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An In Depth Case Study of a Prograded Barrier using GPR (Ground Penetrating Radar) at Papamoa Beach (BoP), New Zealand

1. Abstract:

A prograded barrier stands at Papamoa Beach in the Bay of Plenty region of New Zealand, which formed during the late Holocene approximately 6,000-4,000 years BP. The aim of this study was to use Ground Penetrating Radar (GPR) along the barrier in order to identify past storms and determine both relative event frequency and intensity. The present day beach, intermediate in type, was surveyed and examined in order to demonstrate its characterization. On February 17, 2011, the day data was collected, the beach had been recovering from a storm. This information was used to compare current conditions with past storm occurrences recorded in the GPR data. The data projected twenty-three events with the most severity lying within the foredune. Frequency could not be determined because the subsurface material was not dated during the study. Coastal scientists are anticipating increases in sea level for the future leading to stormier environments. Therefore, researching prograded barriers, which provide strong preservation of its reaction to previous storms, is particularly important.

2. Introduction:

Both short-term and long-term changes in beach morphology referring to storm versus fair weather conditions, and the evolution of barriers along coasts, have been extensively studied. For example, coastal researchers, Ruz and Meur-Ferec (2004), identified common storm surge signatures and explained the reasons for these morphological alterations and specific deposits that occur as a result of storms. However, only until the invention of Ground-Penetrating Radar

(GPR) and its use along the coast have scientists been able to compare past beach profiles with the present and better understand coastal morphology as a whole.

GPR, a geophysical method that uses radar to show stratigraphy, can penetrate through subsurface material composed of fine sands due to their high resistivity. Prograded barriers, characterized by a series of fine-grained beach ridges that have been built seawards by waves and currents, are therefore highly suitable targets for GPR surveys (Bristow 2003). Due to the effects of climate change, coastal scientists expect mean sea levels to rise considerably and storms to increase in intensity (Goodwin 2003). Reconstructing the history of previous storm events allows coastal researchers to understand how prograded barriers have responded in the past in order to better predict future occurrences essential for advances in beach protection and coastal hazards management.

At Papamoa Beach in the Bay of Plenty area of New Zealand, lies a prograded barrier along which beach ridges and a foredune, align perpendicularly to the beach. Foredunes are common end members of prograded barriers and compared to beach ridges, their sands have been more substantially reworked by wind. Thus far, this specific area has not been studied. There has, however, been extensive research conducted in close proximity, approximately 20 km west of Papamoa Beach, but the data has been strictly limited to changes in wave climate and barrier evolution (Shephard and Hesp 2003). Also, several beaches along the northeastern coast of the North Island, New Zealand, have been examined in depth using GPR but the key purpose of these case studies was to examine the effects of relative sea level rise on the formation and evolution of coastal prograded barriers (Dougherty 2011). The main objective of this study is to establish past storm event frequency and severity at Papamoa Beach using GPR, and in the process, compare beach response to these high-energy occurrences with the present day beach morphology. Since this is a new subject for research in coastal science, the knowledge gained by performing this study will provide a more in depth understanding of prograded barriers' morphological response to storms, essential for decision-making at the coast.

3. Background:

Papamoa Beach is located in the Bay of Plenty region on the central eastern coast of the North Island of New Zealand (see Figure 3.1 below). Previous research supports that east coast Holocene prograded barriers in the North Island started forming after the post-glacial marine transgression approximately 12,000 to 6,000 years ago during which eustaic sea level rapidly rose providing accommodation space for sediment to accumulate. Around 6,000-4,000 years B.P. during the Holocene early sea level still-stand, sediment supply overwhelmed the rate of relative sea level rise. Therefore, sands built out seawards and ultimately formed prograded barrier systems. These features retain the highest preservation potential of all coastal features and are therefore ideal for studying changes in beach morphology through time (Dougherty 2011).

Figure 3.1. Papamoa Beach from the perspective of the North Island. Location indicated by the red marker in the Bay of Plenty Region. Within the blue circle lies Matakana Island.

Specifically, Papamoa Beach is composed of primarily white quartzo-feldspathic sands and is intermediate in beach stage (Harray and Healy 1978). Intermediate beaches are in a constant state of dynamism due to constantly changing offshore wave processes and characteristics. At Papamoa Beach, typical beach conditions consist of a moderate offshore gradient, moderate wave energies, and low tidal range of approximately 2.0 m (see figure 3.2 below), all of which are characteristic of intermediate beaches and perfect conditions for the development of prograded barriers (Shephard and Hesp 2003).

Figure 3.2. Papamoa Beach exemplifying typical moderate wave climate conditions and post-storm recovery profile.

Due to the dramatic increase in wave energies from swell to storm conditions, intermediate beaches experience extreme morphological change as a result of storm events. This alteration may be examined by graphing the typical pre-storm vs. post-storm profile and is known as the envelope of change (Jelgersma 1995). This significant amount of alteration occurs as a result of storms, in which high-energy waves flatten a portion of the previous or fair weather condition beachface, deposit coarse sands and heavy minerals onto it, and erode the dune (Dougherty et al. 2004). The resultant morphology is therefore a flattened beachface, which transitions into a steeper upper beachface, and abruptly shifts into an eroded dune scarp. After a storm-event, the beach recovers to its original continuous slope and sediment accretes at the top of the beachface forming a berm. The beach continues to prograde seaward until the next storm event. In most cases, GPR displays the flattened beachface of a storm denoted by a shallow gradient line, which can be used to graph against the typical swell profile and demonstrate the envelope of change (Dougherty 2011).

GPR shows the subsurface material on a computer screen by emitting short pulses of electromagnetic energy into the ground restricted by mineralogy, grain size, water content, and saline concentrations. These parameters control the electrical conduction properties of the material and cause energy to reflect back to the receiver, taking note of stratigraphic changes by travel-time along the waveform. The time measurement is converted into depth by entering the dielectric constant of the material into computer software, commonly RADAN, through which it is travelling. Individual waveforms result when the amplitude of the radar wave contrasts with the dielectric constants. Low wave-amplitude suggests a constant material strictly composed of quartzo-feldspathic sand, while an increase in amplitude represents changes in that sediment correlating with the addition of coarse sands and heavy minerals resulting from storms. Thus these events at Papamoa Beach can be identified and examined for frequency and intensity (Dougherty 2011).

4. Method:

Google Earth and LiDAR (Light Detection And Ranging), an optical remote sensing technology used to relay topography, were used to identify a prograded barrier in the North Island of New Zealand, which had not been previously studied. One was located at Papamoa Beach and because it demonstrated a clear interface between the beach ridges and foredune allowing for stratigraphic comparison, this particular area was chosen for study.

On February 17, 2011, the field data was collected along the prograded barrier containing a beach ridge sequence and subsequent foredune at Papamoa Beach, located on the central eastern coast of the North Island in New Zealand. A 1,350-meter long transect was constructed with 50 meter increments, traversing through both a privately owned property road and Maranui Road. A Sokkia Electronic Total Station was used to obtain surface elevations and later construct a profile of the area. In smaller increments along the foredune and beachface, the same aforementioned method as the previous was conducted. Present day beach condition observations and surveyed profiles were used to draw conclusions concerning beach type and state, and to compare those findings with beachface morphology recorded in the subsurface material.

Barrier stratigraphy was developed using a GSSI (Geophysical Survey System Inc., USA) SIR-2000 GPR system and markings were entered into the system at each increment along the transect. RADAN 6.5 Software was used to analyze the beachfaces embedded in the GPR data. By following specific instructions outlined within the software, normalizations, topographic corrections, and time travel to depth conversions were accomplished. A dielectric constant of six, most widely accepted for prograded barriers, was used to convert travel-time to depth. Also, the gain was adjusted to increase the signal amplitude and show stratigraphic resoulution.

Previous beach profiles recorded in the GPR were identified based on the criteria outlined by Dougherty (2011) and marked in red. All were compared and grouped based on six categories: strongly reflected, weakly reflected, steep sloped, shallow sloped, beach ridge profile, and foredune profile. The slope of those lying within the stratigraphy and of the present day was computed by performing a simple change in x divided by change in y calculation between the lowest and highest point of the profile. This was conducted in order to determine whether each represented storm or fair weather conditions. They were also graphed in order to identify and interpret an envelope of change. A literature search was conducted in order to infer both the present beach state and type, and past beach profiles. Storm frequency was analyzed by examining the amount and relative spacing of storm occurrences, while severity was determined by comparing the gradients of the profiles.

5. Results:

5.1 Beach Observations.

On February 17, 2011 the climate at Papamoa Beach was sunny and moderately windy. Wave heights were approximately 1.0-1.5 m and the beach gradient was relatively continuous. A pole at the base of the dune was wet on the upper portion and dry on the lower portion, which possibly denoted and was later analyzed for erosional activity (see Figure 5.1 below).

Figure 5.1. Line indicating position at which above it the pole was wet and below it the pole was dry.

5.2 Beach Ridge Sequence Profile.

The graph below is the topographic profile of the beach ridge sequence and demonstrates a slight uneven and overall decreasing trend.

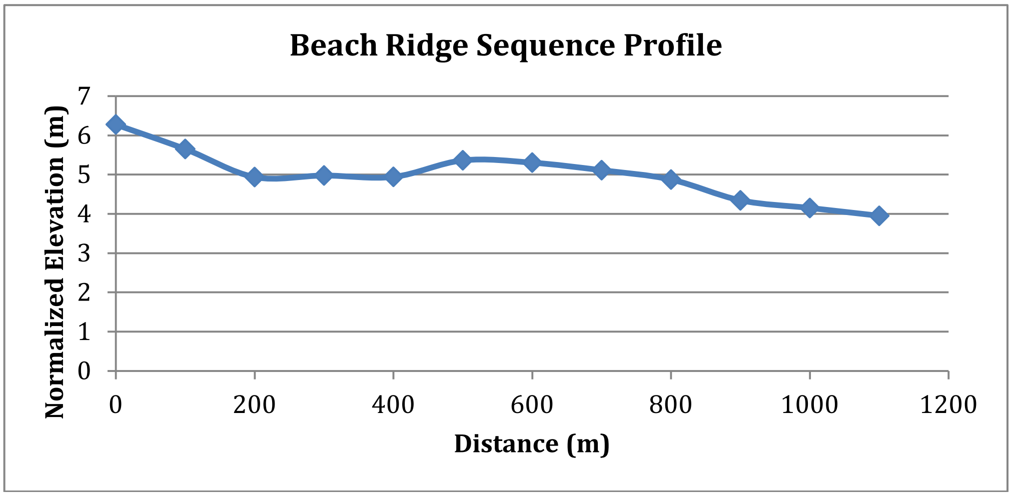

Figure 5.2.1. Beach ridge sequence profile. Distance along the transect represented by the distance in meters across the x-axis versus the vertical displacement represented by normalized elevation in meters along the y-axis.

5.3 Foredune and Present Day Beachface Profiles.

The topographic profile of the foredune and present day beachface are shown on the next page. The dune's landward extent abruptly steepens to the top of the dune, levels, and then generally lowers to the toe of the dune. Directly below the gap indicates the beachface, shallowing seawards. The beach gradient was calculated to be 5.19°.

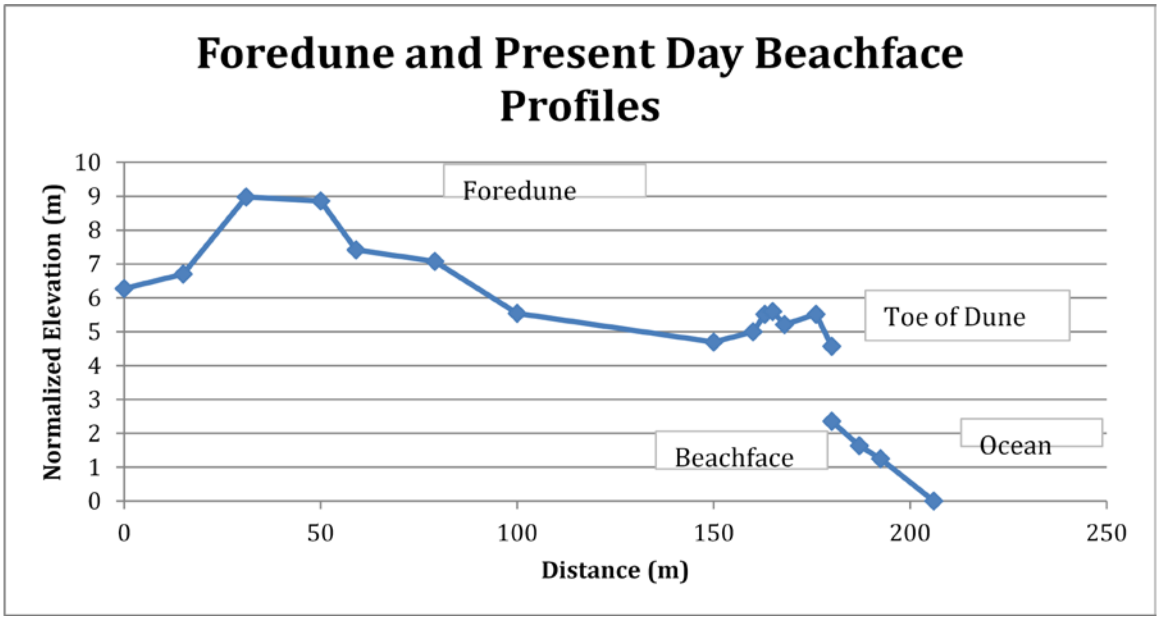

Figure 5.3.1. Foredune and subsequent beach profile. Gap caused by repositioning the total station. Distance in meters across the topography indicated along the x-axis plotted against the normalized elevation in meters along the y-axis.

5.4 Previous Beach Profiles

Twenty-three beach profiles were identified in the GPR data. Six of them, one from each of previously mentioned categories, including their derived gradients are shown below.

5.4.1 Beach Ridge Sequence Beach Profile

A profile identified in the beach ridge sequence (shown on the next page), exemplifies an alteration in the stratigraphy denoted by the high resolution of the sloped line. Its slope was calculated to be 11.87°.

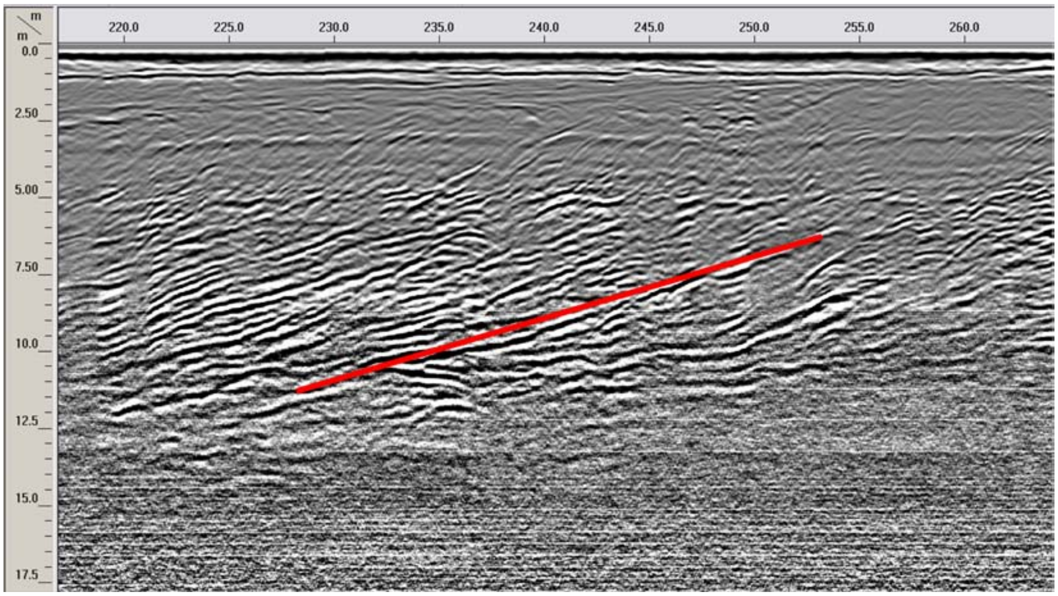

Figure 5.4.1.1. Beach profile recorded in the beach ridge sequence. Red line shows an abrupt positive trend recorded in GPR data taken along the beach ridges. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis deepening downwards.

5.4.2 Foredune Beach Profile

One profile recorded in the foredune is shown on the next page and demonstrates a change in the subsurface material indicated by its high resolution. The slope of the profile was calculated as 24.08°.

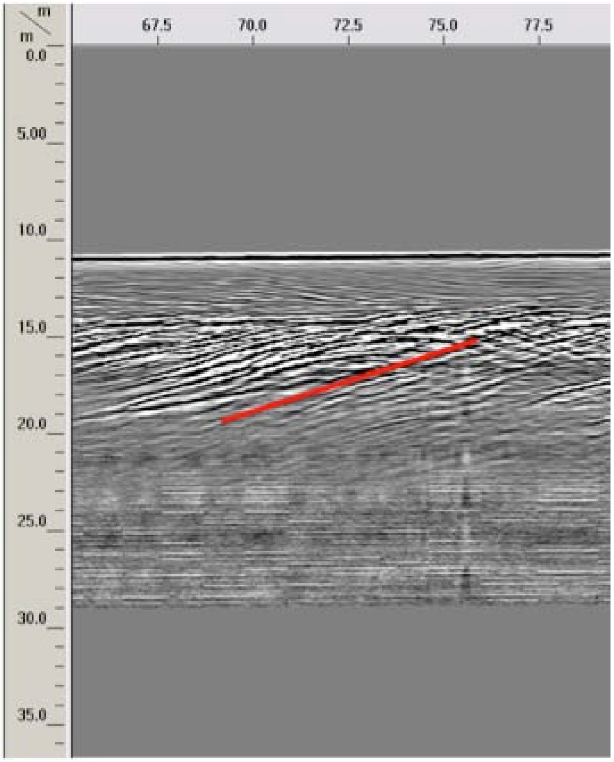

Figure 5.4.2.1. Beach profile recorded in the foredune. Red line indicates a sudden upward trend recorded in GPR data taken along the foredune. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis deepening downwards.

5.4.3 Shallow Sloped Profile

A shallow sloped profile (shown on next page) was identified in the beach ridge sequence and exemplifies an alteration in the subsurface material denoted by the exceptionally strong resolution of the sloped line. Its gradient was calculated to be 5.53°.

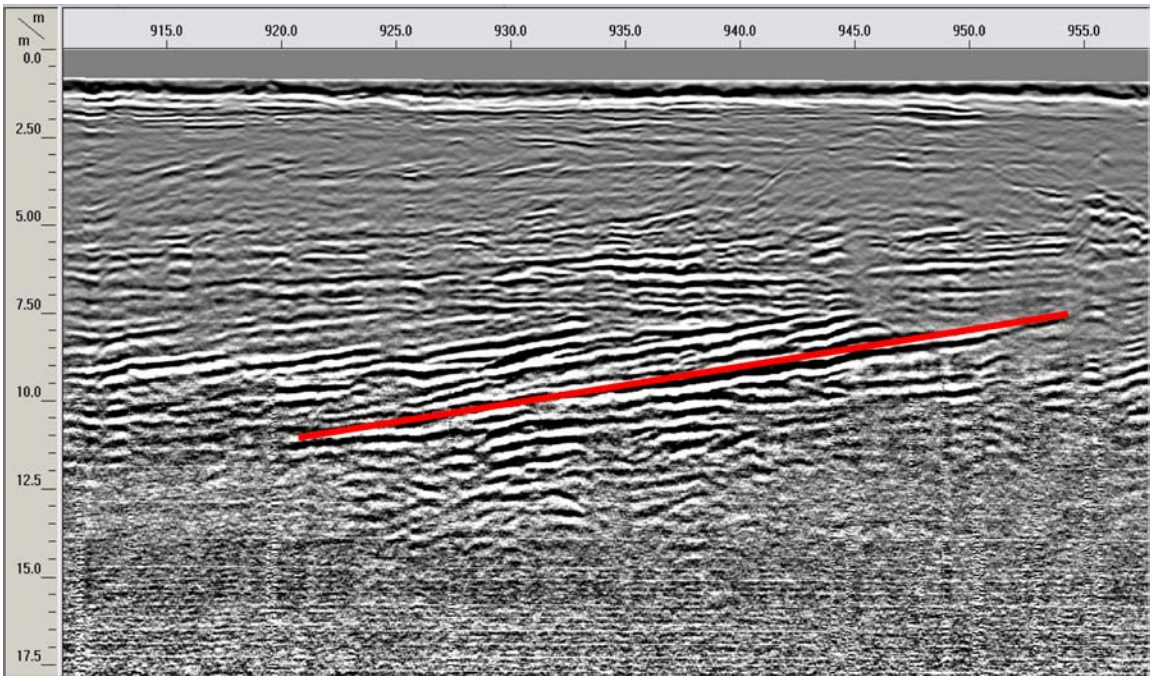

Figure 5.4.3.1. Shallow sloped beach profile recorded in the beach ridge sequence. Red line demonstrates a shallow positive trend recorded in GPR data taken along the beach ridges. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis steepening downwards.

5.4.4 Strongly Reflected Beach Profile

One strongly reflected beach profile recognized in the beach ridge sequence is shown on the next page and represents a change in the stratigraphy indicated by its high resolution. The slope of this profile was calculated as 7.91°.

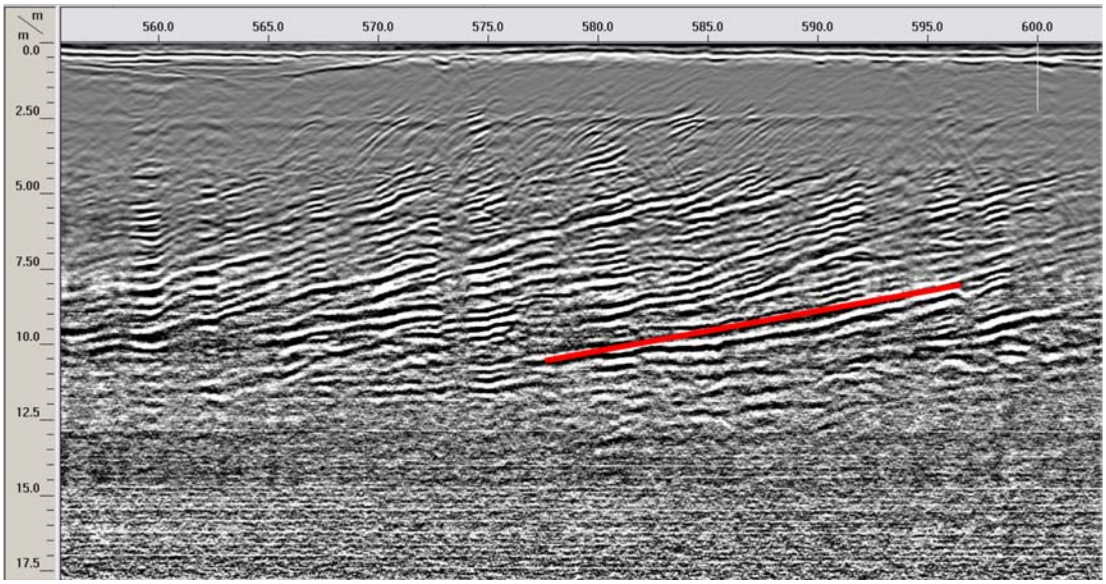

Figure 5.4.4.1. Strongly reflected beach profile recorded in the beach ridge sequence. Red line indicates a gradual upwards trend recorded in GPR data taken along the beach ridges. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis deepening downwards.

5.4.5 Steep Sloped Beach Profile

A steep sloped profile recorded in the beach ridge sequence (shown below), represents minute change in the subsurface material demonstrated by the weak resolution of the sloped line. The slope of this beach profile was calculated to be 22.54°.

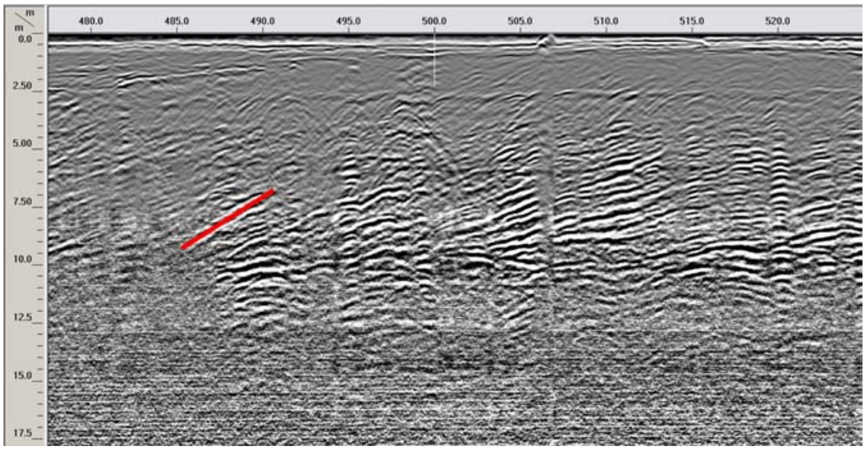

Figure 5.4.5.1. Steep beach profile recorded in the beach ridge sequence. Red line indicates a sudden positive trend recorded in GPR data taken along the beach ridges. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis steepening downwards.

5.4.6 Weakly Reflected Beach Profile

One weakly reflected beach profile identified in the beach ridge sequence is shown below and exemplifies little alteration in the stratigraphy denoted by its weak resolution. Its slope was calculated as 14.74°.

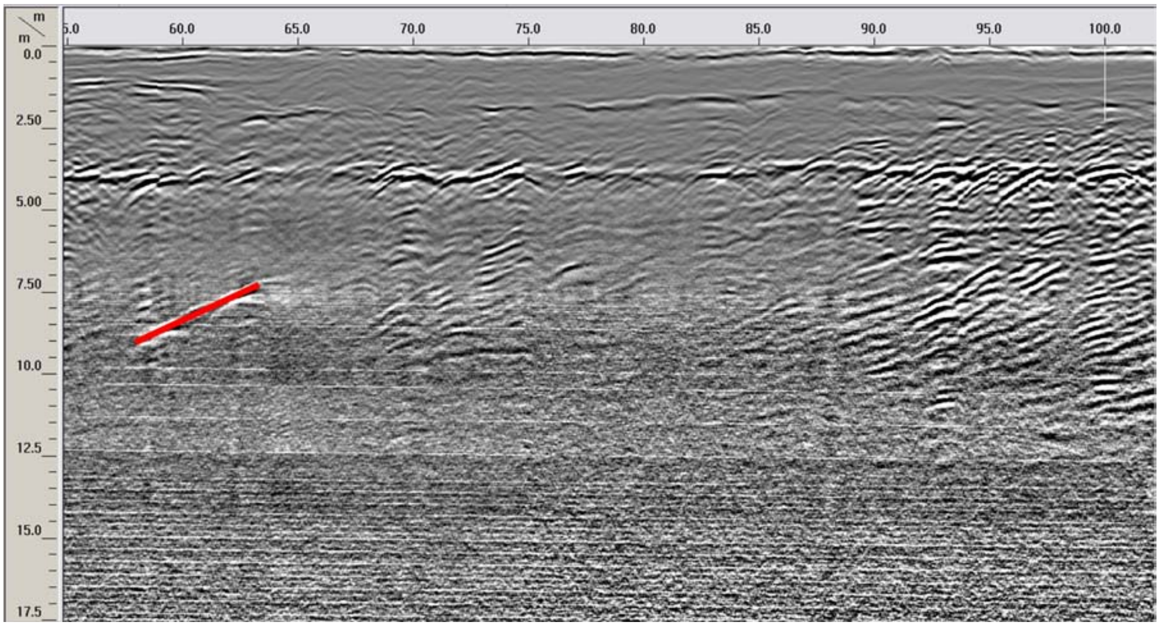

Figure 5.4.6.1. Relatively weakly reflected beach profile recorded in the beach ridge sequence. Red line shows an abrupt positive trend recorded in GPR data taken along the beach ridges. Distance along the transect represented by the distance in meters across the x-axis versus the depth in meters along the y-axis deepening downwards.

5.5 Past Beach Profiles Compared with Present Day Beachface

The "present day" beachface recorded on February 17, 2011 was much shallower than the majority of past beach slopes at Papamoa Beach (shown on next page). All greatly vary and thus do not demonstrate an envelope of change.

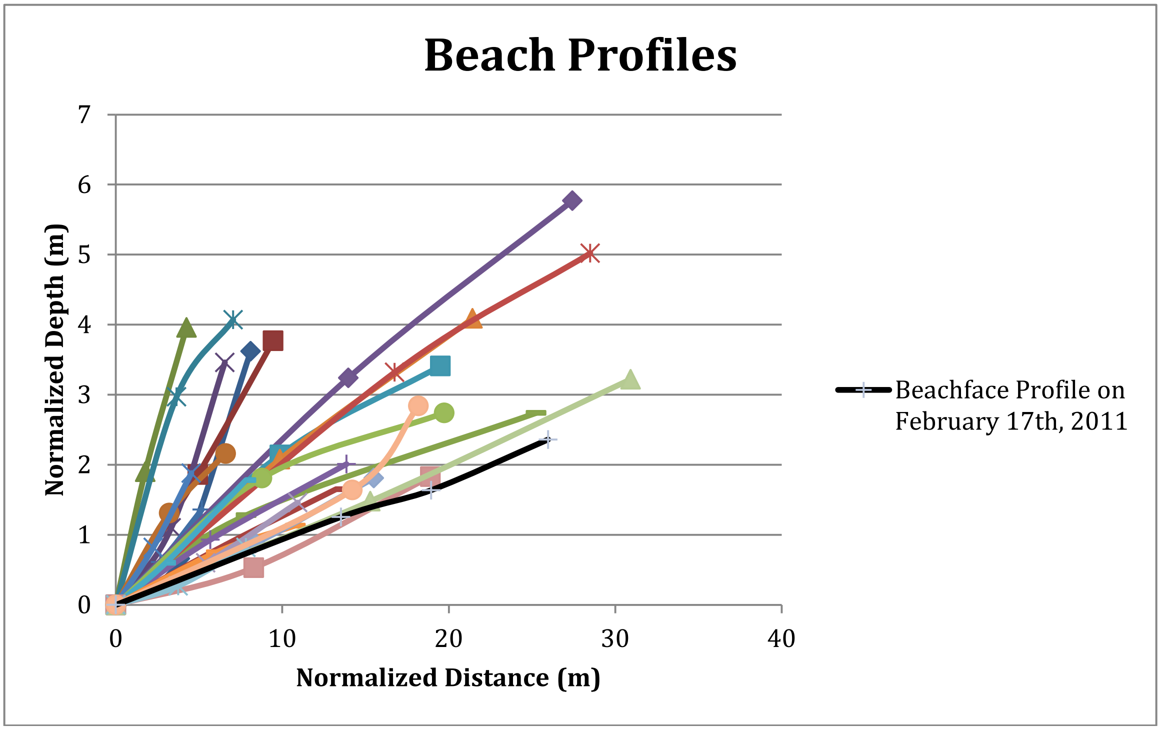

Figure 5.5.1. Papamoa beach profile on February 17th, 2011 compared with past day beach profiles embedded in the GPR data. Distance along the transect denoted by the normalized distance in meters across the x axis versus specific depth within the subsurface represented by the normalized distance in meters along the y-axis.

6. Discussion:

Papamoa Beach is an intermediate beach and was experiencing post-storm recovery on February 17, 2011. Intermediate beaches have moderately high waves (1.0 m-2.5 m) and persist on moderate energy coasts (Short and Wright 1983). Observing that Papamoa experienced average wind speeds resulting in moderate wave energies and wave heights (1.0 m-1.5 m) further supports that this is an intermediate beach. The pole at toe of the dune (previously shown in figure 5.1) indicated that the lower portion previously had sand that stood up against it. Sand extraction was most likely due to storm waves, which rushed up the beachface, wetting the top portion of the pole and eroding sand from the lower portion, leaving it dry. These types of beaches typically range in slope from 1.47° to 4.76° but Papamoa Beach's gradient was calculated to be 5.19° (Short and Wright 1983). A slightly steeper slope in reference to typical beach conditions and this identified removal of sand are representative of the fact that a relatively recent storm event had occurred. As previously discussed, storms flatten a portion of the beachface causing steep upper beachface. As a beach recovers, its average slope returns to a typical fair weather profile and becomes less steep and more continual (Dougherty 2011). Because Papamoa Beach relatively ascended gradually from the shoreline to the dune and its slope was slightly higher than the specified range for intermediate beaches, the beach was recovering from a storm event on the day data was collected.

The beach ridge sequence extending seawards to the foredune and down to the base of the beachface is a prograded barrier. Intermediate beaches are extremely dynamic relating to sediment transport throughout the beach system and are the most spatially and temporally variable compared to reflective and dissipative beaches. Therefore, prograded barriers are characteristic of this specific beach type, which developed as a result of sufficient sediment supply (Davis 2004). According to Figure 5.2.1, the substantial uneven topography in the beach ridge sequence as it trends downwards is representative of erosional followed by accretionary processes. These processes occurred as a result of fair weather conditions intermittently interrupted by storms. Erosion caused these sudden uplifts in topography due to increases in wave energy during storms. During swell conditions sands were deposited and the barrier built seaward, resulting in a gradual decrease in topography. The foredune represents past decreased rate of supply and increased wind energies, which prevented further progradation of the beach ridges. The barrier is currently separated from the ocean due to fair weather accretionary, followed by erosional storm processes, that have and will continue to occur along the present day beachface (Davis 2004), which is shown in Figure 5.3.1.

The profiles identified in the GPR data represent different segments of the beach that appeared as a result of storms. Formerly mentioned, beach gradients of intermediate beaches typically range in slope from 1.47° to 4.76°. However, storm events cause the profile to alter forming a greater steepness in succession from the shoreline to the dune. For the beach ridge sequence, the beach profile's measured angle was 11.87°, and for the foredune the angle was calculated to be 24.08°. According to Noller (2000), the slope of the upper beachface is approximately 12° and the dune scarp angle ranges from 17° to 26°. Therefore, the profile recorded in the beach ridge most likely represents the upper beachface portion of the beach profile, while the slopes preserved in the foredune most likely signify steepened dune scarps (see Figures 5.4.1 and 5.4.2).

The shallow sloped and strongly reflected beach profiles demonstrate the same beach stage to that observed on the date data was collected on Papamoa Beach (see Figures 5.4.3 and 5.4.4). First of all, both of these profiles were exceptionally easy to identify in the GPR data because they were both strongly reflected. As previously discussed, these profiles appear in the data because the coarse material and heavy minerals deposited during storms causes the GPR to increase in amplitude and produce a clearly indicated sloped profile. Higher energy storms correlate with an increase in these deposits and a greater decrease in beach gradient resulting in an exceptionally strongly reflected shallow beach slope (Dougherty 2011). Because the slope of the shallow beach profiles, 5.53°-7.19°, were within a couple degrees of present day beachface, these morphologies represent post-storm recovery.

Both the weakly reflected and exceptionally steep profiles preserved in the GPR data represent steepened dune scarps (see figures 5.4.5 and 5.4.6). This is indicated by their sharp gradients, 22.54° and 14.74°, respectively, extending from the landward extent of upper beachface to the top of the dune. They are both steep and weakly reflected because not large amount of coarse material and heavy minerals were deposited onto the scarp during storms, causing only a minor increase in amplitude (Dougherty 2011). During a storm, high-energy waves surge up the beachface and generally deposit these sediments on the beachface rather than the dune. This occurs because the swash loses its momentum as it travels up the beachface travelling only as far as the berm at the toe of the dune. Sand is then extracted from the dune and transported seawards (Noller 2000). In terms of identifying previous storm events embedded in the GPR data, there was sufficient information collected in order to make solid conclusions because the GPR projected exceptionally clean data throughout the entire transect.

Because storm beach profile segments preserved in the GPR data compared with the post-storm recovery beachface observed on February 17, 2011 all significantly differ in slope, there was no identifiable envelope of change (see figure 5.5.1). Contrary to previous studies, the course material and heavy minerals were deposited mostly on upper beachfaces and dune scarps, signified by their presence in the GPR data, as opposed to the shallowed portion of the beachface during storm events. Due to an inconsistency in preservation, the present day beach profile and the morphologies preserved in the GPR could not be used to analyze and interpret the amount of change from typical storm to post-storm conditions.

Since the slopes of the storm scarps recorded within the foredune are, on average, substantially greater than those recorded in the beach ridge sequence, this data supports that storms at Papamoa Beach have increased in intensity through time. Prograded barriers accrete seawards indicating that the stratigraphy of the beach ridge sequence is older than the subsurface material of the foredune (Davis 2004). A steeper storm scarp is indicative of higher energy waves produced during more severe storms that are able to erode more material from the dune

(Noller 2000). The concentration of and relative spacing between storm events could not be used to determine frequency because sediment does not accrete at a consistent rate after a storm event through time. If cores had used to extract the subsurface material and radiocarbon dating had been used to date previous storm events, storm frequency could have been established (Dougherty 2011). Further storm research based on this study site must be conducted and incorporate these methods in order for coastal scientists to obtain a greater understanding of storm event behavior. Collecting data supporting that storms are in fact increasing in both intensity and frequency is essential in the attempt to convince individuals that the environment is experiencing the effects of climate change.

Conclusions:

GPR was used at Papamoa Beach to study the effects of past storm occurrences and subsequently, establish previous event frequency and intensity. The data supported that Papamoa Beach is an intermediate beach and was in the stage of post-storm recovery during the day data was collected. Preserved in the GPR, twenty-three storms were identified each projecting the upper beachface, dune scarp, or storm-recovery profile. Analysis of the storm scarps supported that storms have increased in severity. Researching this particular study site is important because the outcomes of climate change associated with sea level rise and increases in both wind speed and wave energies, suggest that the east facing coasts of New Zealand may become stormier, specifically in the North Island (Dougherty 2011). Coastal researchers studying the impact of storms are just beginning to embark upon finding exactly how much more powerful and recurrent these events are now than they have been in the past. Protecting the environment from the impacts of storm events including risk to property, development, and life, is essential. Therefore, coastal scientists must attempt to understand the processes of the earth system through in depth study of the past in order to predict future occurrences. Consequently, this will allow individuals to make more informed decisions in an effort to protect coastlines and become more resilient to effects of these natural occurrences.

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