which he attributed to rapid progradation resulting in the features having less time to form. At this stage rapid progradation is only a hypothesis until the paleo beach faces are dated. Our planned future research is to undertake comprehensive dating across the progradation plain in order to establish the relative rates of progradation.

In addition to isostatic sea level fall from ocean siphoning, there is also likely a component of tectonic uplift the area related to the Kowai anticline (Campbell *et al*., 2012). Although the rate of uplift for this specific area has not been quantified, regional uplift in the area adjacent to the north of this progradational plain have been estimated at 0.5 – 1.0 mm/yr (Nicol *et al*., 1994). It is likely that the effect of this uplift is dampened in the immediate study area, because the Kowai anticline is significantly less active than both the Waipara syncline and Kate anticlines, upon which the regional estimate is based. Therefore, whilst we can be confident that relative sea levels were falling during the late Holocene progradation sequence outlined in U2, we cannot from our records differentiate between the respective impacts of isostatic adjustment and localised tectonic uplift.

We also note that continuous sediment supply from the Ashley and Waimakariri Rivers will have gradually shallowed Pegasus Bay through the infilling of accommodation space. The effect of this would have been to displace wave breaking further offshore and reduced energy levels at the shoreline, which appears similar in the stratigraphy to a relative sea level fall. Given that both isostatic sea-level fall and local tectonic uplift is occurring, the sedimentary infilling mechanism is not required for the formation of the beach ridges and the prograding coastal plain. It is likely that the progradational facies observed in the GPR transects are in fact gravelly berm ridges, deposited on the backshore by high-energy wave processes (Scheffers *et al.*, 2012; Nielsen *et al.*, 2017). The subsequent fall in sea level (or offshore displacement of wave breaking through infilling) means they are unable to build in sufficient height, and therefore the beach progrades laterally, marked by the formation of new berm features.

Aside from the progradational plain, we also observed a horizontal bedding unit (U3) which we interpret as indicative of the historical presence of a back-barrier environment that was subsequently disconnected from the sea. Historical mapping to the south of the Kowai River showed extensive marshland behind the beach present in the 1860s, but the maps pertaining to the current study site from that period gave no description on the composition of vegetation or marshland (Johnston, 1961). The mouth of the Kowai River has periodically become blocked, and since 1976 has been artificially breached in order to prevent hinterland flooding (Shulmeister and Kirk, 1997), supporting the assumption that over the Holocene the environment conditions were correct to create a back barrier environment such as that observed in Unit U3 (Figure 4). Additionally, the presence of back-barrier sediments has been confirmed south of the study site by previous coring programmes (Shulmeister and Kirk, 1993).

Storm response

The only occurrence of a prominent change in topography is associated with a large-scale Holocene erosion event, evident in the stratigraphy (Figure 6). No other events of this magnitude are preserved in the stratigraphy, and therefore this can be interpreted as an extreme event, although without access to dating no estimation of return period is possible. The topographic signature is that of a slight depression or swale above the scarped beach, and a prominent ridge offshore over the area of beach recovery. The scarped beach facies in the stratigraphy dip seawards at angles of 11°, much steeper than the truncated beach faces evident towards the hinterland or the beach recovery facies immediately offshore, which all dip seawards at c. 3° (Figure 6). During the course of a storm on MSG beaches, the fine sediment is preferentially removed from the beachface, and the proportion of gravel size sediments left on the beach post storm has been shown to increase by between 6 and 10 % (Bergillos *et al.*, 2016). The angles observed in the stratigraphy compare with observations of the modern day beach in its erosional state, where gradients are typically 11° (Figure 3), with some post storm upper-beach gradients reaching 17°, such as the Nov 2001 profile. It would be expected that beaches undergoing progradation would display shallower gradients, such as the 7° observed in the progradational unit (U2) here. The overwash laminae from the storm event in Figure 6 extends towards the hinterland and overlay on top of the back-barrier lagoon unit (U3). The impact of the event was to retrograde the absolute shoreline position and lower the overall elevation of the barrier, which is a common occurrence for storm events on coarse clastic coasts (Carter and Orford, 1981).

The beach recovery resulted in a prominent ridge forming approximately 15 m offshore of the barrier crest. The ridge is 0.5 – 1 m higher in elevation than the overwashed barrier, and appears to have formed as a series of successive berm deposits under calm conditions (Hine, 1979; Sunamura and Takeda, 1984; Otvos, 2000). Progressive sigmoidal laminations of berm deposit are evident in the stratigraphy (Figure 6), with a preferential seaward dip and evidence of lower erosive surfaces caused by erosion of the lower beachface after berm deposition (Montes *et al.*, 2018). This same cut and fill response has been observed as a driver of beach ridge formation over a large Quaternary sand beach ridge plain (Dougherty, 2018), whereby storm erosion punctuates the progradation sequence, lowers the elevation of the beach and onshore migration of bars during the recovery stage creates the new beach ridge. The ridge at this location is built to a higher elevation than any other in the profile, which is likely a combination of the large return period of the event, the resulting large amount of sediment in the nearshore, and a falling relative sea level. The magnitude of fines preferentially eroded during the storm are therefore abundantly available post-storm to be reworked into an aeolian cap. Under normal (static) sea level conditions, this large ridge would normally be overwashed, lowering its elevation and filling in the swale behind it. However, under the falling relative sea level scenario, the ridge is abandoned in its predominantly accretive state (Dougherty, 2018), with very little evidence for overwash processes reworking the accreted sediment. As sediment supply in the nearshore returns to normal following the pulse from the storm input, the system returns to a gradual progradation as successive swash bars are welded to the beach face and sea levels continue to fall (Carter, 1986). Although the authors agree the most likely cause of the observed scarp is through storm action, they also acknowledge the possibility of causation by some other high-energy event such as tsunami, given the tectonic setting of the South Pacific and the number of tsunami deposits preserved in the archaeological record (McFadgen and Goff, 2007; Nobes *et al*. 2016).

Conclusions:

This paper has described the internal stratigraphy of a Holocene MSG progradational beach ridge system in Canterbury, New Zealand. The progradation plain shows evidence of a well-developed back barrier lagoon environment and well-preserved paleo beach faces. The surface topography of the progradation plain is largely flat and featureless, which is unusual for beach ridge progradation sequences. Here, we hypothesis that this may be the result of rapid progradation following high-energy tectonic activity such as failures of the Hope or Porter's Pass Faults. Failures in these fault systems may initially result in rapid sand dune growth through the input of fines to Pegasus Bay, followed by large inputs of gravel sediments to the coastline over the subsequent 200 years. This increase in sediment supply could result in the rapid progradation hypothesised here, however, a comprehensive coring and dating study is required to ascertain actual rates of progradation across the plain.

A large-scale storm event and the subsequent beach recovery sequence is stratigraphically preserved, and presents a unique insight into how MSG beaches recover from high return period storm events under conditions of falling relative sea levels. In this example, the storm event caused an overall lowering of barrier elevation, and resulted in large-scale overwash laminations reaching the back barrier lagoon. Crucially, the event was of significant magnitude that it has left a depression in the topography still visible today. This has been interpreted as a high magnitude offshore movement of sediment to the nearshore. In the subsequent recovery phase, a beach ridge was seen to form through the consolidation of several swash bars on the upper beachface. There was sufficient sediment available to build a significantly higher new barrier offshore of the pre-storm barrier profile. The clear implication from this study is that large-scale storm events, especially under background conditions of falling relative sea level, can be the trigger for significant beach ridge growth in the immediate recovery phase, because of the magnitude of sediment removed to the nearshore and subsequently available for berm or ridge formation as it is reworked onshore.

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References:

Annan, A. P. (2009) ‘Electromagnetic principles of ground penetrating radar’. in Jol, H. M. (ed.) *Ground Penetrating Radar Theory and Applications*. Elsevier Academic Press, pp. 3–40.

Bergillos, R. J., Ortega-Sánchez, M., Masselink, G. and Losada, M. A. (2016) ‘Morpho-sedimentary dynamics of a micro-tidal mixed sand and gravel beach, Playa Granada, southern Spain’, *Marine Geology*. Elsevier, 379, pp. 28–38. doi: 10.1016/J.MARGEO.2016.05.003.

Billy, J., Robin, N., Hein, C. J., Certain, R. and FitzGerald, D. M. (2014) ‘Internal architecture of mixed sand-and-gravel beach ridges: Miquelon-Langlade Barrier, NW Atlantic’, *Marine Geology*. Elsevier, 357, pp. 53–71. doi: 10.1016/J.MARGEO.2014.07.011.

Blake, G. J. (1968) ‘The rivers and the foreshore sediment of Pegasus Bay, South Island, New Zealand’, *New Zealand Journal of Geology and Geophysics*, 11(1), pp. 225–235. doi: 10.1080/00288306.1968.10423687org/10.1080/00288306.1968.10423687.

Blenkinsopp, C. E., Turner, I. L. and Masselink, G. (2011) ‘Swash zone sediment fluxes: Field observations’, *Coastal Engineering*, 58, pp. 28–44.

Bristow, C. (2009) ‘Ground penetrating radar in aeolian sand dunes’. in Jol, H. M. (ed.) *Ground Penetrating Radar Theory and Applications*. Elsevier Academic Press, pp. 273–297.

Buynevich, I. V., Jol, H. M. and FitzGerald, D. M. (2008) ‘Coastal Environments’, in Jol, H. M. (ed.) *Ground Penetrating Radar Theory and Applications*. Elsevier Academic Press, pp. 299–322.

Byun, D.-S. and Hart, D. E. (2015) ‘Predicting Tidal Heights for New Locations Using 25 h of in situ Sea Level Observations plus Reference Site Records: A Complete Tidal Species Modulation with Tidal Constant Corrections’, *Journal of Atmospheric and Oceanic Technology*, 32(2), pp. 350–371. doi: 10.1175/JTECH-D-14-00030.1.

Campbell, J., Pettinga, J. and Jongens, R. (2012) ‘The tectonic and structural setting of the 4 September 2010 Darfield (Canterbury) earthquake sequence, New Zealand’, *New Zealand Journal of Geology and Geophysics*. Taylor & Francis Group, 55(3), pp. 155–168. doi: 10.1080/00288306.2012.690768.

Carter, R. W. G. (1986) ‘The morphodynamics of beach-ridge formation: Magilligan, Northern Ireland’, *Marine Geology*. Elsevier, 73(3–4), pp. 191–214. doi: 10.1016/0025-3227(86)90015-0.

Carter, R. W. G. and Orford, J. D. (1981) ‘Overwash processes along a gravel beach in south-east Ireland’, *Earth Surface Processes and Landforms*. Wiley-Blackwell, 6(5), pp. 413–426. doi: 10.1002/esp.3290060503.

Cassidy, N. J. (2009) ‘Ground penetrating radar data processing, modelling and analysis’. in Jol, H. M. (ed.) *Ground Penetrating Radar Theory and Applications*. Elsevier Academic Press, pp. 141–176.

Clement, A. J. H., Whitehouse, P. L. and Sloss, C. R. (2016) ‘An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago’, *Quaternary Science Reviews*. Elsevier Ltd, 131, pp. 73–101. doi: 10.1016/j.quascirev.2015.09.025.

Clemmensen, L. B. and Nielsen, L. (2010) 'Internal architecture of a raised beach ridge system (Anholt, Denmark) resolved by ground-penetrating radar investigations', *Sedimentary Geology*. Elsevier B.V., 223(3–4), pp. 281–290. doi: 10.1016/j.sedgeo.2009.11.014.

Dougherty, A. J. (2018) 'Prograded coastal barriers provide paleoenvironmental records of storms and sea level during late Quaternary highstands', *Journal of Quaternary Science*. Wiley-Blackwell, 33(5), pp. 501–517. doi: 10.1002/jqs.3029.

Engels, S. and Roberts, M. C. (2005) 'The Architecture of Prograding Sandy-Gravel Beach Ridges Formed During the Last Holocene Highstand: Southwestern British Columbia, Canada', *Journal of Sedimentary Research*, 75, pp. 1052–1064. doi: 10.2110/jsr.2005.081.

Goff, J. (2008) 'The effects of rapid and catastrophic sedimentation in tectonically active areas', *Sediment Dynamics in Changing Environments*, IAHS Publication 325, pp. 458–461.

Hart, D. E., Marsden, I. E. and Francis, M. (2008) 'Coastal Systems', in Winterbourne, M. et al. (eds) *The Natural History of Canterbury*. 3rd edn, pp. 653–684.

Hesp, P. (1999) 'The beach backshore and beyond', in Short, A. D. (ed.) *Handbook of Beach and Shoreface Morphodynamics*. Chichester: Wiley, pp. 145–169. Available at: https://ci.nii.ac.jp/naid/20000577475/ (Accessed: 10 July 2018).

Hesp, P. and Short, A. D. (1999) 'Barrier morphodynamics', in Short, A. D. (ed.) *Handbook of beach and shoreface morphodynamics*. Chichester: Wiley, pp. 307–333.

Hine, A. (1979) 'Mechanisms of berm development and resulting beach growth along a barrier spit complex', *Sedimentology*. Wiley/Blackwell (10.1111), 26(3), pp. 333–351. doi: 10.1111/j.1365-3091.1979.tb00913.x.

Jennings, R. and Shulmeister, J. (2002) 'A field based classification scheme for gravel beaches', *Marine Geology*, 186(3–4), pp. 211–228.

Johnston, W. B. (1961) 'Locating the Vegetation of Early Canterbury: A Map and the Sources', *Transactions of the Royal Society of New Zealand: Botany*, 1(2), pp. 5–15.

Jol, H. M. and Bristow, C. S. (2003) 'GPR in sediments: advice on data collection, basic processing and interpretation, a good practice guide', in Bristow, C. S. and Jol, H. M. (ed.) *Ground penetrating radar in sediments*, Geological Society: London, Special Publication 211; 9-28.

Jol, H. M., Lawton, D. C. and Smith, D. G. (2003) 'Ground penetrating radar: 2-D and 3-D subsurface imaging of a coastal barrier spit, Long Beach, WA, USA', *Geomorphology*, 53(1–2), pp. 165–181. doi: 10.1016/S0169-555X(02)00352-5.

Kirk, R. and Lauder, G. (2000) *Significant coastal lagoon systems in the South Island, New Zealand. Department of Conservation, Science for Conservation Report 146, Wellington, NZ.*

Kirk, R. M. (1980) 'Mixed sand and gravel beaches', *Progress in Physical Geography*. Sage PublicationsSage CA: Thousand Oaks, CA, 4(2), pp. 189–210. doi: 10.1177/030913338000400203.

McFadgen, B. G. and Goff, J. R. (2007) 'Tsunamis in the New Zealand archaeological record', *Sedimentary Geology*. Elsevier, 200(3–4), pp. 263–274. doi: 10.1016/J.SEDGEO.2007.01.007.

Mitrova, J. X. and Peltier, W. R. (1991) 'On postglacial geoid subsidence over the equatorial oceans', *Journal of Geophysical Research*, 96(B12), pp. 20,053–20,071.

Montes, A., Bujalesky, G. G. and Paredes, J. M. (2018) 'Geomorphology and internal architecture of Holocene sandy-gravel beach ridge plain and barrier spits at Río Chico area, Tierra del Fuego, Argentina', *Journal of South American Earth Sciences*. Pergamon, 84, pp. 172–183. doi: 10.1016/J.JSAMES.2018.03.012.

Neal, A., Pontee, N., Pye, K. and Richards, J. (2002) 'Internal structure of mixed sand and gravel beach deposits revealed using ground-penetrating radar', *Sedimentology*, 49, pp. 789–804. doi: 10.1046/j.1365-3091.2002.00468.x.

Neal, A. (2004) 'Ground-penetrating radar and its use in sedimentology: principles, problems and progress', *Earth Science Reviews*, 6(3–4), pp 261–330.

Nicol, A., Alloway, B. and Tonkin, P. (1994) 'Rates of deformation, uplift, and landscape development associated with active folding in the Waipara area of North Canterbury, New Zealand', *Tectonics*, 13(6), pp. 1327–1344.

Nielsen, L., Bendixen, M., Kroon, A., Hede, M. U., Clemmensen, L. B., Weβling, R. and Elberling, B. (2017) 'Sea-level proxies in Holocene raised beach ridge deposits (Greenland) revealed by ground-penetrating radar', *Scientific Reports*. Nature Publishing Group, 7(1), p. 46460. doi: 10.1038/srep46460.

Nobes, D. C., Jol, H.M. and Duffy, B. (2016) 'Geophysical imaging of disrupted coastal dune stratigraphy and possible mechanisms, Haast, South Westland, New Zealand', *New Zealand Journal of Geology and Geophysics*, 59(3), pp. 426–435.

Otvos, E. G. (2000) 'Beach ridges — definitions and significance', *Geomorphology*, 32(1–2), pp. 83–108. doi: 10.1016/S0169-555X(99)00075-6.

Pitman, S. J. (2014) 'Methods for field measurement and remote sensing of the swash zone', in Cook, S. J., Clarke, L. E., and Nield, J. M. (eds) *Geomorphological Techniques*. London: British Society for Geomorphology.

Scheffers, A., Engel, M., Scheffers, S., Squire, P. and Kelletat, D. (2012) 'Beach ridge systems – archives for Holocene coastal events?', *Progress in Physical Geography*. SAGE PublicationsSage UK: London, England, 36(1), pp. 5–37. doi: 10.1177/0309133311419549.

Shepherd, M. J. (1991). 'Relict and contemporary foredunes as indicators of coastal processes', in Brierley, G. and Chappell, J. (ed.) *Applied Quaternary Studies*, Australian National University, Canberra, Australia, pp. 17–24.

Shulmeister, J. and Kirk, R. M. (1993) 'Evolution of a mixed sand and gravel barrier system in North Canterbury, New Zealand, during Holocene sea-level rise and still-stand', *Sedimentary Geology*, 87(3–4), pp. 215–235. doi: 10.1016/0037-0738(93)90005-P.

Shulmeister, J. and Kirk, R. M. (1996) 'Holocene history and a thermoluminescence based chronology of coastal dune ridges near Leithfield, North Canterbury, New Zealand', *New Zealand Journal of Geology and Geophysics*, 39(1), pp. 25–32. doi: 10.1080/00288306.1996.9514692.

Shulmeister, J. and Kirk, R. M. (1997) 'Holocene fluvial-coastal interactions on a mixed sand and sand and gravel beach system, North Canterbury, New Zealand', *Catena*, 30(4), pp. 337–355. doi: 10.1016/S0341-8162(97)00013-1.

Stephenson, W. and Shulmeister, J. (1999) 'A Holocene progradation record from Okains

Bay, Banks Peninsula, Canterbury, New Zealand', *New Zealand Journal of Geology and Geophysics*, 42(1), pp. 11–19. doi: 10.1080/00288306.1999.9514828.

Sunamura, T. and Takeda, I. (1984) 'Landward Migration of Inner Bars', *Developments in Sedimentology*. Elsevier, 39, pp. 63–78. doi: 10.1016/S0070-4571(08)70141-9.

Taylor, M. and Stone, G. W. (1996) 'Beach-Ridges: A Review', *Journal of Coastal Research*. Coastal Education & Research Foundation, Inc., 12(3), pp. 612–621. doi: 10.2307/4298509.

Wells, A. and Goff, J. (2007) 'Coastal dunes in Westland, New Zealand, provide a record of paleoseismic activity on the Alpine fault', *Geology*, 35(8), pp. 731–734.

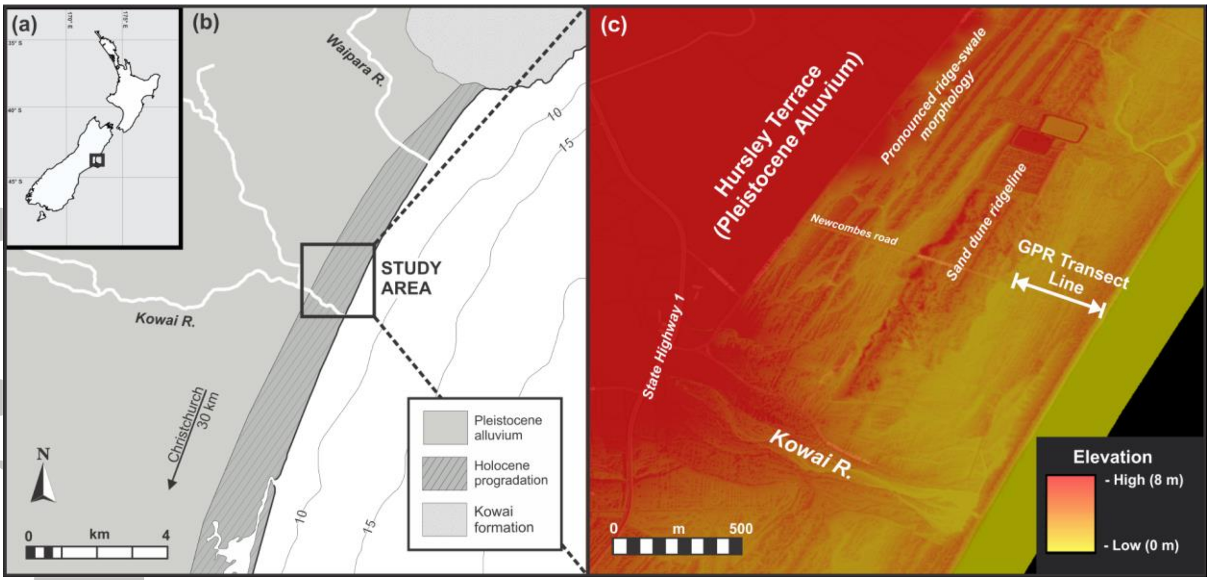

Figure 1. (a) Location of the study site on the Pegasus Bay coastline, South Island, New Zealand. (b) The study site is located upon a Holocene progradational beach plain with overlaid active and relict dune deposits. (c) The progradational plain fronts a terrace 6 m in height cut from alluvial deposits, the location of which is associated with the Holocene transgression. The GPR transect extends 370 m back from the modern day beach in a roughly NW direction. Lidar data courtesy of Land Information New Zealand.

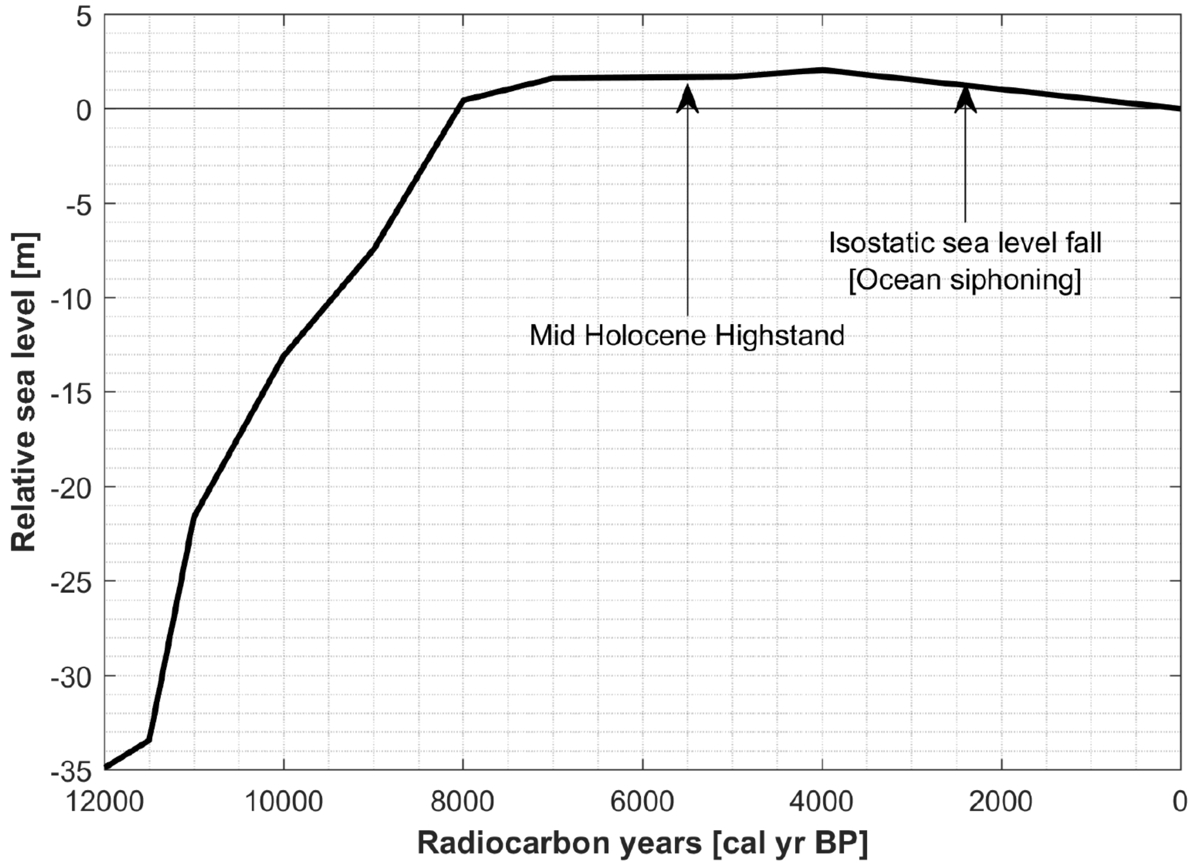

Figure 2. Sea level curve for the Canterbury Coast, New Zealand, adapted from Clement et al. (2016), showing that relative sea levels have been falling in the region over the last c. 4000 years.

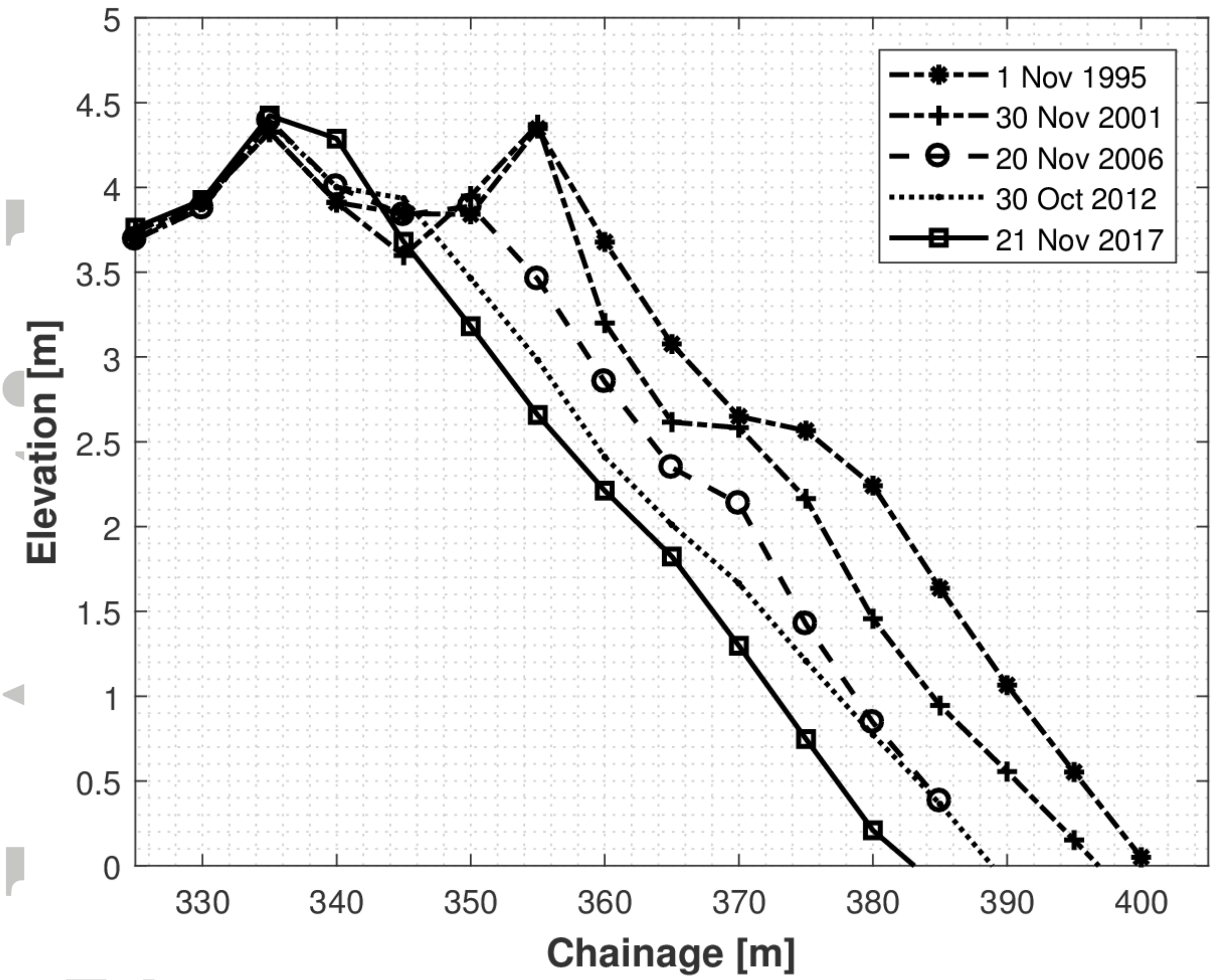

Figure 3. Beach profiles for the active beach and dune system over the period 1995 – 2017. Distances are referenced against the origin of the GPR profiles in Figure 4. Profile data courtesy of Environment Canterbury.

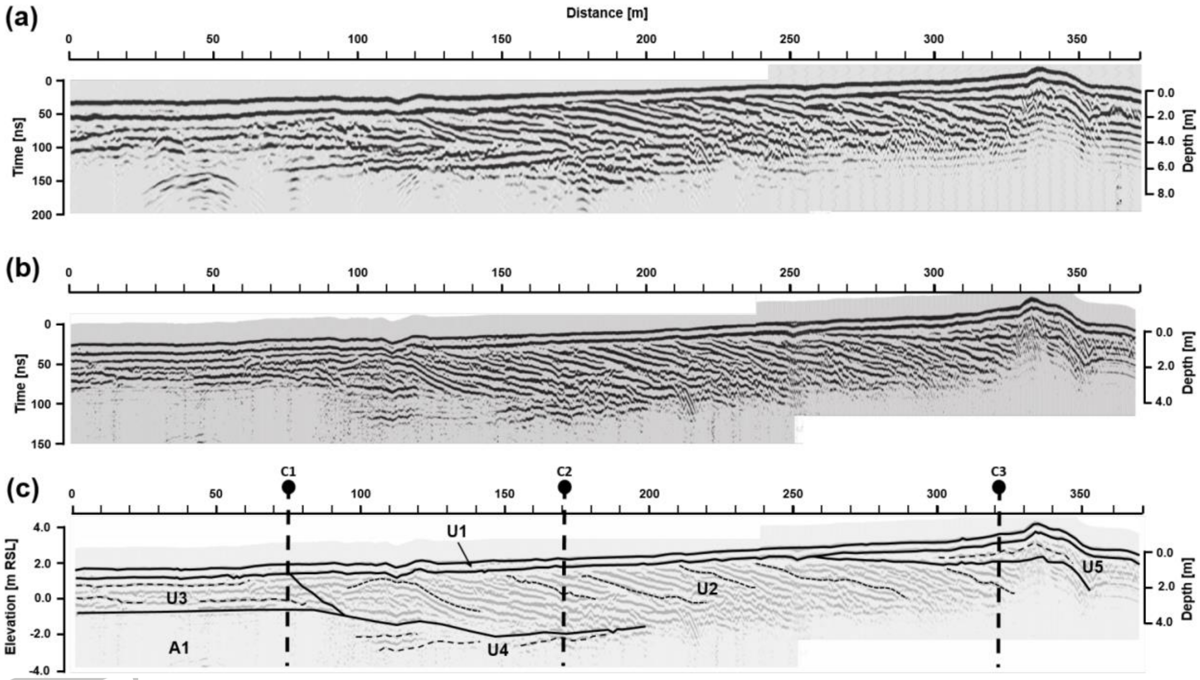

Figure 4. Complete GPR transects collected across the beach-foredune ridge plain using (a) 100 MHz and (b) 200 MHz transmitters. The 200 MHz transect has been interpreted (c) to compose of a number of units, with each unit separated by a solid black line: U1 is representative of the sand veneer across the entire study area; U2 shows gravel beach ridges; U3 shows horizontal reworked bedding, interpreted as fluvial deposition during a prior course of the Kowai River; U4 shows landward dipping bedding on the edge of the fluvial reworking; and U5 is the modern day beach and foredune complex. There is one anomaly (A1) associated with the interference from overhead power lines. Coring locations are indicated by black dashed lines (C1 – C3). Additionally, the height relative to mean sea level (MSL) is included on sub plot (c) for reference.

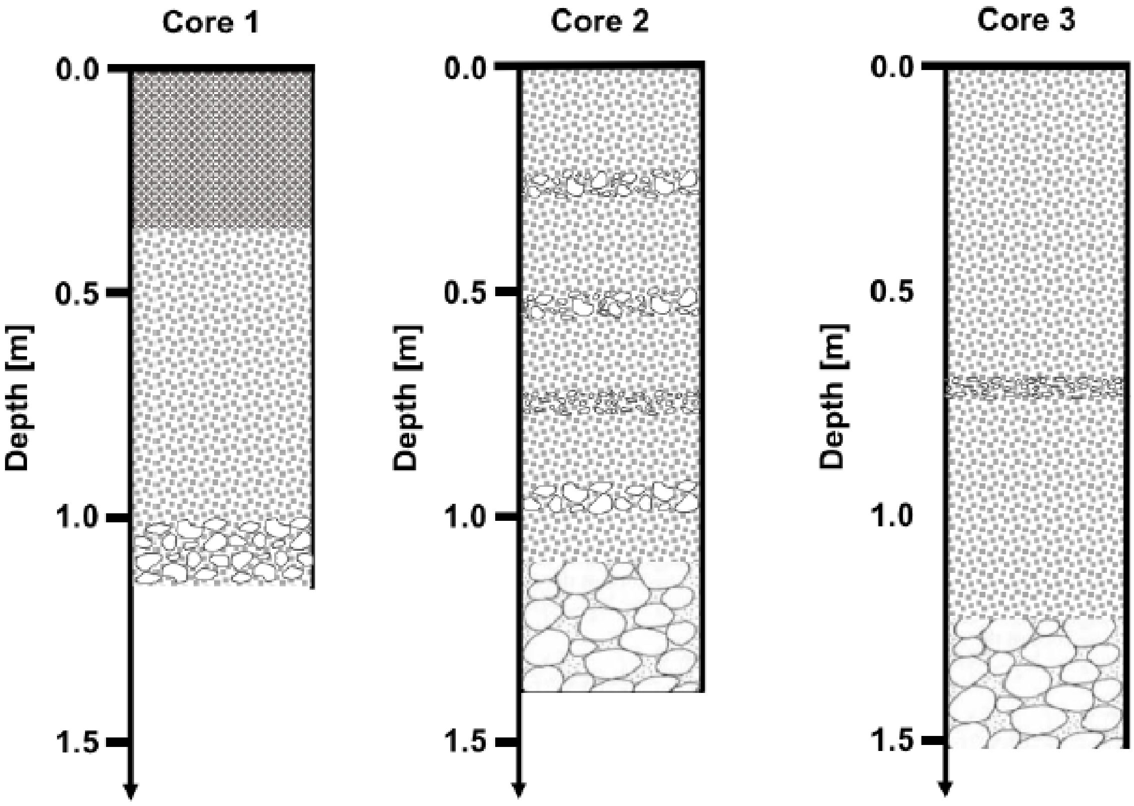

Figure 5. Sediment core records. All cores had a basal unit of large gravel, the top of which was between 1 and 1.25 m depth. In Core 1, atop the basal unit was coarse sand, with a 0.35 m soil cap. In Core 2, above the basal unit was coarse sand with intermittent lenses of gravel deposits. In Core 3, above the basal unit there was coarse sand with one gravel lens.

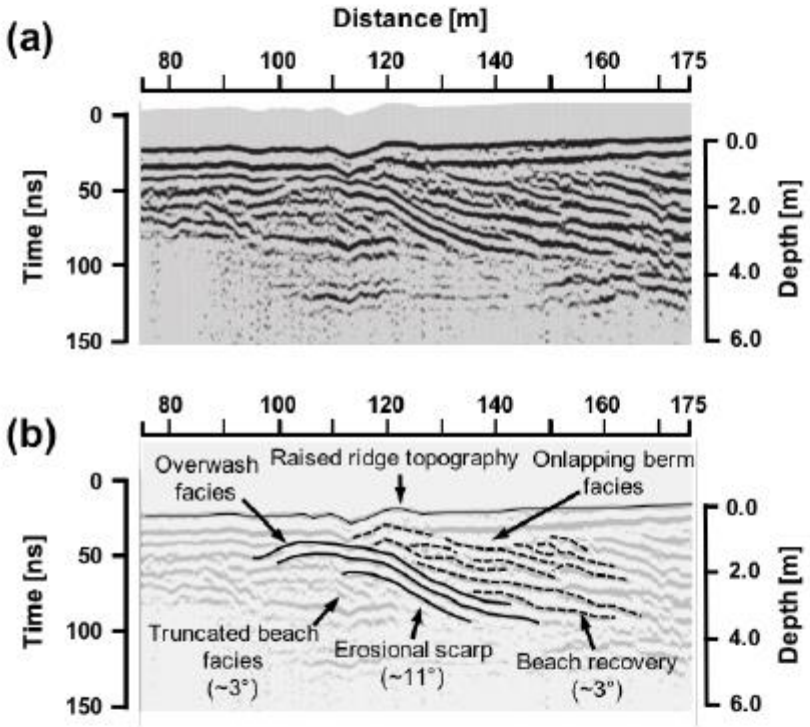

Figure 6. (a) Erosional scarp preserved in 200 MHz transect. (b) The scarp is around 11° steep and is shown to truncate previous beach faces towards the hinterland. Overwash deposits are also visible. Beach recovery is subsequently observed, through the layering of successive berm deposits offshore of the storm scarp.

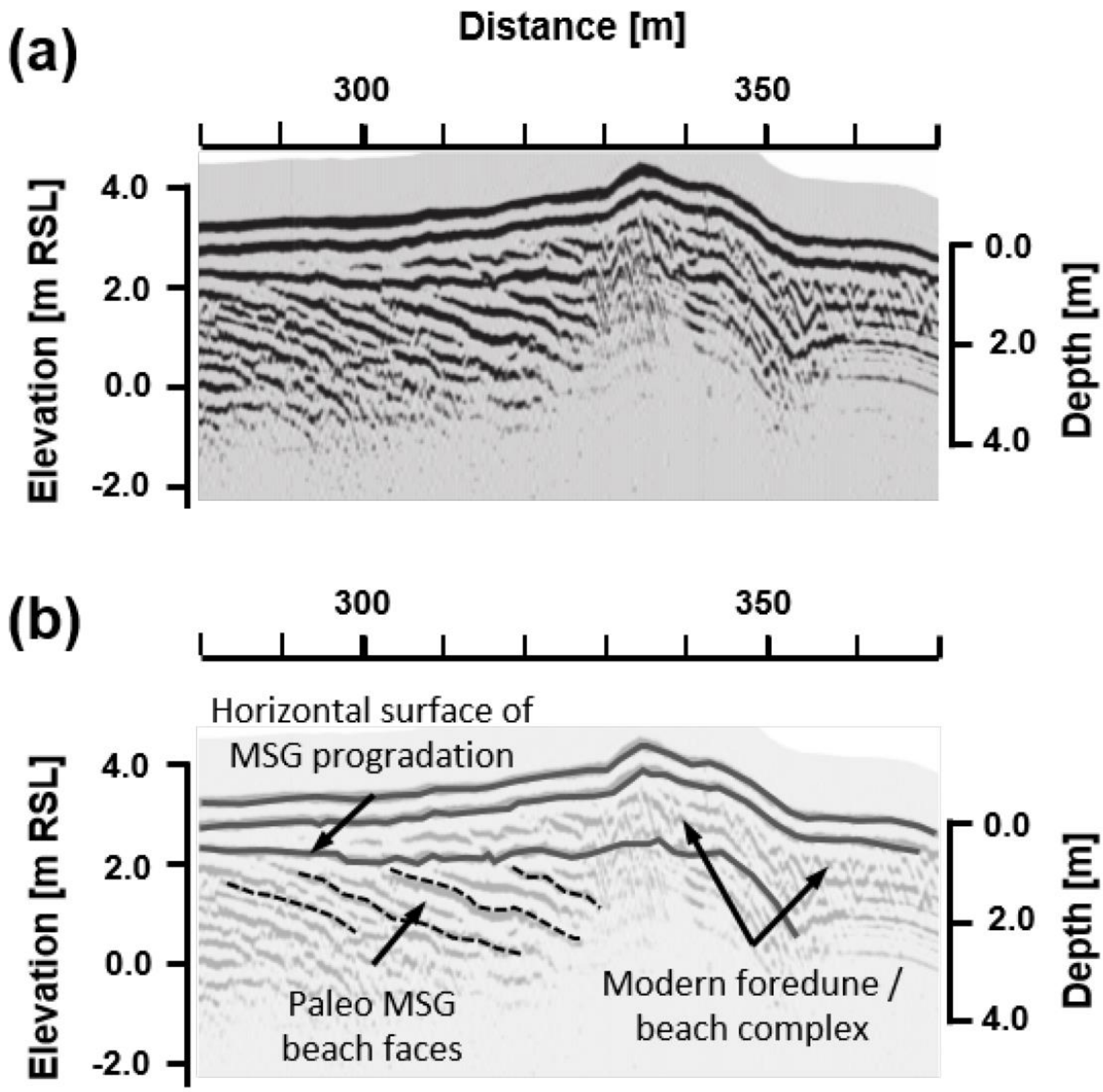

Figure 7. (a) Sequences of dune accretion preserved in 200 MHz transect. (b) Beds of on-lapped sediment appear to have accreted this dune shorewards. Additionally, two layers of bedded sand run horizontally across the transect.

Graphical Abstract: