ASSESSING THE ROLE OF FRAMEWORK GEOLOGY ON BARRIER ISLAND GEOMORPHOLOGY

A Dissertation

by

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ABSTRACT

Extreme storms, hurricanes, nor'easters, and tropical depressions can cause widespread erosion and washover on barrier islands and threaten coastal communities. The strong winds and waves of these storms can erode the beach and dunes, causing significant damage to coastal infrastructure and threatening human lives. Coastal vulnerability and resiliency depend on the coastal morphology (*i.e.* nearshore, beach, and dune morphology) in conjunction with storminess (*i.e.* storm frequency and magnitude) and the rate of sea level rise. Variations in the initial coastal morphology, such as undulations in dune height, can propagate through as heterogeneity in the modern barrier island morphology. Given that the modern landscape can inherit features and patterns of variability through time, it is important to understand what factors influenced the initial coastal morphology in order to more accurately predict future changes in response to storms and sea level rise. Improving the accuracy of future change models requires that we more accurately understand how a multitude of coastal processes interact to change the coastal geomorphology.

This dissertation demonstrates that framework geology is a significant driver of barrier island evolution by setting up initial variation in the beach and dune morphology and modifying normal conditions and coastal processes. Field-based surveys and public DEM data were used to: (1) extract beach, dune, and island morphometrics using a multiscale relative relief approach, (2) quantitatively demonstrate that paleochannels in the framework geology interact with daily wave reflection and refraction patterns to influence the modern barrier island, and (3) demonstrate that paleochannels in the framework geology can have an asymmetric influence on the barrier island morphology, given a persistent alongshore sediment transport gradient. In light of new information about the effects of framework geology on barrier island evolution, this dissertation proposes that the currently accepted theory of formation for Padre Island National Seashore is incomplete and should be re-evaluated in context of framework geology.

DEDICATION

This dissertation is dedicated to my family and friends. My parents, Alan and Julie Wernette, have been extremely supportive and have provided more support than I could have possibly imagined. I am eternally grateful for them and everything they have done to help. I am extremely thankful for the unwavering support of Kenzie Schoemann. I would also like to dedicate this dissertation to my grandmother Pauline Wernette, whom believed that education never stops and learning is a lifelong endeavor.

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NOMENCLATURE

AR	Autoregressive
ARFIMA	Auto-regressive fractionally integrated moving average
BEG	Texas Bureau of Economic Geology
CRM	Coastal relief model
CWT	Continuous wavelet transformation
d	Degree of differencing
DEM	Digital elevation model
DOI	Depth of investigation
DSAS	Digital Shoreline Analysis System
EMI	Electromagnetic induction
GPR	Ground-penetrating radar
ICW	Intracoastal waterway
LCP	Least-cost path
LiDAR	Light detection and ranging
LRD	Long-range dependence
MA	Moving average
masl	meters above sea level
MD	Manual delineation
MIS II	Marine isotope stage II
NGDC	National Geophysical Data Center

NOAA	National Oceanic and Atmospheric Administration
p	Order of autoregressive model
PAIS	Padre Island National Seashore
PSD	Peak spectral density
q	Order of moving average model
R	Statistical software
RR	Relative relief
SASR	Shoreface attached sand ridge
SBT	Space-beats-time
SRD	Short-range dependence
Topobathy	Topo-bathymetric
USGS	United States Geological Survey
WTC	Wavelet coherence
Z_c	Elevation at center pixel (c)
Z_{min}	Minimum elevation within computational window
Z_{max}	Maximum elevation within computational window

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CHAPTER I

INTRODUCTION

Extreme storms, including hurricanes, nor'easters, and tropical depressions, can cause widespread erosion and washover on barrier islands, and thereby threaten coastal communities. The strong winds and waves of these storms can erode the beach and dunes, causing significant damage to coastal infrastructure and create the potential for a loss of life (Elko et al, 2016). Changes to dune morphology and the direction of sediment transport during a storm is controlled by the dune height relative to the water run-up (Sallenger, 2000), where large dunes are more likely to be eroded and sediment transported to the nearshore or offshore. In contrast, smaller dunes are more likely to be overwashed or inundated, resulting in sediment transported landward. Beach and dune recovery following a storm (*i.e.* resiliency) can take years to decades (Houser et al, 2008; Lentz and Hapke, 2011; Houser et al, 2015), and depends on the sediment budget (Hapke, Lentz, et al, 2010) interacting with storms and relative sea level rise (Houser and Hamilton, 2009). Patterns of resiliency (*i.e.* the ability of the coast to recover to its pre-storm state) along the coast determine how barrier islands will respond to sea-level rise; barrier islands exhibiting greater resiliency are more likely to maintain dune height during sea-level rise compared to less resilient areas.

Resiliency of the barrier island depends on the exchange of sediment in the cross-shore and alongshore directions. Sediment is exchanged between the nearshore, beach, and dunes, and the direction and magnitude of this exchange depends on weather and wave conditions relative to the coastal morphology. Nearshore sand bars can migrate onshore and weld with the beach due to wave breaking and shoaling processes. Bar welding nourishes the beach, creating a wider and greater volume beach. A wider beach has a greater effective fetch length over which onshore winds can transport sand inland. The transported sand will be deposited it reaches an object that exerts enough aerodynamic drag to reduce the wind velocity below the threshold of motion. In this way, nearshore morphology provides sediment to the beach, which provides sediment to the dune. Under relatively normal conditions this process tends to move sediment onshore.

In contrast, large waves and elevated water level during a storm can erode the beach and dunes, moving sediment either landward or seaward. If runup (*i.e.* the combination of wave height and water level) exceeds dune height or erodes the dune enough, then the dune can become unstable and be overwashed, transporting sediment landward (Sallenger, 2000; Stockdon et al, 2006; Stockdon et al, 2007). The overwashed sediment is subsequently lost to the beach and dune system during recovery following the storm. Overwash represents a significant by which barrier islands can transgress landward and keep pace with sea level rise. Erosion of the beach and dune is likely to occur in cases where runup does not exceed the dune crest elevation or does not destabilize the dune to the point of overwash. Sediment eroded from the beach and dune can be pulled offshore by large waves during the storm and either deposited in the nearshore bars or offshore. Sediment deposited in the nearshore bars is available to the system during post-storm recovery, although sediment transported to deeper water offshore is beyond the influence of normal wave conditions and is unavailable for post-storm recovery.

Initial patterns in nearshore, beach, and dune morphology interact with wave runup during a storm to influence barrier island transgression. Both the runup and coastal morphology are likely to vary alongshore. One difficulty with current coastal morphodynamic models is that it remains unclear what causes the initial variation in the nearshore, beach, dune morphology (Houser and Mathew, 2011). Recent evidence suggests that the framework geology is a primary driver of coastal morphodynamics, by influencing the bathymetric slope and sediment texture, which, in turn, determines nearshore morphology. The nearshore morphology influences sediment supply to and from the beach, which provides sediment for aeolian transport and dune growth. In this way, understanding how the framework geology influences beach and dune morphology will help guide our ability to guide coastal prediction models that incorporate variations in coastal morphology due to the framework geology. There is a need to better understand beach-dune interaction across a range of beach studies and geologic structures to predict how the system is likely to change in the future.

Accurately predicting future changes to barrier island morphology requires that we understand how the modern coastal morphology has been shaped by past events and how these past events may continue to influence future processes, which is one reason that current morphodynamic models are only able to partially predict future changes to the coastal morphology. Current models only account for free behavior of coastal systems. A free coastal system is one where changes to the nearshore, beach, and dune morphology are not being forced into any particular state by outside influences. In other words, there is no underlying broad-scale geographic control of the nearshore, beach, and dune morphology. The system varies stochastically and without any clear pattern. Vegetation composition and abundance might represent the dominant control of spatial and temporal variability observed in free systems (*e.g.* Judd et al, 2008; Duran and Moore, 2013; Goldstein et al, 2017). Free coastal systems are more likely to operate and influence coastal geomorphology at smaller spatial and temporal scales. The alternative to a completely free system is a forced system, where some overarching factor is causing the morphology to maintain a particular state or to vary predictably and regularly (*e.g.* Houser, 2012; Houser et al, 2015). Forced systems are more likely to influence coastal geomorphology across larger spatial and temporal scales.

Previous research along the U.S. Atlantic and Gulf of Mexico coasts proposed that the framework geology may be a driver of coastal geomorphology at broad geographic scales (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011; Houser, 2012; Houser et al, 2015). Current research examining the relationship between framework geology and coastal morphology focuses on relatively small number of beaches that are all relatively straightforward and do not have a strong framework geology control (Lazarus et al, 2011; Houser et al, 2015).

The current coastal morphodynamic models (*i.e.* Plant and Stockdon, 2012; Sherwood et al, 2014; Wilson et al, 2015) do not explicitly account for the influence of framework geology, despite increasing evidence that framework geology is a driver of coastal geomorphology at broad geographic scales (Elko et al, 2016). Incorporating the effects of framework geology into current models requires that we first quantitatively understand how variations in the framework geology influence coastal geomorphology both spatially and temporally. This dissertation examines the influence of a spatially complex framework geology on barrier island geomorphology. The purpose of this dissertation is to quantitatively test the hypothesis that framework geology is a driver of coastal morphology where there the framework geology is more complex. The specific objectives of this research are to:

(1) Map the subsurface framework geology using electromagnetic induction (EMI)

(2) Extract beach and dune morphometrics from digital elevation models (DEMs)

(3) Model the influence of subsurface framework geology on barrier island morphometrics across multiple spatial scales

(4) Re-examine the evolutionary history of Padre Island National Seashore (PAIS), Texas in context of framework geology

The specific chapters of this dissertation test the overarching hypothesis that the framework geology affects barrier island morphology and evolution by accomplishing the four objectives. Surface morphometrics are extracted from LiDAR-derived digital elevation models (DEMs) using an automated approach based on relative relief (Chapter 2) in order to examine surface-subsurface relationships. Subsurface framework geology was mapped alongshore by interpreting a combination of ground-penetrating radar (GPR) and electromagnetic induction (EMI) survey data. Wavelet decomposition and bicoherence analyses of surface and subsurface data series quantitatively tests the hypothesis that paleochannels in the framework geology influence barrier island morphology within the channel boundaries (Chapter 3). Autoregressive fractionally-integrated moving average (ARFIMA) models provide insight about how the paleochannels influence barrier island morphology in the alongshore direction outside of the channel edges (Chapter 4). Integrating the wavelet and ARFIMA analyses with surface and subsurface morphometrics enables us to re-examine the accepted evolutionary history of PAIS in context of the framework geology (Chapter 5). Since the currently accepted model of PAIS does not explicitly account for framework geology effects, the developmental history of PAIS is re-examined in Chapter 5 in context of new information from Chapters 2 and 3 regarding the alongshore influence of framework geology on barrier island coastal processes. This study focuses on PAIS because the beach and dune morphology varies substantially alongshore and the underlying framework geology is spatially complex.

CHAPTER II

AN AUTOMATED APPROACH TO EXTRACTING BARRIER ISLAND GEOMORPHOLOGY*

Synopsis

The response and recovery of a barrier island to extreme storms depends on the elevation of the dune base and crest, both of which can vary considerably alongshore and through time. Quantifying the response to and recovery from storms requires that we can first identify and differentiate the dune(s) from the beach and back-barrier, which in turn depends on accurate identification and delineation of the dune toe, crest and heel. The purpose of this chapter is to introduce a multi-scale automated approach for extracting beach, dune (dune toe, dune crest and dune heel), and barrier island morphology. The automated approach introduced here extracts the shoreline and back-barrier shoreline based on elevation thresholds, and extracts the dune toe, dune crest and dune heel based on the average relative relief (RR) across multiple spatial scales of analysis. The multi-scale automated RR approach to extracting dune toe, dune crest, and dune heel based upon relative relief is more objective than traditional approaches because every pixel is analyzed across multiple computational scales and the identification of features is based on the calculated RR values. The RR approach out-performed contemporary approaches and

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represents a fast objective means to define important beach and dune features for predicting barrier island response to storms. The RR method also does not require that the dune toe, crest, or heel are spatially continuous, which is important because dune morphology is likely naturally variable alongshore.

Introduction

The response and recovery of a barrier island to extreme storms depends on the elevation of the dune base and crest, both of which can vary considerably alongshore and through time (Houser et al, 2008; Houser and Mathew, 2011; Houser et al, 2015). Based on the storm impact model of Sallenger (2000), the impact of elevated storm surge depends on the ratio of the total water level elevation (tide + storm surge + wave run-up) to the elevation of the dune base and crest. Even a weak hurricane or tropical storm can overwash or inundate low elevation dunes, moving sediment to the back of the island where it is unavailable for dune recovery. Conversely, larger dunes are scarped and the sediment is transported to either the beach or the nearshore, where the eroded sediment is eventually returned to the beach through the landward migration and welding of the innermost nearshore bars. Nearshore bar welding creates a beach with sufficient volume and fetch to initiate dune recovery, assuming dune-building vegetation is present in sufficient density and extent (Houser et al, 2015). Whereas erosion of the beach and dune occurs over hours and days, it can be years to decades before the beach and dune are able to recover to their pre-storm state (Houser et al, 2015). Quantifying the response to and recovery from storms requires that we can first identify and differentiate the dune(s) from the beach and back-barrier, which in turn depends on accurate identification and delineation of the dune toe, crest and heel. Predicting the resiliency of barrier islands to changes in sea level and storminess ultimately depends on our ability to estimate the rate of post-storm dune recovery.

LiDAR-derived digital elevation models (DEMs) are increasingly used to assess the response and recovery of barrier islands to elevated storm surge, but there are no simple morphometric definitions for the beach and dune. Additional information about more general theory and application of geomorphometry to characterizing features can be found in Dragut and Eisank (2011, 2012), Evans (2012), Fisher et al (2004), and Matsuura and Aniya (2012). Contemporary methods for extracting morphological features from LiDAR data include visual interpretation from aerial and satellite imagery (*e.g.* Hapke, Himmelstoss, et al, 2010; Lentz and Hapke, 2011; Fletcher et al, 2012), manually adjusting a series of inflection points derived from smoothed topographic shore-normal transects (*e.g.* Stockdon et al, 2007; Stockdon et al, 2009), and least-cost flow path (LCP) algorithm (c). Each approach is based on a different definition of the dune base and dune crest (Table 1), which affects estimates of the dune height and volume. Since the development of coastal dunes depends on the ability of vegetation to trap sediment transported landward from the beach by the wind, it is reasonable to assume that the boundary between the beach and dune is associated with a change in slope that is dependent on the seasonal pattern of vegetation growth and beach and dune erosion and scarping over a sequence of storm events.

A common approach to feature identification is to reduce a DEM to a series of smoothed shore-normal transects, and identify inflection points based on the change from positive slope gradient to negative slope gradient (Stockdon et al, 2007; Stockdon et al, 2009). The inflection points are interpreted as the dune crest position for a given transect and the dune crest line is extracted by manually connecting and adjusting the series of inflection points. The degree of smoothing directly affects the identified location of the dune crest. The results of this method are significantly limited by the transect spacing and the location of transects, as the morphometry of dune crests can change continuously alongshore. Data in the areas between the shore-normal transects is neglected from any analysis, which generates error and uncertainty. For example, a transect spacing of 1 m will yield a different result than a 5 m or 10 m spacing, depending on the natural variability of the beach and dune morphology. After an automated algorithm has determined the dune crest points from every cross-shore profile, the points are manually edited in order to "*eliminate occasional dune picks associated with spurious LiDAR points*" (p. 61 Stockdon et al, 2009). Manual editing of the extracted points can be time-intensive, requires a-priori knowledge of the local morphology, and injects subjectivity into the extracted location of the dune crest line.

The LCP approach can be used to identify the dune crest and dune toe by utilizing a LCP algorithm to connect two "given endpoints" (Mitasova et al, 2011). The cost function of Mitasova et al (2011) is computed as:

$$J = e^{-bz} \tag{1}$$

Where J is the cost of traversing a cell, z is the elevation of the cell, and b is a tunable parameter. There is no information on how this tunable parameter is determined or how an appropriate value is determined. Absent from this method is a clear and objective method to identify the endpoints, which are likely to come from subjective manual interpretation of the DEM or a similar data source. Another drawback to the LCP approach is its inability to identify the trailing edge of the dune (*i.e.*, dune heel), which is important for calculating dune volume. These different methods for extracting dune morphology are time-intensive for large study areas, depend heavily on the scale of analysis, and/or do not provide a means to extract the dune heel.

The purpose of this chapter is to introduce a multi-scale automated approach for extracting beach, dune (dune toe, dune crest and dune heel), and barrier island morphology. The automated approach introduced here extracts the shoreline and back-barrier shoreline based on elevation thresholds, and extracts the dune toe, dune crest and dune heel based on the average relative relief (RR) across multiple spatial scales of analysis. This approach to feature extraction is not subject to error due to DEM smoothing, visual interpretation, arbitrary cost-function parameterization, and takes into account information across multiple computational scales. The effectiveness of this approach to extract coastal features and metrics is demonstrated using a LiDAR-derived DEM for a portion of North Padre Island, Texas, USA (Figure II.1) because this section of North Padre Island exhibits considerable alongshore variability in dune morphology. The sample DEM used is simply meant to demonstrate that beach, dune and barrier island features can be extracted using an automated approach in an area with variable dune morphology.

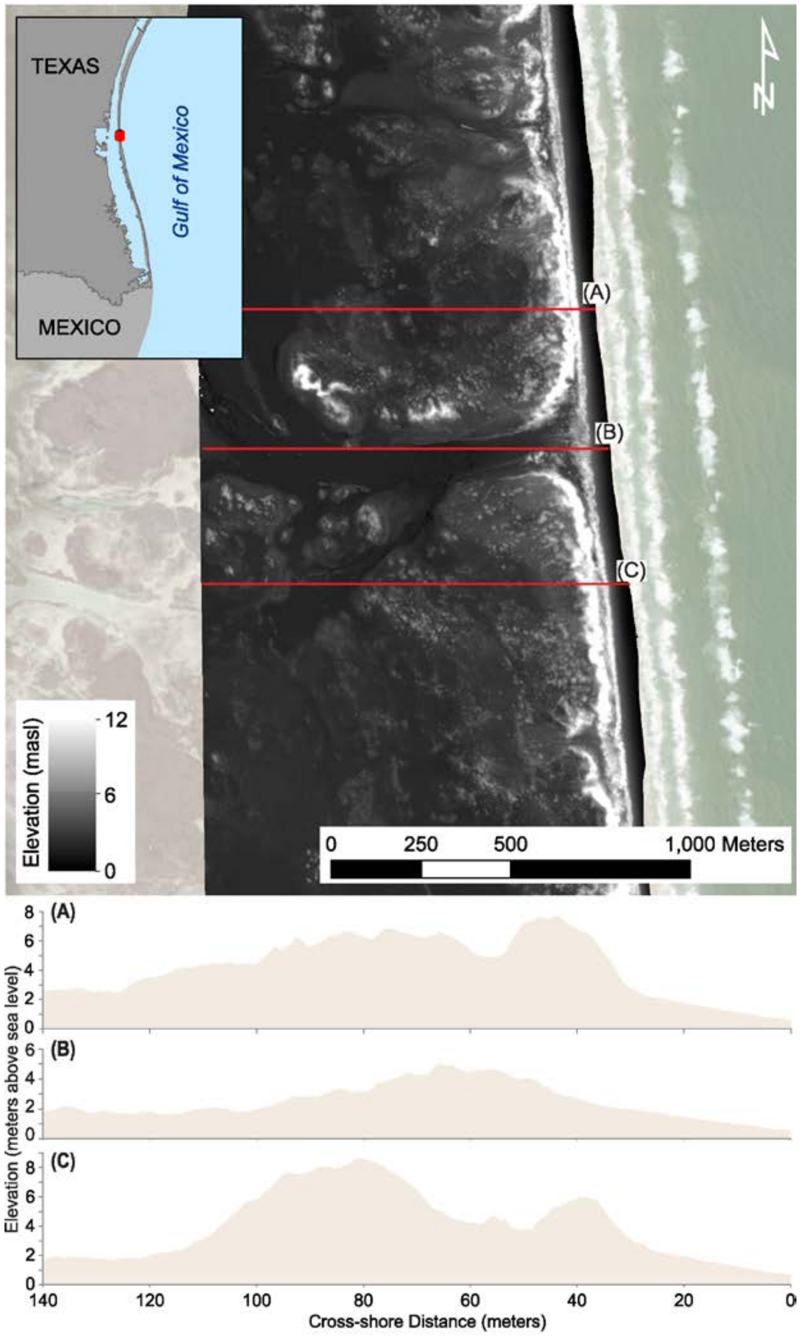

Figure II.1 The case study for the RR approach is located approximately 70 km south of Corpus Christi, TX and is situated on North Padre Island between the Gulf of Mexico and Laguna Madre (inset map). The DEM clearly exhibits a highly variable morphology with a washover channel in the northern portion of the DEM.

Relative Relief and Convergence/Divergence Approaches

Relative relief is an indicator of topographic position, which makes it very useful in identifying morphologic features that include topographic position in the semantic definition. Dune toe, dune crest and dune heel are three coastal geomorphology features that can be differentiated based on their topographic position and adjacency to each other. Consistent with the definitions provided in Table 1, the dune toe is a topographic low (*i.e.* low RR value) that is adjacent to and landward of the shoreline; dune crest is adjacent to and landward of the dune toe, and is a topographic high (*i.e.* high RR value). Similar to dune toe, the dune heel is a topographic low (*i.e.* low RR value), but it is adjacent to and landward of the dune crest. Since elevations on the stoss side of a dune are more heterogeneous than those on the lee side of the dune, the dune heel will have a slightly higher RR value than the dune toe. Relative relief can be computed as:

$$RR_c = \frac{(Z_c - Z_{min})}{(Z_{max} - Z_{min})} \tag{2}$$

where RR_c is the relative relief at the center location of a window, Z_c is the elevation at the center of the window, Z_{min} is the minimum elevation within the specified window, and Z_{max} is the maximum elevation within the specified window. To ensure stability of computed values in cases where there is no relief, RR_c is set equal to 0. The metric is a measure of topographic position and ranges from 0 (local topographic bottom) to 1 (local topographic top). The computational scale (*i.e.* window size) and resolution of the source data affect the identification of any given feature by constraining the available information

(Figure II.2). Since the distance over which a parameter is calculated directly controls the resulting values, calculating geomorphic parameters across multiple scales enables us to examine large scale and small-scale features simultaneously, which is important when analyzing polygenetic landscapes.

Table II.1 Traditional definitions of the “dune toe” and “dune crest”.

	Dune Toe	**Dune Crest**
Lentz and Hapke, 2011	"delineated from elevation and slope changes observed landward of the berm"	"traced using the maximum elevation of the seaward-most dune crest"
Stockdon et al, 2007; Stockdon et al, 2009	"the location of maximum slope change within a region around a coarsely digitized line"	"highest-elevation peak, where the slope changes sign from positive (landward facing) to negative (seaward facing)" "highest elevation peak landward of the shoreline and within a user-defined beach width"
Mitasova et al, 2009; Mitasova et al, 2011	"the location where the beach meets the foredune" “the location where the cross-shore profile deviates the most from a line connecting the dune ridge and shoreline”	"the least cost path between two given end points of the ridge"

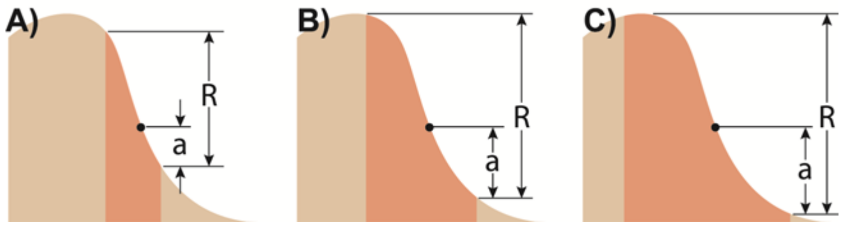

Figure II.2 Example of how changing the window size of the analysis affects the calculated relative relief for a (A) small window size, (B) moderate window size and (C) large window size. The window size directly controls the data used to calculate the parameter.

Features can be extracted by comparing the elevation or average RR value to a threshold that is based on a semantic definition of the landscape feature and the histogram of computed RR values. Automated feature extraction works by moving landward from the shoreline across every row in the DEM until an elevation or RR threshold is crossed. The RR threshold for the dune toe, crest and heel should be based on the histogram of calculated average RR values. Dune crest is conceptually the inverse of the dune toe, such that the RR threshold for the dune crest can be assumed to be the inverse of the dune toe RR threshold, and can be calculated as 1 minus the dune toe RR threshold. The dune height, an essential measure of the ability of a dune to withstand subsequent storms, can be calculated by subtracting the dune toe elevation from the dune crest elevation.

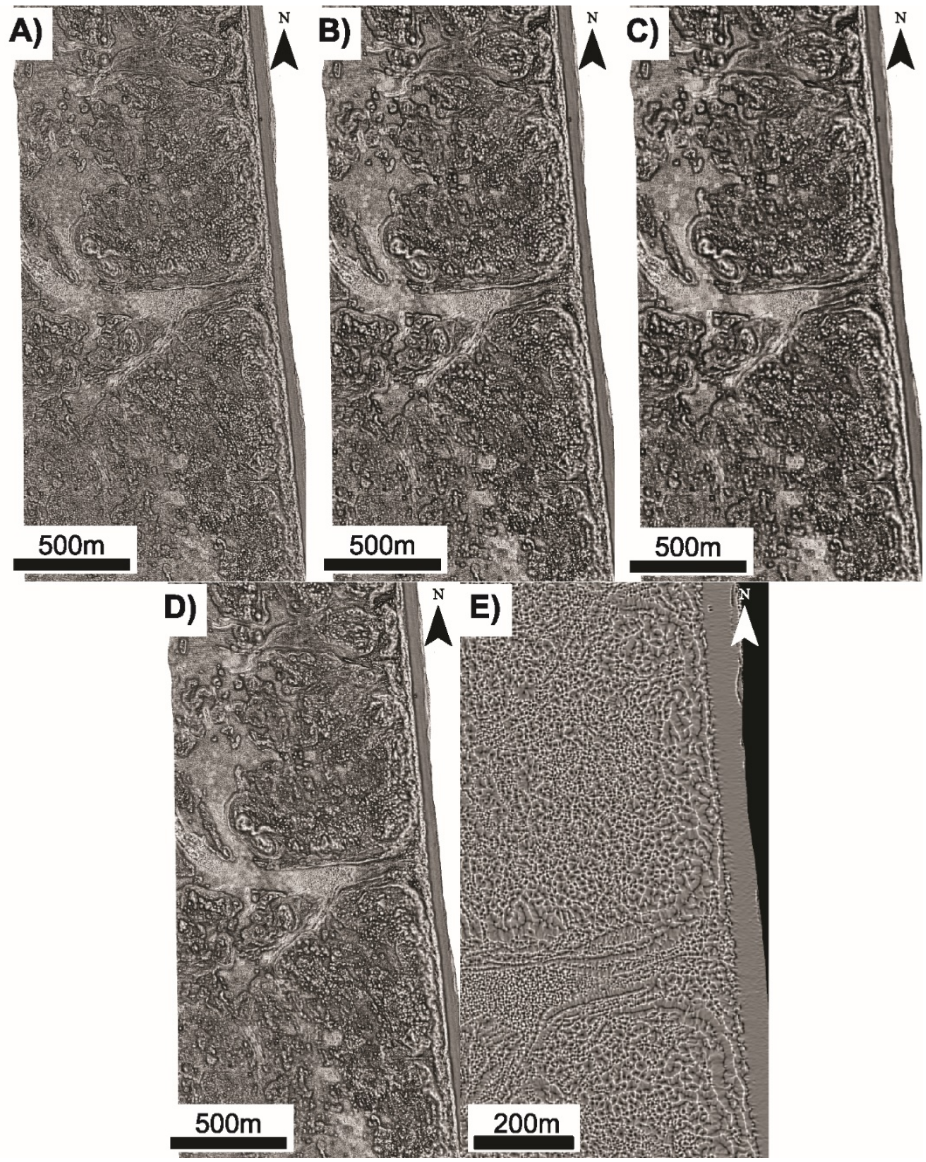

Figure II.3 Effect of window size on the resulting relative relief surface using a (A) 9x9 window, (B) 15x15 window, (C) 21x21 window and (D) average RR across 9x15x21 window sizes. (E) The divergence index computed across the same area.

The computational scale affects the signal-to-noise ratio and distribution of RR values (Figure II.3 and Figure II.4). The RR approach addresses the issue of scale by averaging RR across multiple spatial scales of analysis. Patterns consistent across multiple scales can be thought of as a topographic signal, whereas variation in RR across multiple scales can be thought of as noise. Large windows highlight larger geomorphic features (*i.e.* larger dunes) because a larger window size is not as sensitive to localized topographic variability. This pseudo-spatial averaging approach increases the signal-to-noise (SN) ratio because the signal will be amplified, while the noise reduced, making the average RR an ideal metric for automated feature extraction. The multi-scale spatial averaging approach is very useful because the information consistent across all three RR calculations (*i.e.* signal) is enhanced, while variation only found at a single scale (*i.e.* noise) is reduced. Therefore, the average RR has a greater signal-to-noise ratio by both decreasing landscape noise and amplifying landscape signal. Average RR highlights the dune toe, dune crest and dune heel more effectively than the RR computed using a single window size. The distribution of average RR values across multiple computational scales (Figure II.4) should be used as a foundation for setting the RR thresholds for dune toe, dune crest and dune heel.

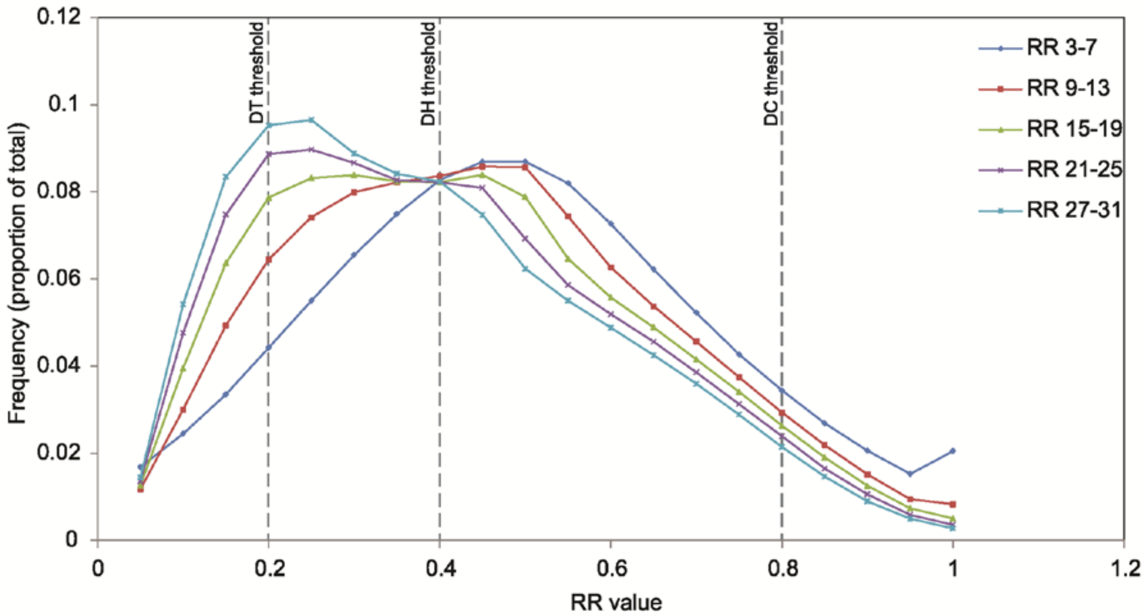

Figure II.4 Effect of window size on the distribution of relative relief values. Note that as the window size increases, the data distribution shifts from normally distributed about a single value to bimodal with a second peak centered on a RR of 0.2. The RR threshold for dune toe, dune crest, and dune heel should be based on the histogram of the calculated average RR values.

An alternative approach is to identify the dune toe, dune crest and dune heel by characterizing the slope azimuth (ϕ) divergence and convergence over an area with respect to each location on the landscape. For example, the dune toe is represented by locations exhibiting maximum convergence at the base of a dune and the dune crest is a location of maximum divergence. A divergent index (DI) that represents divergence and convergence can be computed as:

$$DI = (\cos\phi_c - \cos\phi_i) + (\sin\phi_c - \sin\phi_i) \quad (3)$$

where ϕ_c represents the slope azimuth for the center location of a window, and ϕ_i represents the planimetric azimuth of the *i*th location in a window, with the origin being the center location. The DI is relatively high over dune crests, and relatively low at the base of dunes where the local azimuth orientations are convergent (Figure II.4). Given this approach, areas of maximum divergence (minimum convergence) can be used to identify dune peaks or crests, and maximum convergence can be used to identify the dune toe, although accurate characterizations depend on the measurement scale of the DEM and the computational scale of analysis (*i.e.* window size). Based on tacit knowledge of North Padre Island beach and dune morphology, we computed the divergence index using a window size of 5 by 5 pixels.

Results

The feasibility of the proposed multi-scale automated approach to extract the shoreline, dune toe, dune crest, dune heel and back-barrier shoreline is shown in Figure II.5 and Figure II.6. These features were effectively extracted by averaging the RR values across window sizes of 21, 23, and 25 m because the second mode centered on 0.2 begins to appear at these large window sizes (Figure II.4). The selected window sizes were based on personal experience and knowledge of variability in dune morphology throughout the study area. The approximate horizontal distance between dune crest and dune toe, based on field observations, is approximately 11 m. Since RR is computed based on the elevation of the center pixel relative to the maximum and minimum elevations within the computational window, setting the initial computational window size to 21 m increases the likelihood that RR at the dune toe location is an extreme local minimum. Doubling the approximate average horizontal distance between dune toe and dune crest also increases the likelihood that the dune crest location is a local RR maximum. Extracting features using large window sizes is more likely to select general features, without being as sensitive to fine-scale variability inherent to LiDAR-derived DEMs. In other words, the average RR for large window sizes is more likely to encapsulate the entire crest and toe of the dune. This means that the dune toe and dune crest RR values are more likely to be at the minimum and maximum, respectively, within the window.

Shoreline and Back-barrier Shoreline

The shoreline can be identified as the location landward of the surf zone where the elevation crosses above 0.02 m above sea-level (masl). Ideally, this threshold would be set to 0.0 masl; however, this is not feasible with the red-wavelength LiDAR-derived DEM used here because waves in the surf zone (visible to red-wavelength LiDAR) regularly exceed 0.0 masl. The back-barrier shoreline can be determined as the location landward of the shoreline where elevation crosses below 1.0 masl. This threshold was determined because the water-plane elevation is approximately 1.0 m higher on the back-barrier side of the island than it is on the open ocean side of the island.

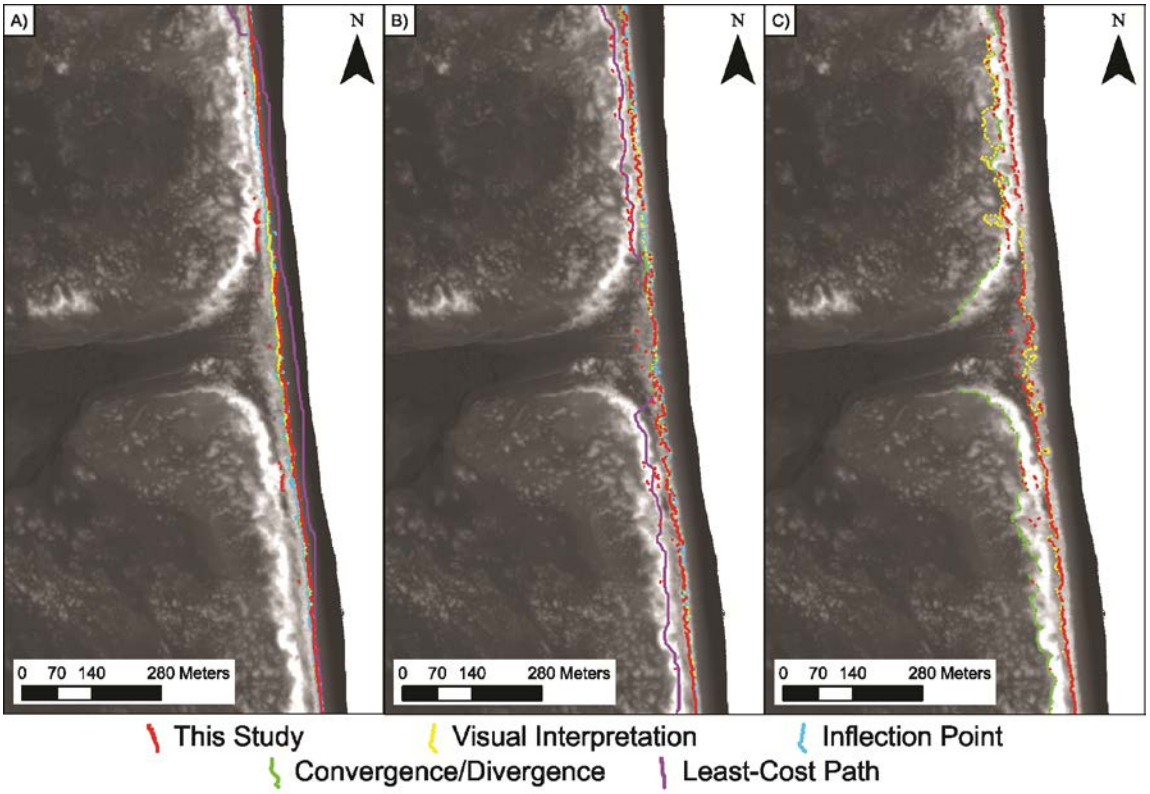

Figure II.5 Comparison of the (A) dune toe, (B) dune crest (C) and dune heel as extracted by the approach from this study and contemporary approaches.

Dune Toe

The dune toe can be identified as the first location landward of the shoreline where the average RR crosses 0.2. This threshold was determined based on the histogram of average RR values across multiple scales (Figure II.4) and conceptual understanding of what constitutes the beach-dune interface. As the window size increases, the data distribution shifts from normally distributed about a single value to bimodal with a second peak centered on a RR of 0.2. Although the dune toe morphology is variable alongshore, it is most likely to occur within the lowermost 20^{th} percentile of the surrounding topography (*i.e.* RR ≤ 0.20). Dune toe position, as extracted by the proposed automated RR approach, is different than conventional methods (Figure II.5 and Figure II.6). The extracted dune toe appears to be more consistent with contemporary understanding of dune morphology compared to the other methods for extracting the dune toe, as the dune toe from this study appears to more accurately capture the most seaward inflection point described in the traditional definitions of the beach-dune interface. The dune toe is seaward of the maximum seaward extent of vegetation (*i.e.* vegetation line; Figure II.6), which serves as a conventional indicator of dune toe position, as this is the point of sediment deposition in the cross-shore. The dune toe position extracted using the automated RR, visual interpretation, and DI approaches have similar dune toe elevation distributions that are generally higher than the inflection point and LCP approaches (Figure II.7).

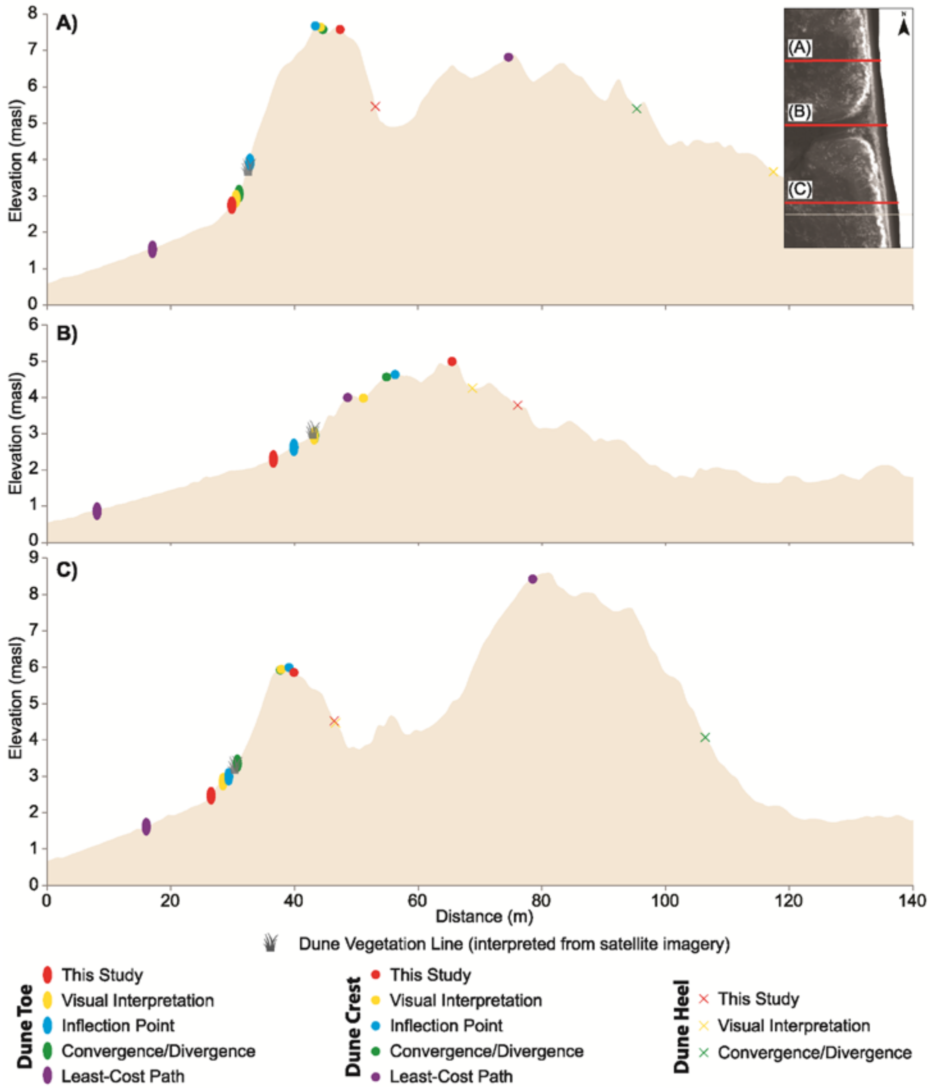

Figure II.6 Location of the dune toe, dune crest and dune heel across all methods for profiles A, B and C. Profiles A and C are not washed over; however, profile B is located within an overwash channel. The dune vegetation line is interpreted from satellite imagery as the maximum seaward extent of vegetation. Dune heel position using the convergence/divergence approach is absent from profile B because there was no line of convergence behind the dune crest within the overwash channel.

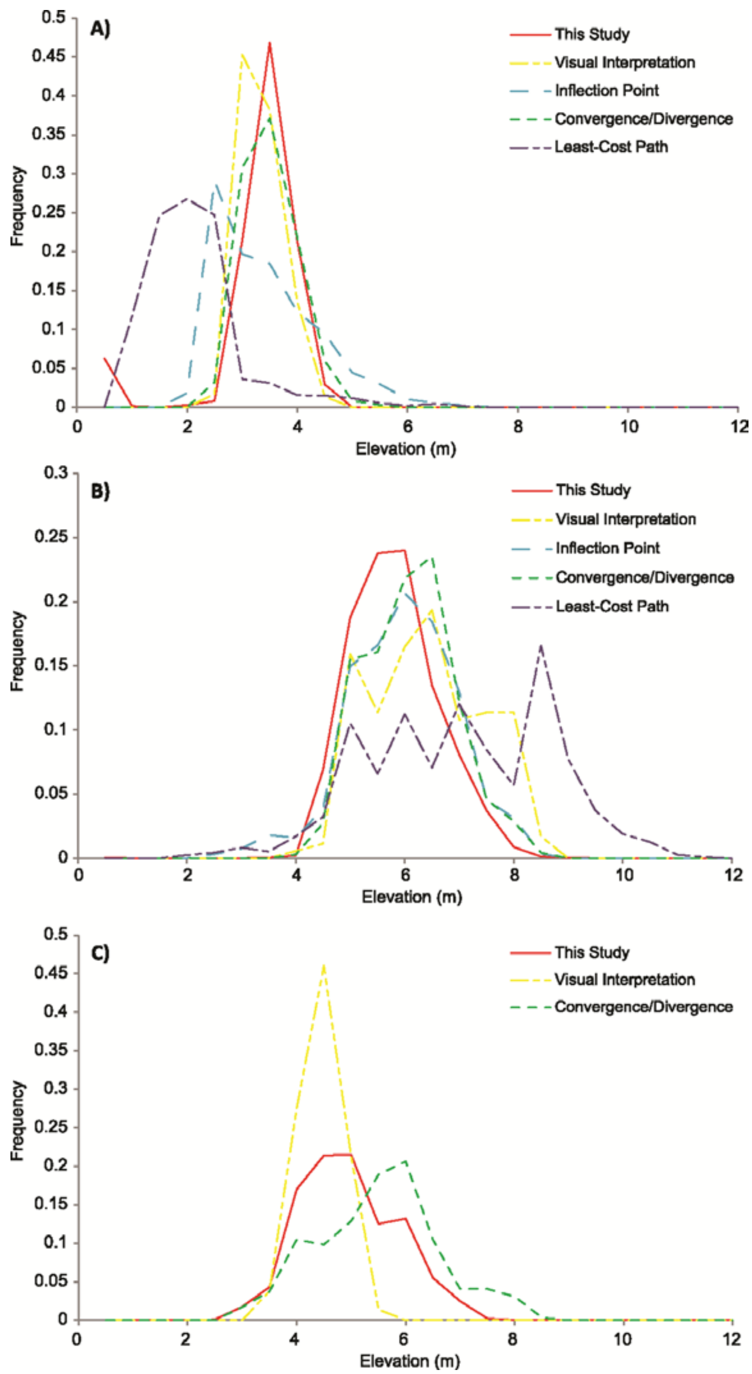

Figure II.7 Histogram of the elevation distribution extracted from this study and contemporary approaches for the (A) dune toe, (B) dune crest and (C) dune heel.

Dune Crest

Dune crest position was determined as the location landward of the dune toe where RR values cross 0.8, because it is conceptually the inverse of the dune toe. The dune crest position extracted by the multi-scale automated approach is also different from the contemporary methods (Figure II.5 and Figure II.6). The multi-scale RR approach out-performs the contemporary methods most notably in the washover channel (Figure II.7), where the RR extracted crest is located directly on the peak elevation of the foredune and other approaches are either downslope to either side of the peak elevation or on another adjacent elevation peak. The dune crest extracted using LCP is most different from the automated RR extracted dune crest, where the LCP dune crest jumps to the secondary dune ridge in the central two-thirds of the DEM. It should be noted that pre-processing the DEM to remove the secondary dune ridge would likely force the LCP extracted dune crest to stay along the foredune; however, this pre-processing is subjective, time-intensive, and requires a-priori knowledge of the local morphology. Additionally, the dune crest extracted using the automated RR approach has a more consistent elevation distribution compared to the other methods (Figure II.7). The visual interpretation and LCP dune toe elevations are multi-modal because both methods tended to jump to the secondary dune crest in some locations of the island.

Dune Heel

Similar to the dune toe, the dune heel is a topographic low that is landward of the dune crest. However, elevations landward of the dune crest are more variable, and a higher

RR threshold should be set to account for this increased variability when extracting the dune heel. The RR threshold used to extract the dune heel was set to 0.4 because this is the inflection point in the average RR histogram as the window size increases (Figure II.4). This slightly higher RR threshold for dune heel accounts for the greater variability in elevation along the lee side of the dune. Dune heel extracted using the automated RR approach differs from the manually interpreted dune heel and DI dune heel (Figure II.5 and Figure II.6). It is not possible to compare the multi-scale RR extracted dune heel to the inflection point or LCP approaches because both inflection point and LCP conventional approaches cannot be used to identify the dune heel.

Conclusion

This chapter describes the ability of a new multi-scale approach for extracting key geomorphic features (*e.g.* dune toe, dune crest, dune heel) from a high-resolution DEM of North Padre Island, Texas, USA. The multi-scale RR approach demonstrated by this study utilizes an automated approach based upon thresholding for extracting key geomorphic features, such as the shoreline, dune toe, dune crest, dune heel and back-barrier shoreline. The multi-scale automated RR approach to extracting dune toe, dune crest, and dune heel based upon relative relief is more objective than traditional approaches because every pixel is analyzed across multiple computational scales and the identification of features is based on the calculated RR values. The RR approach out-performed visual interpretation, least-cost path (LCP), and shore-normal transect inflection point approaches and represents a fast objective means to define important beach and dune features for predicting barrier island response to storms. The RR approach does not require the user to manually interpret the morphology from a DEM (Hapke, Himmelstoss, et al, 2010; Lentz and Hapke, 2011; Fletcher et al, 2012), manually adjust and edit a series of inflection points that were derived from artificially smoothed DEM profiles (Stockdon et al, 2007; Stockdon et al, 2009), input a set of arbitrary start and end points to an arbitrary cost function for LCP analysis (Mitasova et al, 2011). In addition, the average RR approach is able to extract the dune toe, dune crest and dune heel; whereas, the DI approach is limited to extracting the dune toe and dune crest. The RR method also does not require that the dune toe, crest, or heel are spatially continuous, which is important because dune morphology is likely naturally variable alongshore (Houser et al, 2008; Houser and Mathew, 2011; Houser et al, 2015). For example, dunes within a washover channel are more discontinuous than dunes to either side of the channel. The approach, however, does require the selection of reasonable threshold values, which can be based on the observed distribution of RR values across the DEM. This chapter demonstrates that the average RR approach can be automated and is a feasible approach to extracting barrier island morphology. Additional research is required to (1) test the broader geographic applicability of the average RR approach, (2) automate the selection of appropriate threshold parameters and (3) automate the selection of an appropriate window size. Automating the selection of threshold parameters and window sizes represents a significant challenge as both of these factors will likely vary spatially in response to alongshore variations in dune morphology.

CHAPTER III

INFLUENCE OF A SPATIALLY COMPLEX FRAMEWORK GEOLOGY ON ISLAND GEOMORPHOLOGY

Synopsis

Barrier island response and recovery to storms and sea level rise can exhibit both free and forced behavior, which affects island transgression. The influence of framework geology on barrier island geomorphology and geomorphic change has previously been examined in areas where the framework geology is relatively simple or rhythmic. The purpose of this chapter is to examine the influence of framework geology on beach and dune geomorphology at Padre Island National Seashore (PAIS), where the framework geology is variable. Alongshore beach and dune morphometrics and offshore bathymetric profiles were extracted from a topobathy digital elevation model (DEM) using an automated approach. An electromagnetic induction (EMI) survey of PAIS was used to map the subsurface framework geology. Wavelet decomposition, peak spectral density (PSD), and bicoherence analyses were used to test for spatial relationships between and within the extracted alongshore metrics. PSD trendlines demonstrate that beach and dune morphometrics are structurally controlled. Hotspots in wavelet coherence plots between framework geology and alongshore island morphometrics indicate that paleochannels dissecting the island influence the beach and dune morphometrics. Bicoherence analysis of alongshore beach and dune morphometrics indicates that low-frequency oscillations

due to framework geology significantly interact with higher-frequency oscillations. This chapter presents new evidence that the framework geology interacts non-linearly with daily coastal processes to influence barrier island geomorphology. Accurately predicting future barrier island geomorphology is predicated on comprehensively understanding how a multitude of coastal processes interact. This chapter statistically demonstrates that the framework geology influences daily coastal processes non-linearly, which should be integrated into future barrier island change models.

Introduction

Barrier island morphology is the product of past and present processes operating over pre-existing topography and bathymetry. Modelling the large-scale behavior of coastal environments is of paramount importance to local, state, and federal agencies and has been recognized by the U.S. Geological Survey (USGS) as an essential focus. Studies of barrier islands along the U.S. Atlantic and Gulf of Mexico coasts demonstrate that subsurface geology influences patterns of island development and transgression at broad geographic scales (Riggs et al, 1995; Lazarus et al, 2011; Lentz and Hapke, 2011; Houser, 2012; Schwab et al, 2013), although previous studies have focused on coasts with relatively straightforward framework geology. Improving our understanding of the role of subsurface geology on coastal development was recognized by Riggs et al (1995), stating that "*it is imperative to incorporate the geologic framework into all models concerning the large-scale behavior of any coastal system*" (p. 215). Used here, framework geology is defined as any subsurface variation in geologic structure, where geologic structure can be caused by variations in sediment type (*i.e.* sand vs. silt), differences in compaction, or significant changes in the subsurface organic content or mineralogy. Examples of framework geology features identified along the U.S. coast include relict infilled paleochannels (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006), mud-core ridges (Houser and Mathew, 2011; Houser, 2012; Houser et al, 2015), shore-oblique gravel ridges (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011), and submerged outwash fan headlands (Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014). The influence of framework geology on barrier island geomorphology is often overlooked when predicting future change and managing coastal resources.

The importance of modelling historical coastal morphology and predicting future coastal morphological changes and vulnerability is highlighted by recent work focused on: (1) improving our understanding and predictions of storm impacts, (2) improving long-term coastal change assessments, and (3) understanding coastal vulnerability to climate change and sea-level rise. Current models for predicting coastal morphologic change used by the USGS (*i.e.* XBeach) classify the expected dune response as swash, collision, overwash, or inundation, based on the Sallenger (2000) storm-impact model, where the swash regime is the least impactful to dune morphology and overwash and inundation have the potential to completely erode the dune. Classification performed using a Bayesian Network (BN) approach where water run-up is simulated over the modern beach and dune topography (Stockdon et al, 2006; Plant and Stockdon, 2012; Long et al, 2014; Wilson et al, 2015). The BN approach is a valuable approach to predicting future changes, although it is subject to uncertainty in the beach slope and dune height parameters and is limited by its ability to classify the expected response into one of four categories. One way to improve our long-term models of coastal morphology is to incorporate the effects of framework geology, which is often expressed in the nearshore bathymetry as shore-oblique bar and trough structures.

Offshore shore-oblique bar and trough structures have been documented at South Padre Island, Texas, (Houser and Mathew, 2011), Pensacola Beach, Florida, (Houser et al, 2008; Houser, 2012; Houser et al, 2015), along the southeastern U.S. Atlantic coast (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011), and at Fire Island, New York (Lentz and Hapke, 2011; Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014). At South Padre Island, the origin of the bar and trough features is unclear, although it is plausible that they are formed from the ancestral Rio Grande paleo-river delta, which has been identified by Simms et al (2007) and Anderson et al (2016). Presumably, sediment from the delta has been reworked into the modern bar and trough sequences by waves approaching the coast at oblique angles. Troughs in the nearshore bathymetry correspond to narrow sections of the beach and taller dunes.

Shore-oblique bars at Pensacola correspond to mud-core ridges formed through overwash processes during island transgression (Hyne and Goodell, 1967; Stone, 1991). Similar structures are present along portions of the southeastern U.S. Atlantic coast and are related to relict subsurface paleochannels infilled during Holocene sea-level transgression (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006). Shoreface attached sand ridges (*i.e.* SASR; shore-oblique ridges) present at Fire Island, NY are proposed to be oceanographically formed and maintained, with a sandy submerged headland as the sediment source (Schwab et al, 2014; Warner et al, 2014). The origin of shore-oblique ridges and swales at South Padre Island remains unclear, although it is plausible that they are composed of reworked sediment derived from the ancestral Rio Grande paleo-river delta, identified by Simms et al (2007) and Anderson et al (2016). Presumably, sediment from the delta has been reworked into the modern bar and trough sequences by waves approaching the coast at oblique angles. Troughs in the nearshore bathymetry along South Padre Island correspond to narrow sections of the beach and taller dunes. The prevailing hypothesis about the location and morphology of many shore-oblique bar and trough features is that their location and morphology is influenced by framework geology interacting with and influencing oceanographic wave refraction patterns (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Houser, 2012; Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014).

Shoreline variability and erosional hotspots along the southeastern U.S. coast have also been linked to shore-oblique bars and infilled paleochannels in the framework geology (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011), where relict infilled paleochannels are associated with areas exhibiting punctuated shoreline change. Lazarus et al (2011) suggested that dominant driver of shoreline change varies over distinct spatial scales and that the dominant coastal processes will likely gradually transition along this continuum. For example, Lazarus et al (2011) suggested that surf-zone currents, as reflected by sand bar dynamics, is the dominant driver of coastal geomorphology between 30 m and 500 m alongshore length scales, but that wave propagation over complicated bathymetry, as reflected by persistent kilometer-scale bedforms, begins to influence coastal geomorphology at 300 m alongshore length scales. At the broadest alongshore length scales, it was hypothesized that the dominant driver of coastal geomorphology is wave-driven alongshore sediment transport gradients, although this hypothesis was not testable because the dataset did not extend far enough along the coast. The linear transition of dominant coastal processes with increasing alongshore length scales suggests that finer-scale processes cease to be a significant driver of coastal morphology at larger alongshore length scales. This hypothesis does not account for the influence of framework geology in coastal evolution, nor does it account for potential interactions between broad-scale processes and fine-scale processes.

The purpose of this chapter is to test the hypothesis that framework geology interacts with more frequent coastal processes to influence barrier island geomorphology. Previous research has focused solely on the influence of framework geology at discrete alongshore length scales; however, it is feasible that the framework geology influences broad-scale coastal processes, which interact non-linearly with finer-scale coastal processes (*i.e.* nearshore and shoreface wave-dominated sediment transport), to modify coastal geomorphology. This chapter represents an opportunity to quantify the interaction between large- and small-scale coastal processes by using a combination of wavelet decomposition, bicoherence analyses, and wavelet coherence. Wavelet decomposition provides valuable insight into phase relationships between different island morphology variables, while bicoherence analyses help identify non-linear interactions between long-term (broad-scale) coastal processes and short-term (fine-scale) coastal processes. An extension of wavelet decomposition, wavelet coherence provides information about phase relationships between two variables. Understanding and quantifying the influence of framework geology as it interacts with shorter-term coastal processes is vital to managing coastal resources for short- and long-term sustainability.

Regional Setting

Padre Island National Seashore is a U.S. National Seashore encompassing a large portion of the longest continuous barrier island in the world. Located along the south Texas, USA coast, PAIS represents an ideal location to test for and quantify the influence of framework geology on long-term coastal morphology because it has documented geomorphic variability in the subsurface framework geology (Figure III.1; Fisk, 1959; Simms et al, 2007; Anderson et al, 2016). In addition, the modern surface morphology appears significantly different in the central part of the island compared to the northern and southern parts of the island. Central PAIS is characterized by large, relatively continuous dunes, compared to the elongated parabolic dunes in the north and the heavily scarped and dissected dunes in the south. It is separated from the mainland by Laguna Madre and the Intracoastal Waterway (ICW), which was dredged during the 1950s.

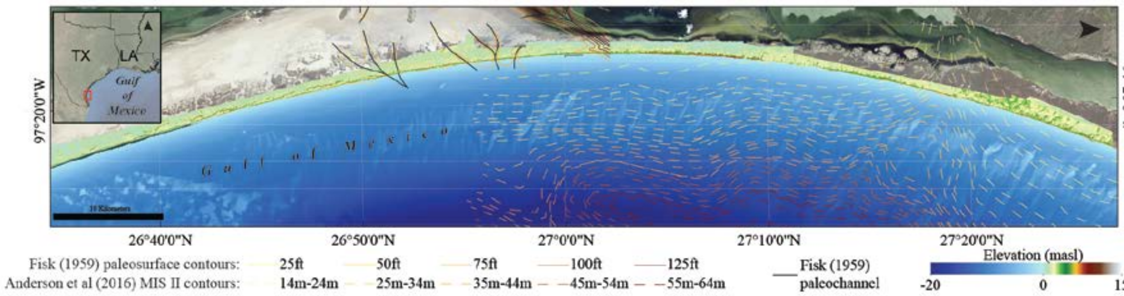

Figure III.1 Padre Island National Seashore topobathy DEM with MIS II subsurface contour lines from Fisk (1959) and Anderson et al (2016).

A previous study of the Laguna Madre and PAIS area used seismic surveys and sediment cores to demonstrate that there is significant variation in the underlying subsurface geology (Figure III.1; Fisk, 1959). While the study did not cover the entire length of Laguna Madre and PAIS, results indicated that there are multiple paleochannels dissecting the central part of Laguna Madre and PAIS. These channels were hypothesized to have been incised into the Pleistocene mud surface and infilled with sands during Holocene sea-level transgression. This chronology is consistent with the prevailing theory of formation of PAIS proposed by Weise and White (1980), where the island was initially a series of disconnected barrier islands during the last glacial maximum (~18ka). During this time, a series of channels were incised into the paleo-topographic surface. Rapid sea-level transgression during the late-Pleistocene and Holocene drown the relict dunes and submerged other dunes located approximately 80 km inland, resulting in disconnected offshore shoals in the current location of PAIS. Sand from the relict Pleistocene dunes (~80 km offshore) and sediment discharged from rivers was reworked via alongshore currents around 2.8 ka, causing the disconnected shoals to coalesce into a more continuous shoal. It was hypothesized that sediment from the offshore relict dunes and river discharge eventually supplied enough sediment to cause the shoals to aggrade vertically enough to emerge as the modern barrier island (Weise and White, 1980).

Anderson et al (2016) integrated offshore seismic surveys throughout the Gulf of Mexico to identify and extract the marine isotope stage (MIS) II paleo-surface (Figure III.1). Knick points in the MIS II surface offshore of PAIS indicate that the island is dissected by at least two substantial paleochannels. The southern channel visible in the surface is in relative agreement with the location of the channel identified by Fisk (1959) in Laguna Madre and PAIS. This channel appears to make an abrupt bend to the north offshore of PAIS, and eventually intersects a large northern paleochannel immediately adjacent to Baffin Bay. Simms et al (2007) and Anderson et al (2016) identified this paleochannel as the ancestral Los Olmos, San Fernando, and Patronila Creeks that were drowned during the most recent sea level transgression and eventually filled with sediment. The combination of relict infilled paleochannels and complex modern island geomorphology make PAIS an ideal location to test the hypothesis that the framework geology influences barrier island geomorphology through interactions with higher-frequency processes.

Methods

Subsurface Framework Geology

Information about the subsurface framework geologic structure was derived from a ~100 km long electromagnetic induction (EMI) survey. Subsurface apparent conductivity was measured every 10m along the backbeach at 3 kHz, 10 kHz, and 15 kHz using a GSSI EMProfiler 400 portable handheld device. Previous research demonstrates that EMI is a valuable tool for investigating subsurface geologic structure in a marine coastal environment (Weymer et al, 2016). The current paper builds on previous work by utilizing an alongshore EMI survey as a proxy for subsurface framework geology. Areas of lower apparent conductivity are interpreted as areas where the Pleistocene ravinement surface is deeper from the modern surface and the instrument is only measuring the conductivity of the Holocene sands overlying the Pleistocene paleo-surface. Conversely, a shallower Pleistocene ravinement surface is represented by areas of higher apparent conductivity because the finer sediment ravinement is more conductive than the overlying Holocene sands.

Surface Morphology

Surface morphology for PAIS is derived from LiDAR data accessible from NOAA's Digital Coast. Raw point cloud data was processed into a digital elevation model (DEM) using System for Automated Geoscientific Analyses (SAGA) GIS software. A semivariogram was fit to the raw point cloud elevation values to account for spatial structure in the point cloud. An ordinary kriging algorithm was used with the semivariogram parameters to interpolate the point cloud to a continuous 1m resolution DEM. The LiDAR data available was acquired using a sensor operating in the red portion of the electromagnetic spectrum, and, as a result, does not capture subaqueous surfaces. Since the LiDAR-derived DEM does not include the bathymetric surface, depth to water bottom was obtained from a National Geophysical Data Center (NGDC) coastal relief model (CRM). The CRM and DEM were fused at the land-water interface, resulting in a seamless topo-bathymetric (topobathy) DEM.

Island morphometrics were extracted from the topobathy DEM using a multi-resolution automated approach based on relative relief (Wernette et al, 2016). The shoreline location was extracted as 0.2 meters above sea level (masl), which is slightly above the tallest breaking wave present in the DEM. Beach width, beach volume, dune height, dune volume, island width, and island volume were extracted every 1 m along ~100 km of PAIS, resulting in a series of continuous alongshore signals (Figure III.2). The shoreline extracted from the topobathy DEM was offset seaward in 1 km intervals up to 7km offshore in order to get bathymetric depth profiles along the entire island (Figure III.2).

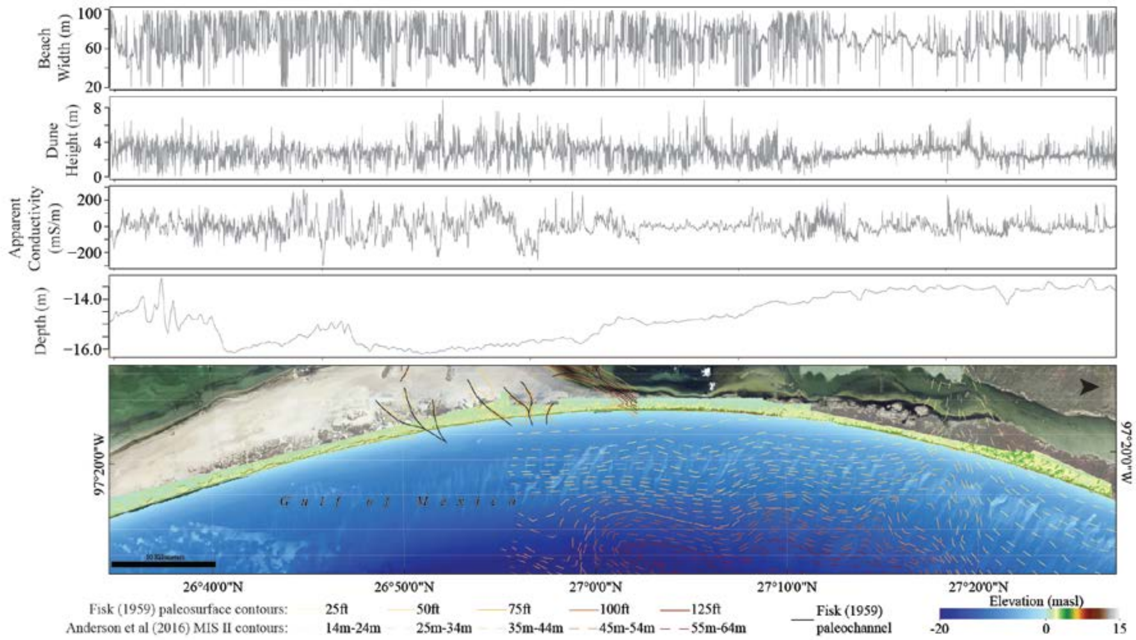

Figure III.2 Sample alongshore spatial data series for barrier island surface, subsurface, and bathymetric morphology. From top to bottom, the alongshore spatial data series are: beach width, dune height, apparent conductivity, and 4 km offshore bathymetric depth profile.

Shoreline Change

Monitoring patterns of long- and shore-term shoreline change is a continuing focus of the Texas Bureau of Economic Geology (BEG). Historical shoreline position along much of the Texas Gulf of Mexico coast was derived from a combination of historical maps, aerial imagery, and LiDAR. The provided BEG shoreline change values were computed using intermittent shoreline position data from 1950 to 2007 (67 years). Shoreline change analysis was conducted by the BEG using the digital shoreline analysis system (DSAS), which employs a series of traditional shore-orthogonal transects extending from a baseline. In order to assess long-term patterns of shoreline change, we utilize the end-point rate (EPR) approach. The EPR change estimate is a simple linear distance between the locations along a transect where the shoreline at time t_0 and shoreline at time t_1 intersect the transect. These intersecting points represent the sum of short-term processes to influence long-term shoreline change.

Wavelet Decomposition and Peak Spectral Density

The extracted island metrics and bathymetric profiles are analogous to time-series, where space (*i.e.* geographic latitude) was substituted for time. Each of the alongshore metrics was decomposed using a continuous wavelet transformations (CWT) with a complex Morlet wavelet. All wavelet decomposition analysis was conducted using the *biwavelet* package in R (Gouhier et al, 2016). Statistically significant areas of the wavelet plots were identified using Chi-square analysis by comparing the extracted waveform to a simulated red-noise signal. Wavelets serve as a valuable approach to extract detailed information about the spatial structure at all length scales along the entire length of PAIS. Peak spectral density (PSD) was subsequently extracted from the CWT transformation at multiple spatial scales using AutoSignal©, signal processing software. Plotting the computed PSD variance against the alongshore scales (*i.e.* wavelength) provides useful information about the spatial structure of the alongshore data. In order to improve interpretation of the PSD plots, a logarithmic stretch was applied to both variance and alongshore wavelength axes.

Power trendlines (*i.e.* trendlines fit using a power function) were fitted to each of the PSD morphometrics in order to examine whether the extracted signal was white noise, structurally controlled (*i.e.* pink noise), or red noise (*i.e.* Brownian motion). A trendline with slope approaching 0 is considered white noise, and is completely locally dependent and does not have any larger scale control. Metrics with slopes approaching 1 are considered pink noise, and represent patterns that are structurally controlled. Steeper sloping trendlines approaching 2 or greater are considered red noise (*i.e.* Brownian motion). Red noise signals are dissipative and tend to lack significant small-scale variability. PSD trendlines provide useful insight into the degree to which a signal exhibits structural control across a range of spatial scales.

Bispectrum and Bicoherence

It is feasible that some metrics may have fine-scale patterns of variability superimposed on broader-scale patterns. One useful approach to examining and testing for these non-linear interactions is by computing the bispectrum of a signal. Bispectrum works by measuring the degree of phase coupling between two different wavelet scales. Although bispectrum is often computed using Fourier transform, we computed bispectrum using CWT information extracted from each metric because CWT provides more continuous information about the data structure. The bispectrum of a given signal was computed in R using equation 4.

$$B_{yxx}(a1, a2) = \int W_y^* (a, \tau) W_x(a1, \tau) W_x(a2, \tau), d\tau \qquad (4)$$

where $a1$ and $a2$ are wavelet components of different scale lengths of $x(t)$ and a is a wavelet component of $y(t)$ (Elsayed 2006a). The wavelet transform of signal y is represented by W_y and the wavelet transform of signal x is represented by W_x. W_y^* represents the complex conjugate of W_y. This computation assumes that the frequency sum rule is satisfied such that $1/a = 1/a1 + 1/a2$.

The bicoherence (*i.e.* bispectral coherency) is useful for quantifying frequency coupling by squaring and normalizing the computed bispectrum. The advantage of bicoherence over bispectrum is that bicoherence values range from 0 (i.*e.* random phase coupling) to 1 (*i.e.* perfect phase coupling); therefore, bicoherence is easier to interpret than the bispectrum. Bicoherence ($[b_{yxx}(a1, a2)]^2$)was computed using equation 5, which was previously used to examine statistical correlation within wind and wave data (Elsayed, 2006a, b).

$$[b_{yxx}(a1, a2)]^2 = \frac{\left|B_{yxx}(a1,a2)\right|^2}{[\int |W_x(a1,\tau)W_x(a2,\tau)|^2 d\tau]\left[\int \left|W_y^*(a,\tau)\right|^2 d\tau\right]} \qquad (5)$$

where $B_{yxx}(a1, a2)$ is the bispectrum of the signal at frequencies $a1$ and $a2$. Bispectrum and bicoherence analysis have been applied to analyzing oceanographic wind-wave and wave-wave interactions (Elsayed, 2006a, b). In the current paper, bicoherence is utilized to assess the degree of phase coupling within a given signal in order to examine how fine-scale patterns and processes are coupled with broader-scale patterns and processes to influence coastal geomorphology. Bicoherence is a valuable approach to examine statistical relationships within a single or between multiple time- or spatial-series.

Results

EMI Framework Geology

Similar patterns are present across all three frequencies of the EMI wavelet plots (Figure III.3). The 3kHz apparent conductivity appears to have a more variable structure at smaller length scales. The waveform in the southern part of PAIS is stronger at length scales less than ~250 m from ~7 km to 17 km, 65 km to 72 km, and 80 km to 88 km north of Mansfield Channel (Figure III.3). Conversely, the central part of PAIS appears to be much more chaotic with very low statistical significance in the waveform between ~45km and 62km. EMI data at all three frequencies appear to have a similar PSD structure, which supports the use of any one frequency as a measure of subsurface framework geology. The power trendline fit to the EMI PSD is ~1.44 with an R^2 of 0.98 (Figure III.4), indicating that the power trendline fits the data very well. Bicoherence analysis of the apparent conductivity wavelet coefficient indicates that there are two higher frequency signals at ~20 m and ~380 m wavelengths superimposed on a lower-frequency oscillation at ~1,613 m wavelength (Figure III.5). The strongest non-linear interaction is between signals of ~380 m and ~1,613 m wavelengths.

Bathymetric Framework Geology

A series of ridges and swales are rhythmic in the southern portion of PAIS bathymetry and absent in the northern two-thirds of the island (Figure III.3). The statistically significant hotspots in the CWT plots at approximately 1 km alongshore length scales migrate north as the bathymetric profile moves farther offshore, indicating that the ridges and swales are oblique to the overall shoreline orientation. The power trendline is similar for each of the 1 km through 7 km bathymetric profiles (~1.83; Figure III.4), indicating that the bathymetric structure is trending toward dissipative or red noise, but still appears to be slightly structurally controlled.

Long-term Shoreline Change Behavior

Shoreline change along PAIS is statistically significant in the southern part of the island, between approximately 5 km to 23 km north of Mansfield Channel (Figure III.3). This area of the island also is also statistically significant in the EMI data, which suggests that there is a relationship between the subsurface framework geology and shoreline change at PAIS. The statistically significant shoreline change hotspot between approximately 5km to 10km north of Mansfield Channel correspond spatially to shore-oblique bars evident in the coastal relief model. Given how close southern PAIS is to South Padre Island, it is likely that the ridge and swale complex in south PAIS represents a northern extension of the South Padre Island ridge and swale complex. Similarly, it follows that shoreline change is greater along southern PAIS where waves refract around ridges and dissipate energy in the swales. This imbalance in energy results in a variable shoreline position, depending on variations in the approaching waves.

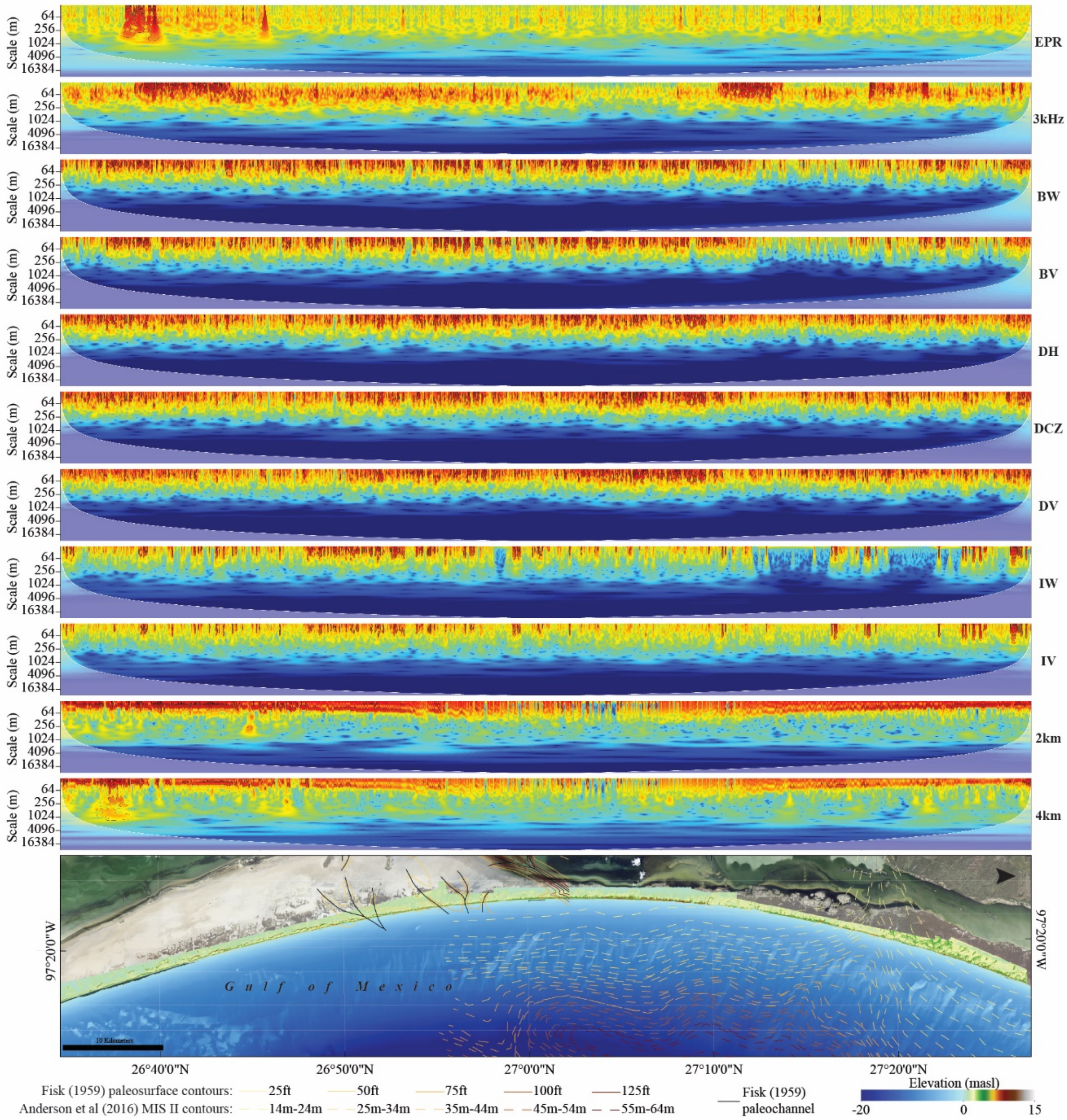

Figure III.3 Continuous wavelet transformations (CWT) for individual spatial series. Plots are aligned spatially with the map at the bottom based on latitude. Warmer colors are more significant, with statistically significant areas outlined in black.

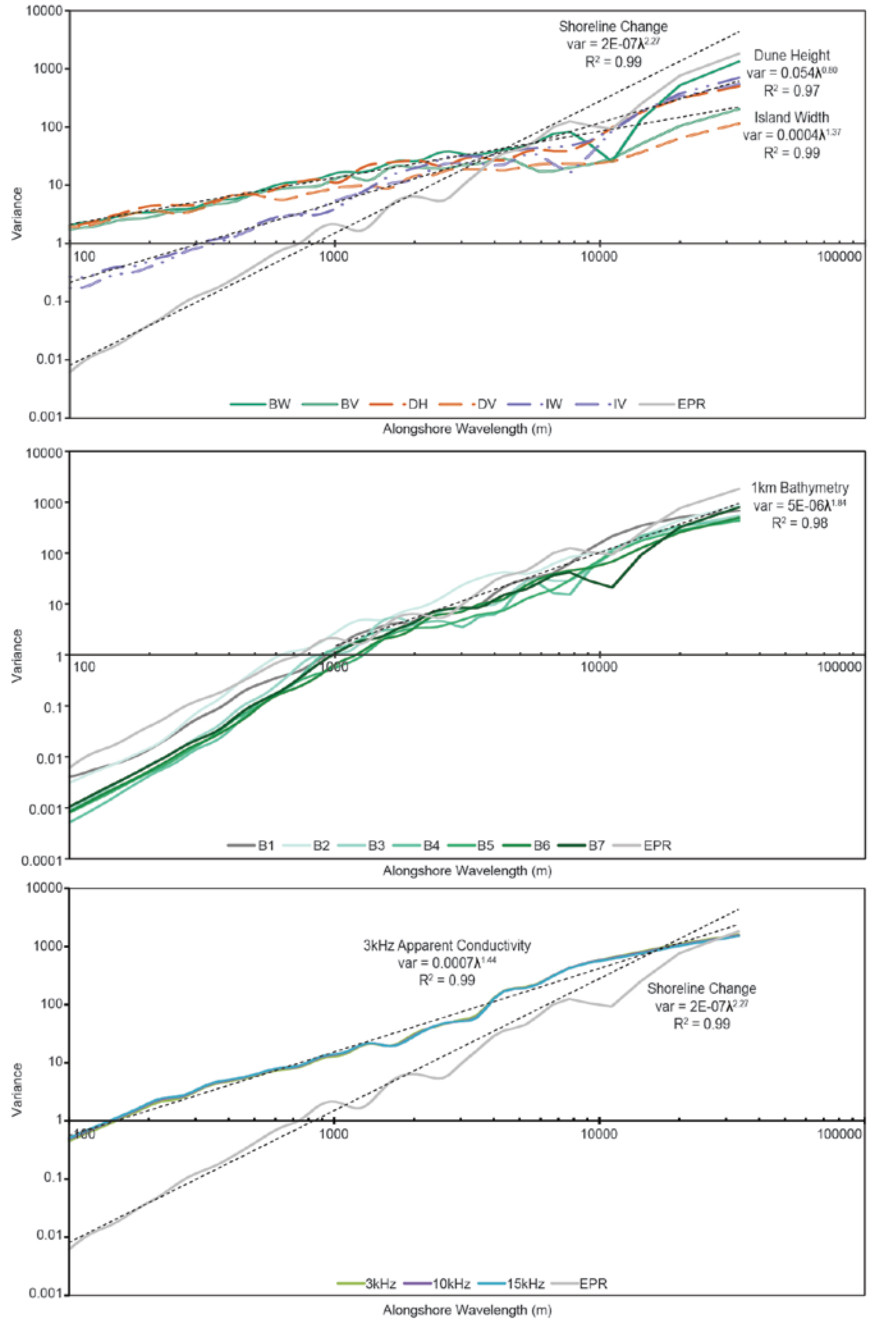

Figure III.4 Peak spectral density (PSD) plots of decomposed framework geology spatial series. Trendline slopes provide valuable information about the degree to which the spatial series is white noise, structurally controlled, or dissipative.

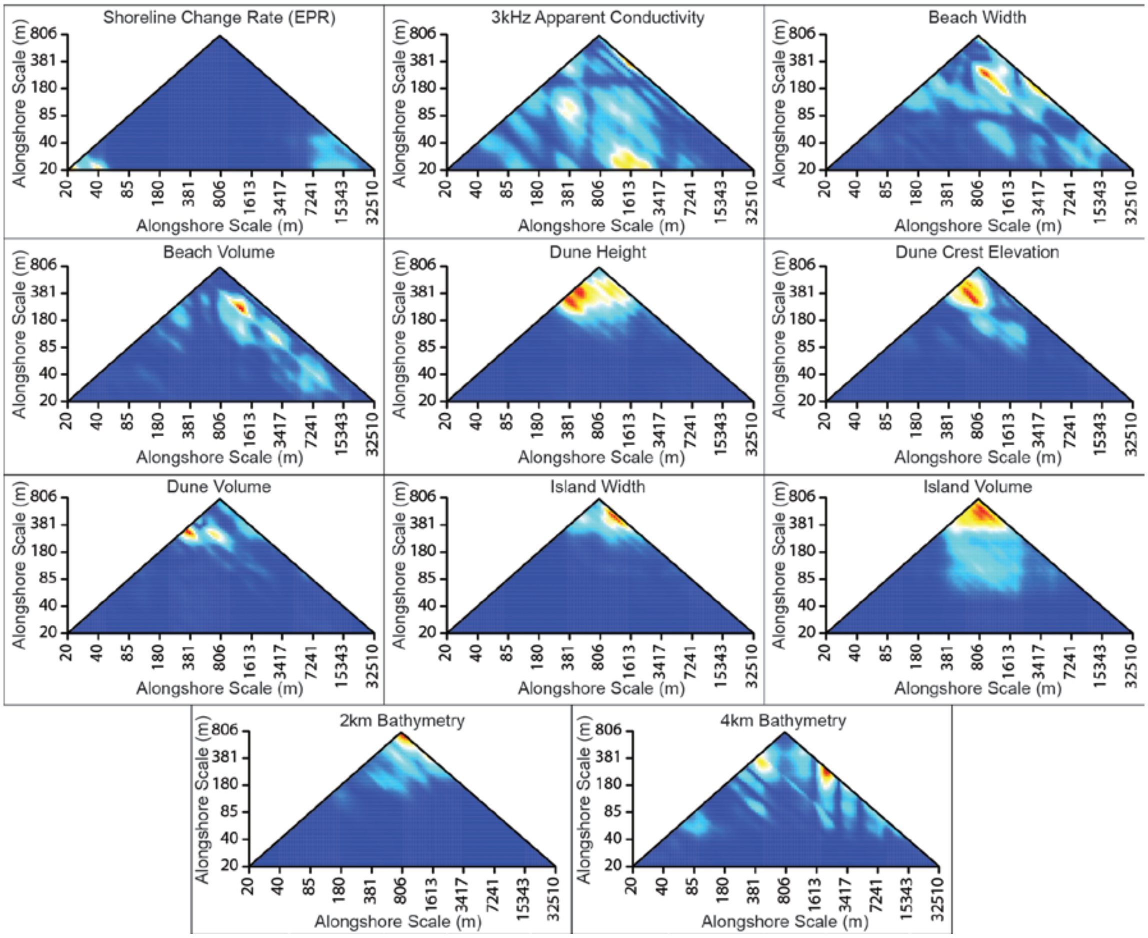

Figure III.5 Bicoherence plots for each spatial data series provide insight into the scales interacting non-linearly. Two series bicoherence plots are useful for evaluating the degree to which two spatial series are non-linearly related.

The long-term EPR shoreline change is fit by a power trendline with slope ~2.26 (Figure III.4), indicating that the long-term shoreline change is dissipative at scales between 100 m and 33,333 m. The high R^2 value in both parts of the curve (>0.88) indicates that long-term shoreline change is appropriately fit by a power law trendline. No significant patterns are present in the shoreline change bicoherence plot (Figure III.5) that would suggest non-linear interactions are influencing the overall shoreline change rates.

Barrier Island Morphology

Beach width and beach volume both exhibit alongshore variability, with the greatest variability concentrated at scales smaller than ~250 m (Figure III.3). Approximately 70 km from the Mansfield Channel there is less statistically significant structure and the overall strength of the wavelet decreases. Also around 70 km from Mansfield Channel, dune height and dune volume wavelet plots become less statistically significant than in the central part of the island, as displayed by more cooler colors around 70 km north of the Mansfield Channel. The most significant change in significance and wavelet transformation is the abrupt decrease in island width significance around 70 km. The island morphometrics are best fit by power trendlines with slopes ranging from ~0.79 to ~1.37 (Figure III.4). The R^2 value is very high for all trendlines, indicating that the power trendlines are an appropriate measure of the data structure. All island metrics can be characterized as pink noise (slope ~ 1; Figure III.4), which suggests that the signal is structurally controlled. While island width and island volume have slightly steeper trendlines than the other metrics, both trendlines are still approximately 1. Based on the PSD trendline slopes, all of the alongshore island metrics are structurally controlled at a range of alongshore length scales. Furthermore, because none of the metrics deviates substantially from ~1, it follows that the barrier island morphometrics may be controlled by a single common factor along the entire island, such as structure in the framework geology.

Several of the island morphometric bicoherence plots indicate significant non-linear interactions occur at distinct scales. Beach width and beach volume both exhibit non-linear interaction between oscillations at ~1200 m and ~280 m, as indicated by the red hotspots in Figure III.5. Oscillations at 280 m interact non-linearly with signals between ~380 m and 800 m in the dune height, dune crest elevation, and dune volume. Island width and island volume spatial series appear to be influenced by the interaction between 1200 m and 380 m.

Wavelet Coherence

Cross-wavelet coherence analysis of the 3 kHz EMI and dune height signals demonstrate that the relatively minor shore-perpendicular paleochannels identified by Fisk (1959) are out of phase with dune height at approximately 1 km to 3.5 km alongshore length scales (Figure III.6 and Figure III.7). In other words, taller dunes are present in these areas of lower apparent conductivity, which is indicative of and inverse relationship between shallower subsurface paleochannels and taller dunes in the south-central part of the island. Conversely, apparent conductivity and dune height are in-phase where the paleochannel forming modern Baffin Bay dissects PAIS (Figure III.6 and Figure III.8).

The WTC plot between each of the 2 km and 4 km offshore bathymetry with beach width and dune height exhibit statistically significant relationships (Figure III.6). The 2 km – beach width coherence has the greatest overall statistical significance, with hotspots between ~1 km and 3.5 km alongshore length scales. Many of the largest alongshore statistically significant hotspots where the bathymetry and beach width are anti-phase are adjacent to previously identified paleochannels, such as ~30 to 45 km from Mansfield Channel. At these same locations 2 km bathymetry and dune height are in-phase (Figure

III.7). Bathymetry at 4 km offshore does not exhibit as clear a pattern with the beach width as the 2 km bathymetry, although the 4 km bathymetry is statistically significantly in-phase with the dune height proximal to the series of paleochannels (Figure III.6).

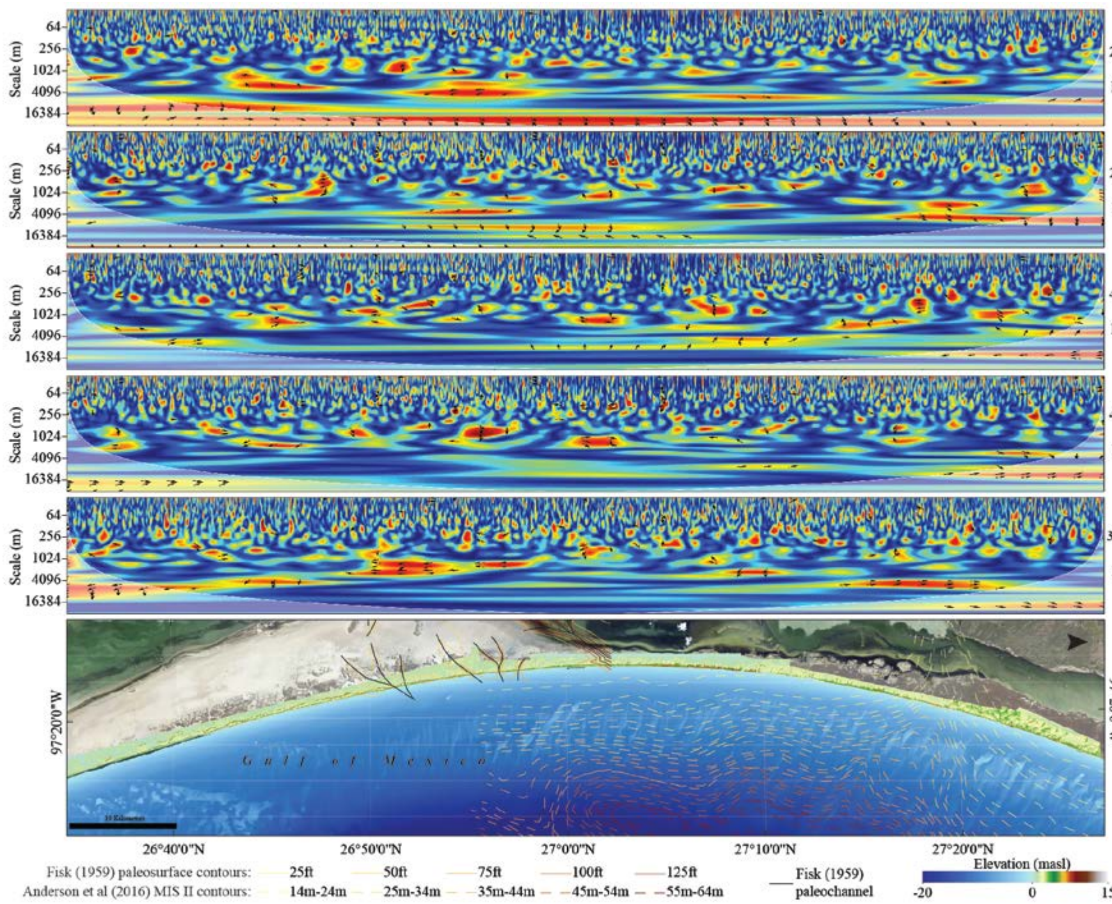

Figure III.6 Wavelet coherence (WTC) of different combinations of two alongshore spatial series. Plots are aligned spatially with the map at the bottom based on latitude. Warmer colors are more significant, with statistically significant areas outlined in black. Arrows pointing to the left indicate anti-phase relationships, while arrows pointing to the right indicate in-phase relationships.

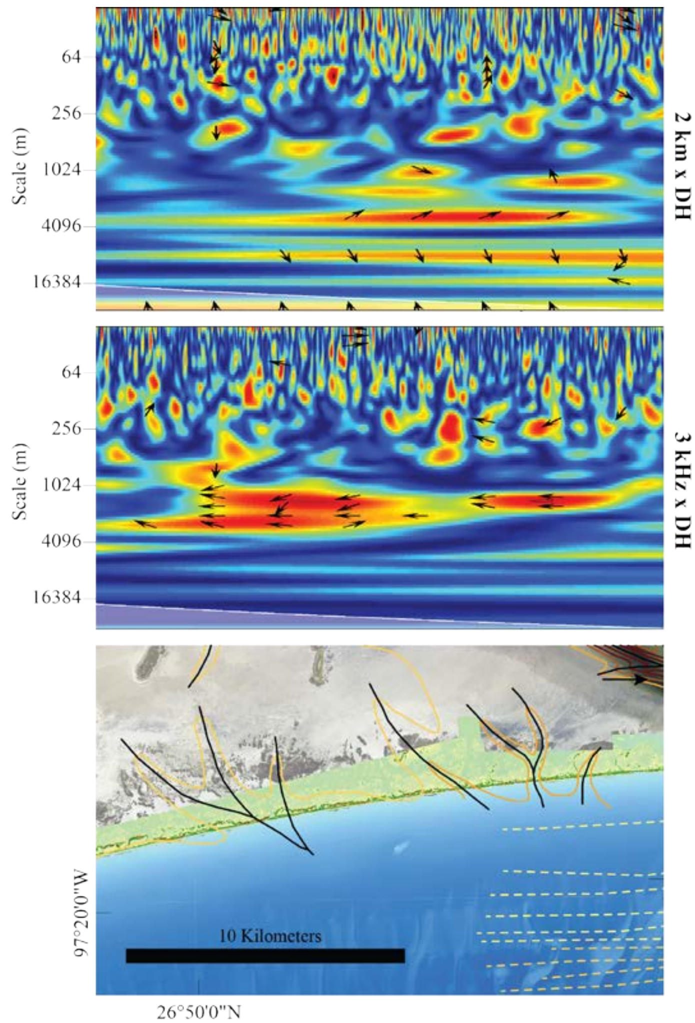

Figure III.7 Wavelet coherence of dune height and framework geology parameters along central PAIS, where Fisk (1959) previously identified paleochannels in the MIS II surface. There is a statistically significant in-phase relationship between dune height and the 2 km offshore bathymetric profile at ~4000 m alongshore length scales, and a statistically significant anti-phase relationship between dune height and the 3 kHz EMI survey at ~1000-3500 m alongshore length scales.

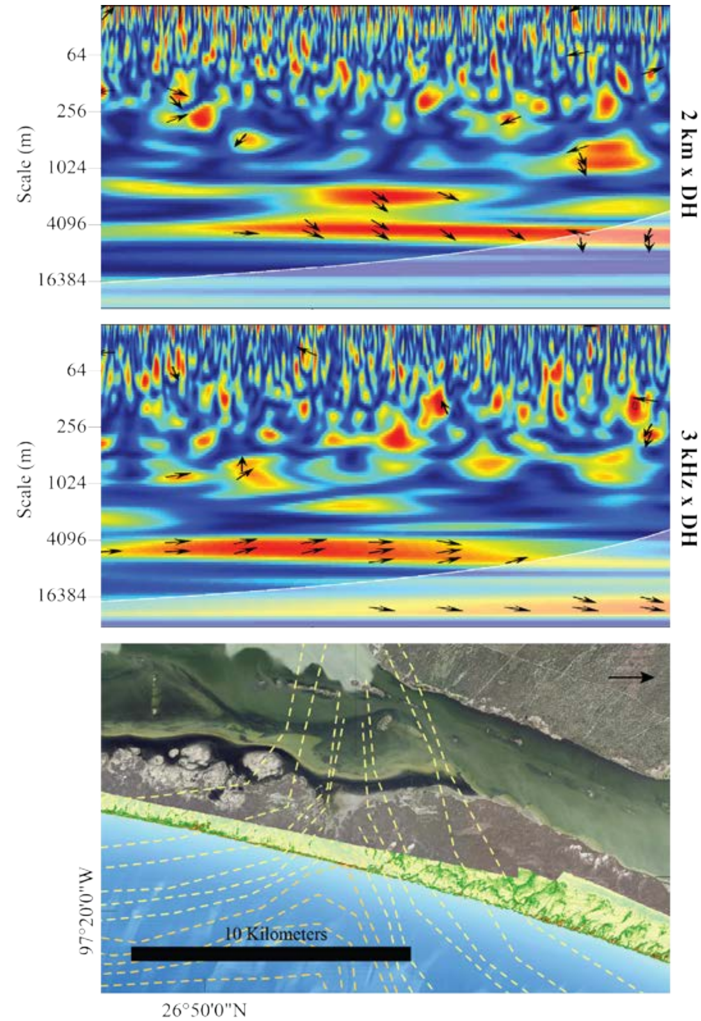

Figure III.8 Wavelet coherence of dune height and framework geology parameters of PAIS adjacent to the paleochannel forming modern-day Baffin Bay. Both wavelet coherence plots exhibit in-phase relationship between wavelet coefficients of the two spatial series. Dune height and the 2 km offshore bathymetry are statistically in-phase at ~1500-4500 m alongshore length scales, while dune height and the 3 kHz EMI survey are in-phase at alongshore length scales from ~4000 m to ~5500 m.

Discussion

Wavelet decomposition of framework geology and modern island morphometrics demonstrates that the modern PAIS barrier island morphology is influenced by paleochannels in the framework geology. Shore-oblique ridges present in the southern part of PAIS are likely an extension of the ridge and swale complex at South Padre Island identified by Houser and Mathew (2011). Similar oblique ridges are also present along Santa Rosa Island, FL (Houser and Barrett, 2010; Houser, 2012; Houser et al, 2015), Fire Island, NY (Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014), and Cape Cod, MA. Since the oblique ridges are only present overlying the ancestral Rio Grande River paleodelta, it is feasible that the modern ridges are formed from deltaic sediments reworked by waves. While it remains unclear why these ridges are relatively consistently spaced at ~1 km at PAIS, it is plausible that this spacing corresponds to oceanographic forcing by waves, similar to Pensacola, Cape Cod, and Fire Island (Hapke, Lentz, et al, 2010; Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014; Hapke et al, 2016).

Statistically significant shoreline change hotspots in the southern portion of PAIS are spatially coincident with nearshore ridge and swale features (Figure III.9). Ridges in the southern PAIS nearshore bathymetry are aligned with lower dunes and more frequent dune gaps, while swales are aligned with more continuous dunes (Figure III.9). Increased shoreline variability adjacent to shore-oblique ridges is consistent with patterns in beach and dune morphology identified along Santa Rosa Island (Houser et al, 2008; Houser and Barrett, 2010; Houser, 2012) and the eastern US coast (Schupp et al, 2006; Lazarus et al, 2011). Previous studies have suggested that the offshore bathymetric ridges influence wave refraction patterns and influence beach morphology. The variable beach state influences the amount of sediment available for aeolian transport inland to form dunes, ultimately influencing dune morphology along the island. Furthermore, Houser and

Mathew (2011) suggests that South Padre Island and, by extension, southern North Padre Island are supply-limited systems, whereas Santa Rosa and many systems along the eastern US are transport-limited. Variation in the island surface morphology due to the framework geology has important implications for understanding how PAIS and other barrier islands with variable framework geology were formed and are likely to change in the future.

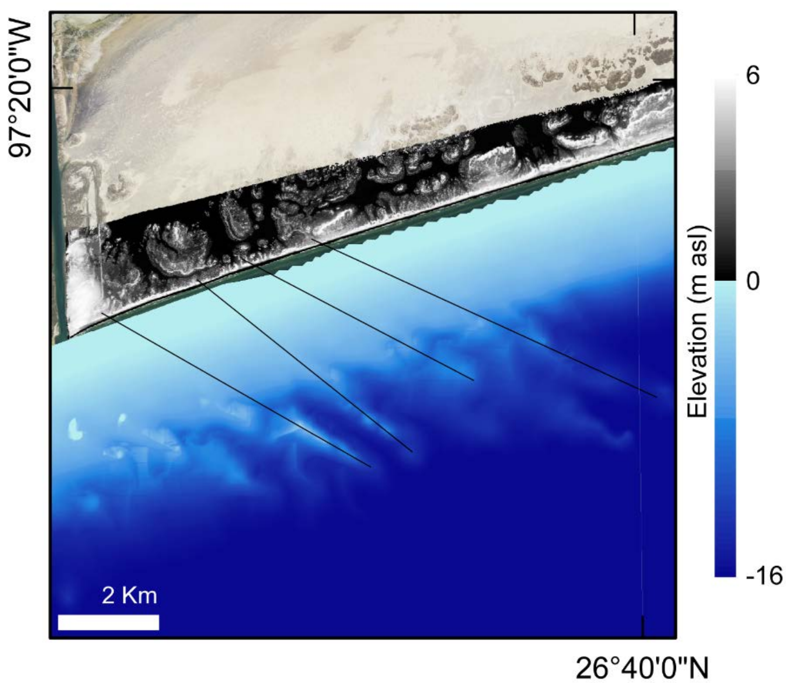

Figure III.9 Southern PAIS framework geology likely represents a northern extension of ridges and swales from South Padre Island. Ridges in the nearshore (represented by black shore-oblique lines) align with areas of smaller dunes with frequent dune gaps.

The interaction of framework geology with more frequent and localized coastal processes is highlighted by the surface morphometric bicoherence plots. In the current paper, bicoherence served as a test for non-linear relationships within each surface, subsurface, onshore, and offshore morphometric spatial series. Beach width and beach volume both exhibit statistically significant non-linear interaction between fine-scale processes (*i.e.* daily wave refraction patterns) and large-scale framework geology (*i.e.* paleochannels; shore-oblique ridges and swales). This non-linear interaction suggests that neither framework geology, nor more frequent coastal processes solely influence beach morphology. Instead, the modern beach morphology is the result of higher-frequency coastal processes interacting with large-scale beach morphology patterns that were initially set up by the framework geology. A similar pattern of non-linear interaction is present in the dune crest elevation, dune height, and dune volume bicoherence plots, where high-frequency coastal processes, operating between 300 m and 380 m alongshore length scales, interact with lower-frequency (~800 m to 1500 m alongshore length scales) patterns of dune morphology. In both cases, the lower-frequency oscillations are consistent with the average spacing of shore-oblique ridges (~1 km to 1.5 km between ridges) and interpreted to reflect how large-scale variations in the framework geology influenced initial variations in the dune morphology.

Ridges and swales in southern PAIS are likely initially derived from ancestral Rio Grande paleo-delta sediments that were re-worked by oceanographic wave forcing. The ridges and swales influence modern wave refraction patterns, concentrating energy along the ridge and dissipating it along the swale. In this way, the paleo-topographic surface of southern PAIS continues to influence modern coastal processes directly affecting sediment availability and sediment transport gradients. Shore-oblique ridges along southern PAIS are likely an extension of the ridge and swale complex from South Padre Island. Since South Padre Island is a supply limited system (Houser and Mathew, 2011), it follows that taller dunes in southern PAIS are aligned with ridges in the nearshore bathymetry, as is the case with South Padre Island.

Paleochannels in the framework geology correlate to larger and more continuous dunes along the northern two-thirds of PAIS. Several areas of the EMI and dune height wavelet coherence plot are statistically significant between alongshore length scales of ~1 km and 3.5 km (Figure III.6). Many of the paleochannels south of the ancestral Nueces River (modern day Baffin Bay) are statistically out-of-phase with the dune height, indicating that dunes are taller within the paleochannels. Conversely, subsurface framework geology and dune height are in-phase where the ancestral Nueces River crosses PAIS. While the exact mechanism for the different influence of various paleochannels is unclear, it is feasible that the statistically significant hotspots between 1 km and 3.5 km in south-central PAIS is a direct result of the ~1 km to 3.5 km spacing between channels. In this way, the signal from one channel is likely to overlap with the signal of an adjacent channel, resulting in an apparent continuous signal. Conversely, larger paleochannels (*i.e.* deeper and wider) dissecting PAIS at a high angle would be statistically significant at larger alongshore length scales. The ancestral Nueces River channel is an excellent example of this, where the influence of the channel is evident at larger alongshore length scales (~4 km), but is not present at smaller length scales (Figure III.6). The large paleochannel dissecting PAIS at an oblique angle appears statistically significant at very large alongshore length scales (~4 km to 10 km). This large alongshore length scale is likely cause by the angle at which the paleochannel intersects the island, which directly impacts coastal processes along a larger total length of PAIS. Statistically significant hotspots in the WTC plots demonstrate that paleochannels in the framework geology do influence barrier island geomorphology and transgression by affecting patterns of wave refraction within the paleochannel itself, although it remains unclear at what scale a particular paleochannel influences the adjacent alongshore island morphology.

This chapter quantitatively demonstrates that the framework geology influences barrier island geomorphology by affecting broad-scale coastal processes interacting with finer-scale processes at distinct alongshore wavelengths. Understanding how the broad-scale and fine-scale processes interact to modify the coastal morphology is essential to refining models predicting how the coast will change in the future. Areas where framework geology initially caused large dunes to form, such as within a relict infilled paleochannel, are more likely to withstand a storm and less likely to overwash. Conversely, small dunes set up by the framework geology are more likely to be overwashed during a storm. In this way, areas of the island with smaller dunes can be considered more vulnerable than areas with larger dunes. Patterns of coastal vulnerability drive barrier island transgression because areas of the island where the framework geology has set up a higher elevation dune crest and taller dunes are more likely to resist overwash and inundation processes and transgress slower than areas where the framework geology has set up a lower elevation dune crest. Similarly, it can be inferred that areas of a barrier island without a substantial variation in the framework geology are more likely to transgress more stochastically, by comparison to a framework geology forced system.

Balancing long- and short-term coastal management should seek to understand how the coast is both free and forced. This chapter demonstrates that the framework geology can influence initial variations in the beach and dune morphology, which persist through time. While coastal engineering projects are primarily focused on shorter-term (~5-10 year) goals, sustainable coastal management requires balancing the short-term goals of a project with long-term natural behavior of the coast. Using wavelet analyses, peak spectral density, and bicoherence analyses can provide coastal managers with a more comprehensive understanding of how the coast developed initially. Understanding how initial patterns in the beach and dune morphology were initially set by the framework geology is valuable when predicting future changes in the coastal morphology since variations in the dune morphology directly affect barrier island resiliency.

Specifically to PAIS, results of this chapter suggest that the accepted theory of formation for PAIS (see Weise and White, 1980) is incomplete and should be re-evaluated in context of the variable framework geology. The prevailing theory of PAIS development does not incorporate recent research demonstrating that channels in the paleo-topography can influence barrier island development. The currently accepted theory of PAIS formation is inconsistent with how the framework geology has influenced barrier island development at other similar sites, and further work is required to more accurately refine the precise geochronological evolution of PAIS.

Conclusion

This chapter demonstrates that the modern PAIS surface morphology is related to the subsurface and offshore framework geology, and that framework geology interacts with finer-scale coastal processes to influence island morphology at distinct spatial scales. Interpreting lower-frequency oscillations as the influence of framework geology on the initial island geomorphology and higher-frequency oscillations as the daily to decadal coastal processes, this chapter demonstrates that coastal processes driving barrier island geomorphology do not transition linearly as previously hypothesized. Rather, wavelet and bicoherence results support a new hypothesis that daily coastal processes interact with larger-scale patterns in nearshore bathymetry across two or more distinct spatial scales to set up and modify the coastal geomorphology. Dune height and volume wavelet plots exhibit statistically significant areas adjacent to subsurface paleochannels, which suggests that the modern island development has inherited dune morphology and characteristics initially set-up by the Pleistocene paleo-topography. Furthermore, all of the island surface morphometrics have a slope ~1, indicating that the barrier island morphology is structurally controlled. This scale range corresponds to the spacing of shore-oblique bathymetric ridges along South Padre Island and the southern part of PAIS. The interaction of low-frequency (*i.e.* millennial scale) and high-frequency (*i.e.* daily through decadal scale) coastal processes represents a significant challenge in geomorphological research, although quantifying this interaction provides valuable insight into how the coast is likely to change in response to future storms and sea level rise.

CHAPTER IV

LONG-RANGE DEPENDENCE IN FRAMEWORK GEOLOGY: IMPLICATIONS FOR BARRIER ISLAND RESILIENCY

Synopsis

Barrier island transgression patterns and rates are controlled by the variation in beach and dune morphology. Large dunes are less susceptible to overwash during storms than smaller dunes. In order to better understand how the coast is likely to change in the future, it is vital to explore how and why the modern coastal morphology varies alongshore. This chapter expands on previous research by demonstrating that the framework geology can influence coastal geomorphology asymmetrically along the coast. The influence of relict paleochannels along Padre Island National Seashore, Texas was quantified by isolating the long-range dependence (LRD) parameter in autoregressive fractionally-integrated moving average (ARFIMA) models. ARFIMA models were fit across all scales and a moving window approach was used to examine how LRD varied with computational scale and location along the island. The resulting LRD matrices were plotted by latitude to place the results in context of previously identified variations in the framework geology. Results indicate that is not constant alongshore for all surface morphometrics. Many flares in the LRD plots correlate to relict infilled paleochannels in the framework geology, indicating that the framework geology has influenced the morphology of PAIS. Barrier island surface morphology LRD is strongest at large

paleochannels and decreases to the north. The spatial patterns in LRD surface morphometrics and framework geology variations demonstrate that the influence of paleochannels in the framework geology can be asymmetric where the alongshore sediment transport gradient is unidirectional. The asymmetric influence of framework geology on coastal morphology has long-term implications for coastal management activities because it dictates the long-term behavior of a barrier island. Coastal management projects should first seek to understand how the framework geology influences coastal processes in order to more effectively balance long-term natural variability with short-term societal pressure.

Introduction

Effective barrier island management requires a comprehensive understanding how an island has changed in the past and how it is likely to change in the future. Since the modern barrier island morphology is the product of past and present coastal processes acting over pre-existing morphologies, understanding how an island developed can provide valuable insight into how it may continue to evolve. Continued sea level rise and future climatic uncertainty represent significant threats to many coastal communities (U.S. Environmental Protection Agency, 2016). Patterns of geomorphic variability may vary along the coast due to the interaction of beach and dune morphology with storm run-up and sea level. Understanding how beach and dune morphology has interacted with storms and sea level rise in the past can provide insight into how the barrier island is likely to change in response to future storms and sea level rise.

Waves during a storm interact with the nearshore, beach, and dunes to influence patterns of vulnerability along a barrier island. Initial variations in the nearshore, beach, and dune morphology are initially influenced by the framework geology (Houser et al, 2015). In this chapter, the term “framework geology” is defined as any subsurface variation in geologic structure, where geologic structure can be caused by variations in sediment type (*i.e.* sand vs. silt), differences in compaction, or significant changes in the subsurface organic content or mineralogy. This term encompasses the subsurface and offshore geologic structure, which may include rhythmic bar and swale structures (Houser and Mathew, 2011; Houser, 2012; Houser et al, 2015), shoreface attached sand ridges (SASR) overlying offshore glacial outwash headlands (Hapke, Lentz, et al, 2010; Schwab et al, 2013), or buried infilled paleochannels (Fisk, 1959; McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Simms et al, 2010; Anderson et al, 2016). Since the framework geology can provide insight into historical patterns of island transgression (Houser, 2012; Houser et al, 2015), it is vital to comprehensively understand how the framework geology influences barrier island evolutions. Despite its importance, framework geology remains absent from contemporary barrier island change models.

The influence of framework geology on barrier island morphology is well documented by work along the New York, Florida, and North Carolina coasts. Submerged glacial outwash headlands along Fire Island, NY reflected in the nearshore bathymetry as a series of shore-oblique ridges and swales (Hapke, Lentz, et al, 2010; Schwab et al, 2013). The nearshore bathymetry impacts sediment transport gradients along the island, which has implications for beach and dune response and recovery following a storm. Using sediment cores in conjunction with ground-penetrating radar (GPR) and seismic surveys, Houser (2012) demonstrated that variations in shoreline change patterns, beach width, and dune height corresponded to ridges and swales at Pensacola, FL. Shoreline position was more stable along the ridges, resulting in a wider beach (Houser, 2012). The wider beach, in turn, provided more sediment for onshore winds to create taller and more persistent dunes (Houser, 2012). Paleochannels dissecting the southeastern U.S. Atlantic coast also align with hotspots of shoreline change (Schupp et al, 2006; Lazarus et al, 2011); however, recent modelling suggests that other factors more completely explains variation in the foredune crest elevation.

Recent numerical modelling studies have argued that shoreline change patterns and coastal dune morphology are self-organized and framework geology is not a significant factor influencing coastal geomorphology (Lazarus et al, 2011; Lazarus, 2016; Goldstein et al, 2017). Wavelet decomposition of shoreline change data along the North Carolina Outer Banks suggested that "*shoreline change at small spatial scales (less than kilometers) does not represent a peak in the shoreline change signal and that [shoreline] change at larger spatial scales dominates the [shoreline change] signal*" (p. 1, Lazarus et al, 2011). This implies that variations in the framework geology, such as paleochannels, do not influence long-term shoreline change. Another study concluded that variation in the foredune crest elevation is dominantly controlled by vegetation distribution and growth rates in conjunction with elapsed time between storms (Goldstein et al, 2017), again implying that framework geology is does not significantly impact broad-scale and long-term barrier island geomorphology. Presently there exists an apparent discourse between numerical modelling studies and remote-sensing and field-based studies as to the role of framework geology in barrier island geomorphology.

The purpose of this chapter is to test the hypothesis that relict infilled paleochannels in the framework geology play a significant role in influencing barrier island geomorphology at a range of alongshore length scales. Based on the combination of a variable framework geology and persistent southerly alongshore current it is feasible that the framework geology may influence barrier island geomorphology at discrete spatial scales and that this influence may be asymmetric. Central to this hypothesis is the idea that the modern island morphology itself is scale-dependent up to some alongshore length scale. Padre Island National Seashore (PAIS) represents an ideal location to test this hypothesis because previous studies have documented significant variability in the subsurface framework geology (Figure IV.1; Fisk, 1959; Anderson et al, 2016) and there is substantial alongshore variation in beach and dune morphology. Given that the dominant current along the central Texas coast flows from north to south (Sionneau et al, 2008), it follows that the dominant alongshore sediment transport gradient also flows from north to south. It is feasible that paleochannels along PAIS would have had interacted with the alongshore sediment transport gradient and asymmetrically influenced the barrier island geomorphology during island transgression. In this scenario, areas updrift of a paleochannel would be distinctly different from areas downdrift of the paleochannel because the channel acts as a sediment sink in the coastal sediment budget. The results of this chapter are valuable to managing coastal resources in areas with complex underlying and offshore framework geology.

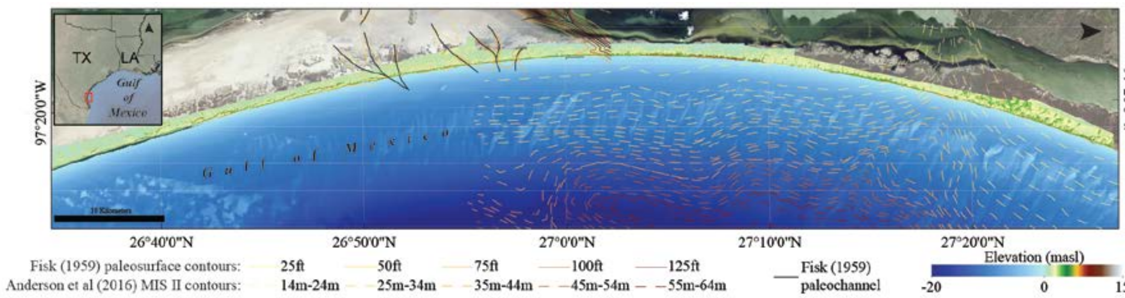

Figure IV.1 Padre Island National Seashore topobathy DEM with MIS II subsurface contour lines from Fisk (1959) and Anderson et al (2016).

Regional Setting

Padre Island National Seashore encompasses a large portion of the longest continuous barrier island in the world. Located along the south Texas, USA coast, PAIS represents an ideal location to quantify the alongshore influence of framework geology on barrier island geomorphology because of the multiple paleochannels dissecting the island (Figure IV.1; Fisk, 1959; Simms et al, 2007; Anderson et al, 2016). Similarly, the modern surface morphology varies alongshore. Central PAIS is characterized by large, relatively continuous dunes, compared to the elongated parabolic dunes along northern PAIS and the heavily scarped and dissected dunes in southern PAIS. Padre Island is separated from the mainland by Laguna Madre, Baffin Bay, and the Intracoastal Waterway (ICW), which was dredged during the 1950s.

Multiple paleochannels dissect the framework geology of central PAIS and Laguna Madre (Figure IV.1; Fisk, 1959). These channels were hypothesized to have been incised into the Pleistocene paleo-surface and infilled during Holocene transgression. The prevailing theory of formation of PAIS is that the island was initially a series of disconnected barrier islands during the last glacial maximum (~18ka), when a series of channels were incised into the paleo-topographic surface (Weise and White, 1980). Rapid sea-level transgression during the late-Pleistocene and Holocene drown the relict dunes and submerged other dunes located approximately 80 km inland, resulting in disconnected offshore shoals in the current location of PAIS. The disconnected shoals coalesced around 2.8 ka because sand from the relict Pleistocene dunes (~80 km offshore) and sediment discharged from rivers was reworked via alongshore currents, resulting in a continuous subaqueous shoal. Eventually sediment from offshore relict dunes and increased river discharge supplied enough sediment to the shoals that they aggraded vertically, becoming subaerially exposed in the same location as the modern barrier island (Weise and White, 1980).

A series of studies in the Gulf of Mexico have focused on extracting the marine isotope stage (MIS) II paleo-surface, including the area offshore of PAIS (Figure IV.1; Fisk, 1959; Simms et al, 2010; Anderson et al, 2016). Maps of the MIS II surface indicate that PAIS is dissected by at least two substantial paleochannels. One large channel dissects PAIS at an oblique angle near “the hole” in Laguna Madre, an area immediately landward of PAIS characterized by consistently deeper water (Fisk, 1959). Based on knick points in the MIS II paleo-surface, this large channel appears to meander from a northeasterly orientation to easterly orientation as it crosses PAIS, eventually flowing into a large paleochannel adjacent to Baffin Bay. The large paleochannel forming Baffin Bay is the combined ancestral Los Olmos, San Fernando, and Patronila Creeks, which was drowned due to sea level transgression and eventually filled with sediment (Simms et al, 2010). Complexities in the framework geology and modern island geomorphology make PAIS an ideal location to examine how framework geology influences barrier island geomorphology.

Methods

Data Sources and Validation

Examining the relationships between surface and subsurface barrier island geomorphology requires continuous alongshore data for surface morphology and subsurface framework geology. Barrier island surface morphometrics (*i.e.* beach width, beach volume, dune toe elevation, dune crest elevation, dune height, dune volume, island width, and island volume) were extracted every 1 m along the entire length of PAIS using an automated multi-scale approach (Wernette et al, 2016). This approach is advantageous because it is less subjective and more efficient than conventional approaches to extracting island morphology. Offshore bathymetric depth profiles were extracted every 1 m from a National Geophysical Data Center (NGDC) coastal relief model (CRM; Figure IV.1).

Information about the subsurface framework geology of the coast was derived from a ~100 km alongshore electromagnetic induction (EMI) survey. EMI works by inducing a primary electromagnetic field in the subsurface halfspace and measuring the deformation (*i.e.* response) of a secondary current. From the secondary field deformation, it is possible to compute the apparent conductivity of the halfspace at a specific frequency. While the apparent conductivity is influenced by a multitude of factors (Huang and Won, 2000; Huang, 2005), recent fieldwork suggests that hydrology has a minimal influence on the subsurface conductivity at PAIS, relative to the influence of stratigraphic and lithologic variation. A series of piezometer shore-normal transects were collected in fall 2016, which indicated that sand was dry within the first 2 meters of the surface along the backbeach. Since the EMI surveys were collected within this envelope, the piezometer measurements support the use of EMI as a proxy for the subsurface framework geology. Previous research confines the location of several paleochannels based on EMI surveys, while the current paper aims to determine the alongshore influence of the paleochannels.

ARFIMA Statistical Modeling of Spatial-Series

Auto-regressive fractionally integrated moving average (ARFIMA) models are useful for assessing the influence of short- and long-range dependence (SRD and LRD, respectively) on a single time data series. ARFIMA has been most widely applied in predicting financial market behavior; however, it is possible to analyze spatial data series by substituting space for time. Predicting future behavior of a time series, such as a financial market, is possible because time series are unidirectional. The future behavior of the market is dependent on the previous market behavior. Spatial data series are distinct from time series because spatial series are not unidirectional. The value within a spatial series is not solely dependent on the behavior of the series in one direction, but is influenced by the entire surrounding landscape. This bi-directional nature means that ARFIMA models should not be applied to extrapolate beyond the span of the spatial series and predict landscape morphology outside of the spatial series. In this chapter ARFIMA is used to analyze a series of barrier island spatial data series for directional dependencies within the data series. It is not used to predict morphology beyond the extent of the spatial data series.

While previous research demonstrated that ARFIMA modelling can provide insight into long-range dependence patterns in alongshore barrier island surface and subsurface morphology at discrete scales (Weymer et al, in review), the current paper expands the ARFIMA approach to analyze alongshore morphometrics at all scales along the entire length of spatial data series. In other words, while previous research utilized arbitrary alongshore lengths and locations to characterize LRD along PAIS, the current paper is assessing LRD at all alongshore length scales along the entire length of PAIS. In this sense, the current paper presents a new approach to assessing how LRD changes alongshore and links these changes to coastal processes and barrier island evolution.

ARFIMA modeling in the geosciences remains relatively unexplored, despite its potential for better understanding spatial and temporal patterns of variability in complex datasets. The most significant advantage of ARFIMA models over other statistical models is that ARFIMA can account for and isolate (1) auto-regressive (AR) relationships, (2) LRD, and/or (3) moving average (MA) relationships in a single dataset by fitting *p*, *d*, and *q* parameters, respectively. While many complete models include all three parameters, it is possible to isolate the influence of AR (*p*), LRD (*d*), or MA (*q*) within the data in order to better understand more specifically how the data is structured. Locations with a strong AR influence represent cases where the data at that location is dependent on a clear local trend decreasing in one direction. Locations with strong MA influence are best modelled by the local average of the surrounding values at a particular spatial scale. Areas modelled by strong LRD are dependent on values throughout the entire spatial data series at a particular alongshore length scale. By isolating one of the three parameters, it is possible to distinguish the degree to which LRD influences a data series, independent of any SRD influence. This ability to distinguish and isolate LRD from SRD is unique and represents the most significant reason that ARFIMA models were used to test for directional dependencies in coastal geomorphology.

In this chapter, the effects of LRD within each spatial data series was isolated using a *0, d, 0* ARFIMA model. Each ARFIMA model was fit using the *fracdiff* package (Fraley et al, 2012) in R (R Core Team, 2016), where the *p* and *q* parameters were set equal to 0. Setting both *p* and *q* parameters to 0 eliminates short-range autoregressive and moving average from the fitted models. Each surface, subsurface, and bathymetric spatial data series was 96,991 measurements long in total. Each spatial series was divided into ~250 unique computational windows, corresponding to alongshore length scales, ranging from two observations (2 m alongshore length scale) to the entire 96,991 observations (96,991 m alongshore length scale). While the number of computational windows can be decreased or increased, it is important to keep in mind that the ARFIMA modelling process is computationally intensive. Increasing the number of computational windows would provide more detailed information about the structure of the dataset, but would significantly increase the computing power required to fit the models. Decreasing the number of computational scales would decrease the computing power required and speed up the computations; however, it would become more difficult to resolve the scales at which the structure breaks down. The range of computational windows could also be adjusted to a specific range, depending on the nature of the research. At each scale the computational window is moved along the dataset and the appropriate *d* parameter is computed. The fitted *d* parameter is then assigned to the center of the window at the corresponding length scale. Repeating this process for each individual alongshore length scale yields a matrix of values, where the row corresponds to the alongshore length scale of the data subset used to compute the *d* parameter, and the column represents the alongshore location of the center of the computational window. This matrix can be plotted similar to a wavelet plot in order to examine spatial patterns of LRD throughout the entire dataset at all length scales.

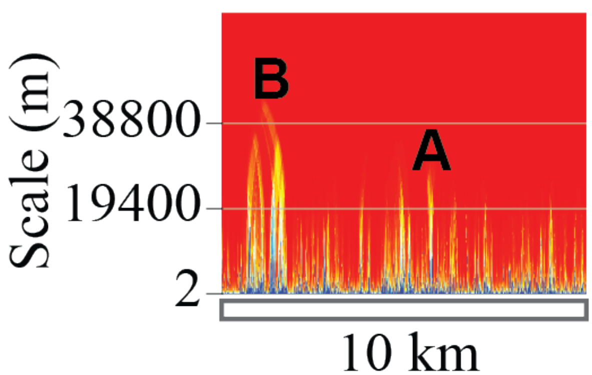

Figure IV.2 Example LRD plot using alongshore dune height at PAIS. The y-axis represents the alongshore length scale (in meters), and the x-axis represents the alongshore location. LRD is persistent at greater alongshore length scales at location B than location A. Additionally, location B is asymmetric, which may suggest a directional dependence in the data series.

Interpreting LRD Plots

Figure IV.2 represents a sample LRD plot using a 4 km alongshore portion of PAIS dune height, where the x-axis represents the alongshore position or space (in meters) and the y-axis represents the alongshore spatial scale (in meters). Plots are oriented by latitude on the x-axis, from south (left) to north (right). In this chapter, all plots utilize a color ramp from blue to red, where blue hues represent smaller *d* parameter values and red hues represent larger *d* parameter values. Given this color scheme, locations or segments of the data lacking LRD are likely to appear as 'flares' or flames. Each of the flares in, such as the flare at location A, represent the scale and areas of the dataset where LRD begins to break down in favor of SRD. The LRD begins at some location at a broad spatial scale and decreases to some finer spatial scale. In the case of the flare at location A (Figure IV.2) we can see that dune height series exhibits strong LRD at scales broader than ~20 km alongshore. This suggests that dune height at location A is related to adjacent values down to ~10 km on both sides of A. Morphology at scales finer than ~20 m is more locally dependent. In this respect, ARFIMA represents an approach to determine the limiting scale to self-similarity.

Depending on the structure of the geology and morphology, it is feasible that the LRD may not appear to be symmetrical. Long-range dependence is asymmetric at location B, where the LRD begins to break down more rapidly to the right side of the plot than the left. While the physical interpretation of a LRD plot depends on the variable, asymmetric flares can be broadly interpreted as areas where the variable is more locally dependent on the surrounding values at the scales and in the direction that the flare tips. In the case of flare B, dune height is more dependent on adjacent values to the north up to ~39 km alongshore. Asymmetries in the LRD plots can provide valuable information about the underlying structure influencing the variable of interest.

Results

The shoreline change LRD plot exhibits the greatest LRD values along the length of PAIS (Figure IV.3). Most flares present in the shoreline change LRD are at relatively fine spatial scales, shorter than a few kilometers. Peaks in the shoreline change LRD plot are very narrow, suggesting that the long-term shoreline change is dominantly dissipative with only minor undulations due to localized coastal processes. Waves impacting the coast can erode sediment from one area and transport it to another area, resulting in fine-scale undulations in the shoreline orientation. Although fine-scale variations in the nearshore bathymetry, such as nearshore bars and troughs, can affect patterns of erosion and deposition along the coast, long-term shoreline change is the result of cumulative daily wave processes eroding undulations in the shoreline shape and dissipating any short-term undulations. Therefore, it follows that the long-term shoreline change LRD plot would exhibit a large amount of LRD. This is consistent with previous research demonstrating broad-scale and long-term shoreline change is dissipative (Lazarus et al, 2011).

Beach width LRD is more variable than shoreline change (Figure IV.3), with the least amount of variability concentrated in the southern third of the island. Flares in the southern third of PAIS are likely present because transverse ridges in the nearshore bathymetry affect localized wave refraction patterns, thereby influencing fine-scale patterns in beach morphology. Patterns in the beach morphology in southern PAIS are likely more localized because the incoming wave energy is refracted around the transverse ridges, which impacts sediment transport gradients along this part of the island. Any variations in beach morphology are more locally influenced by relatively closely spaced transverse ridges (~0.8 km to 1.5 km alongshore spacing), resulting in broad-scale LRD along southern PAIS.

The central third of PAIS is characterized by several significant flares in LRD, with many of the strongest flares adjacent to infilled paleochannels previously identified by Fisk (1959) (Figure IV.4). The scale at which LRD transitions to SRD is at the broadest alongshore length scales proximal to Baffin Bay and this threshold decreases in scale to the north (Figure IV.3 and Figure IV.5). Given a dominant southerly alongshore current and sediment transport gradient, patterns in the beach morphology LRD plot suggests that the paleochannels are influencing updrift areas of the beach preferentially. It is plausible that the two large paleochannels acted as significant sediment sinks during barrier island formation. The beach north of the large paleochannel identified by Fisk (1959) would have been nourished by sediment discharged from the ancestral Los Olmos, San Fernando, and Patronila Creeks, now forming Baffin Bay. Similarly, the beach north of the ancestral Los Olmos, San Fernando, and Patronila Creeks paleochannel would have been nourished by sediment from the ancestral Nueces River. In this way, beach morphology updrift of the large paleochannels would impact beach morphology within and south of the large paleochannels.

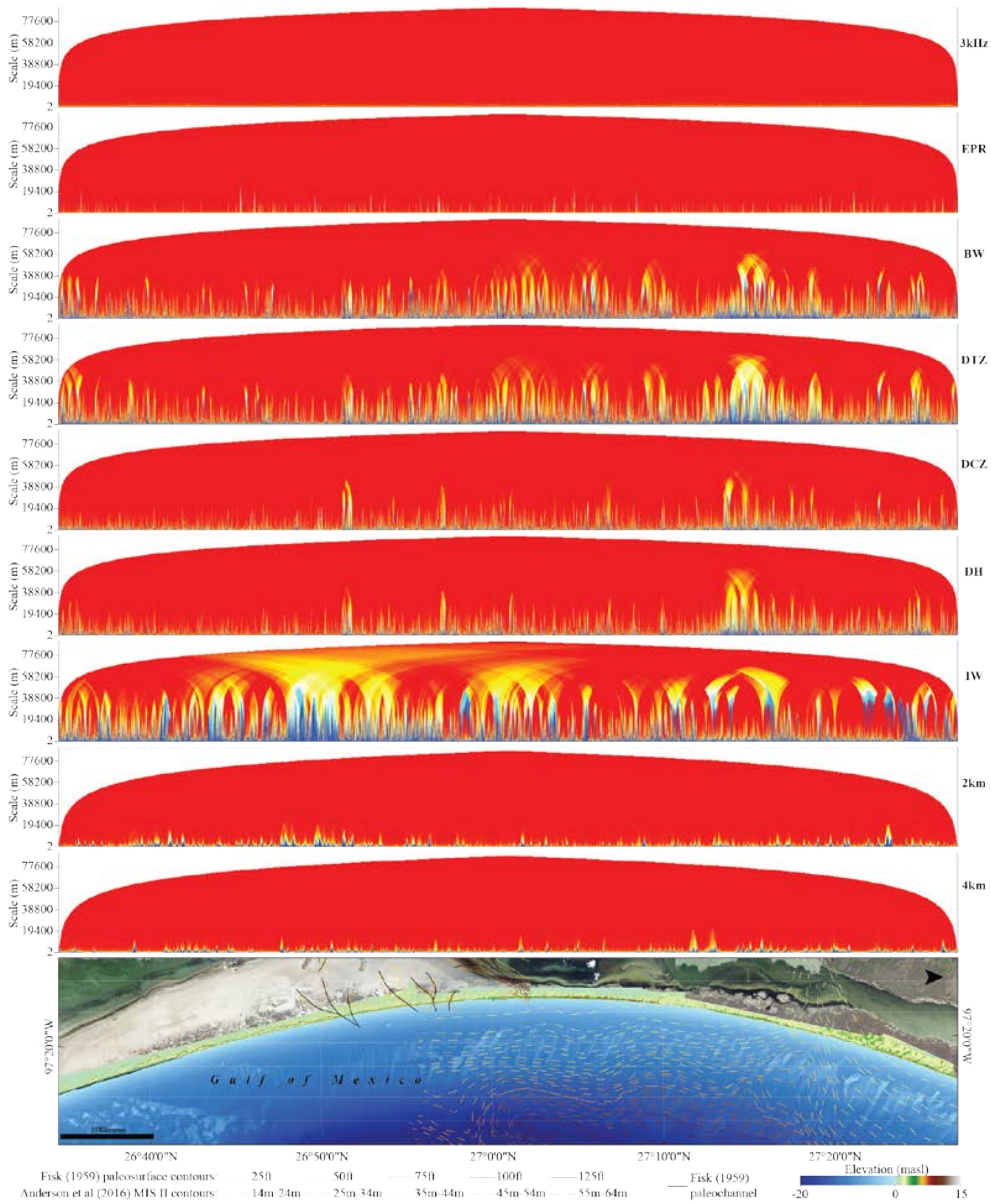

Figure IV.3 Long-range dependence plots of alongshore morphometrics. All LRD plots are aligned with the map based on latitude. Previously documented variability in the framework geology is indicated by the contour lines representing the MIS II paleo-surface (Fisk, 1959; Anderson et al, 2016).

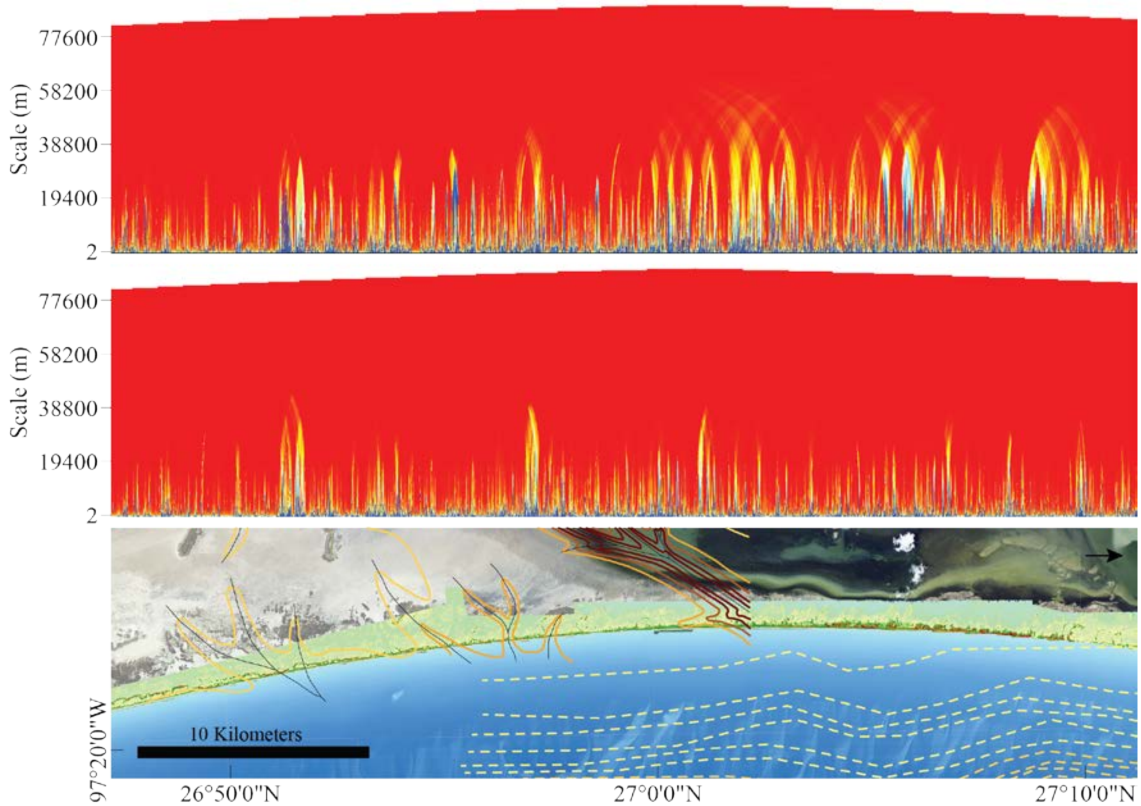

Figure IV.4 Beach width (top) and dune height (bottom) LRD plots for central PAIS, where Fisk (1959) identified a series of relict infilled paleochannels dissecting the island. The scale at which LRD breaks down in favor of SRD is greatest at the southern edge of large paleochannels, and this scale gradually decreases to the north. Smaller paleochannels do not appear to be as influential to the modern beach and dune morphology, suggesting that small channels may not have as significant an influence as larger channels.

Alongshore LRD in the dune crest elevation and dune height varies similarly to beach width LRD along PAIS (Figure IV.3, Figure IV.4, and Figure IV.5). The southern third of PAIS is characterized by LRD-SRD transitioning at larger alongshore length scales than the northern two-thirds of the island (Figure IV.3). The most significant flares are proximal to the ancestral Los Olmos, San Fernando, and Patronila Creeks paleochannels dissecting central PAIS and the ancestral Nueces River paleochannel extending into Baffin Bay. Given that the dominant alongshore sediment transport gradient is from north to south and that the beach morphology exhibits an asymmetric LRD to the north of the large paleochannels, it follows that LRD and SRD patterns in dune morphology would exhibit similar asymmetry to beach morphology.

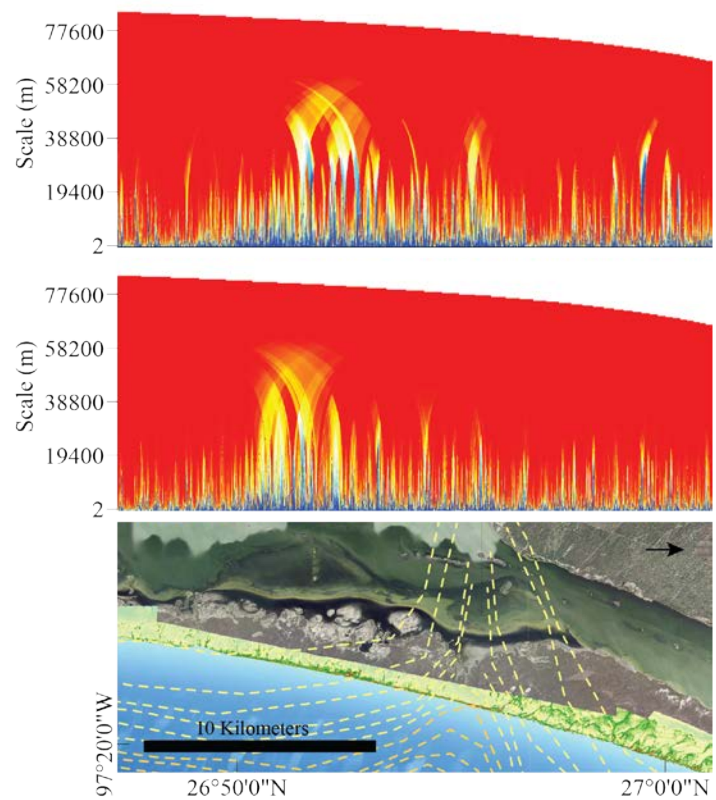

Figure IV.5 Beach width (top) and dune height (bottom) LRD plots for PAIS adjacent to the ancestral Los Olmos, San Fernando, and Patronila Creeks, forming the modern Baffin Bay. LRD breaks down in favor of SRD at the largest scales at the southern edge of the previously identified paleochannel. The scale at which LRD breaks down to SRD decreases gradually to the north of the channel, suggesting that the paleochannel asymmetrically influenced beach and dune morphology.

The transition from dune height LRD to SRD in occurs at the largest scale approximately 35 km alongshore length scales (Figure IV.3 and Figure IV.5). This maximum occurs at the southern edge of the ancestral Los Olmos, San Fernando, and Patronila Creeks paleochannel, adjacent to Baffin Bay (Figure IV.5). The alongshore length scale can be interpreted as the alongshore distance that the paleochannel affected wave refraction patterns and sediment distribution along the beach, ultimately affecting sediment supply to develop larger dunes. It follows that paleochannel influence on dune crest elevation and dune height would be asymmetric, with greater LRD to the north of paleochannels, assuming paleochannels inhibited southern alongshore sediment transport and starved the beach downdrift. The wide beach updrift of a paleochannel represents a larger sediment supply and greater fetch for aeolian transport and dune growth.

Island width exhibits the greatest alongshore variability in LRD of all island and framework geology morphometrics (Figure IV.3). Areas of short dunes are likely to be overwashed during a storm, transporting sediment to the landward margin of the island. Waves and currents along the landward margin of the island erode the washover fans and redistribute sediment along the island. In this sense, the island width at one location is directly influenced by sedimentation patterns along the adjacent parts of the island. Undulations in the Gulf of Mexico shoreline are smoothed out over the long-term, thereby reducing the likelihood that patterns in island width are solely caused by shoreline change patterns. This repeat overwash, followed by sediment redistribution along the backbarrier shoreline, represents the mechanism that barrier islands can transgress landward and keep up with sea level rise. The island width LRD plot demonstrates that island width is dependent on broad- and fine-scale patterns of change.

Bathymetric depth profiles at 2 km and 4 km offshore exhibit substantial LRD at broad scales but breaks down at scales finer than ~15 km alongshore (Figure IV.3). Long-range dependence breaks down at larger alongshore length scales in the 2 km bathymetry, compared to the 4 km bathymetry. Since modern coastal processes continue to affect alongshore sediment transport, large undulations in the bathymetry are smoothed out over time by sediment redistributed along the coast. Finer scale variations in the modern nearshore bathymetry occur at similar spatial scales as previously identified at PAIS (Chapter 3). The 2 km bathymetric profile LRD breaks down at broader spatial scales than the 4 km bathymetry (Figure IV.3). This suggests that localized variations in coastal processes manifest in the nearshore bathymetry closer to the shoreline. Wave shoaling and breaking will erode and deposit sediment along the coast, impacting bathymetric structure closer to the shoreline.

Subsurface apparent conductivity exhibits substantial LRD along the entire length of PAIS (Figure IV.3). The substantial LRD along much of the island supports previous work by Weymer et al (in review), which demonstrated that subsurface framework geology exhibits LRD at discrete locations and alongshore length scales. Patterns in the subsurface framework geology LRD plot demonstrate that the framework geology is self-similar at broader scales, and that this structure varies very little alongshore and with scale. The large LRD values at broad spatial scales demonstrate that the paleo-topographic structure is trending towards a homogenous surface over very broad spatial scales. Since the framework geology is a reflection of the paleo-topography and the modern barrier island surface is dissipative at very broad scales, based on large LRD values at broad scales in the modern barrier island morphology, it follows that the framework geology is dissipative.

Discussion

Dune height is an important morphometric to examine the influence of framework geology on barrier island morphology, since initial patterns in dune height and dune crest elevation can persist through time. Areas of tall dunes are more likely to resist overwash and inundation processes during a storm, and instead be partially eroded and deposited on the beach and nearshore. Following the storm, sediment deposited in the nearshore is available for beach recovery through nearshore bar migration and welding. Onshore winds can transport sediment inland (*i.e.* from the beach to dune) following a storm, promoting dune recovery and development. Conversely, areas with shorter or no dunes are more likely to be overwashed or completely inundated, resulting in the net landward transportation of sediment to the backbarrier. Since dune sand is not deposited in the nearshore or along the beach during the storm, sediment is not available for nearshore, beach and, eventually, dune recovery. In this way, variations in dune height and dune crest elevation are likely to persist through time by directly affecting patterns of overwash and represent a control on patterns of coastal resiliency. Identifying processes that set up modern patterns in dune morphology provides valuable insight into how the barrier island formed and how it continues to be influenced by the framework geology. Since dune height and development is partially a function of beach width, it follows that beach width is a valuable morphometric to evaluate for patterns of LRD and SRD.

Flares in the LRD plots are interpreted as areas where the morphometrics are more locally dependent on the adjacent values. Since flares in the LRD plots are most pronounced adjacent to the infilled paleochannels and decrease to the north (Figure IV.3, Figure IV.4, and Figure IV.5), this spatial correlation supports the hypothesis that the modern barrier island morphology was influenced by variations in the framework geology (Figure IV.6). Paleochannels along PAIS range in scale, with the smallest channels only ~13 m below the modern surface and the deepest and widest channels ~50 to ~64 m deep. Regardless of the paleochannel dimensions, patterns in the LRD plots demonstrate that paleochannels affect the nearshore bathymetry and modern island morphometrics asymmetrically and decrease in minimum alongshore scale to the north. Beach and dune morphology updrift of a paleochannel directly affects sediment available for areas of the beach downdrift. Given that a paleochannel would have acted as a sediment sink for excess sediment transported alongshore, it follows that LRD values would remain high at fine spatial scales updrift of the paleochannel locations (Figure IV.6).

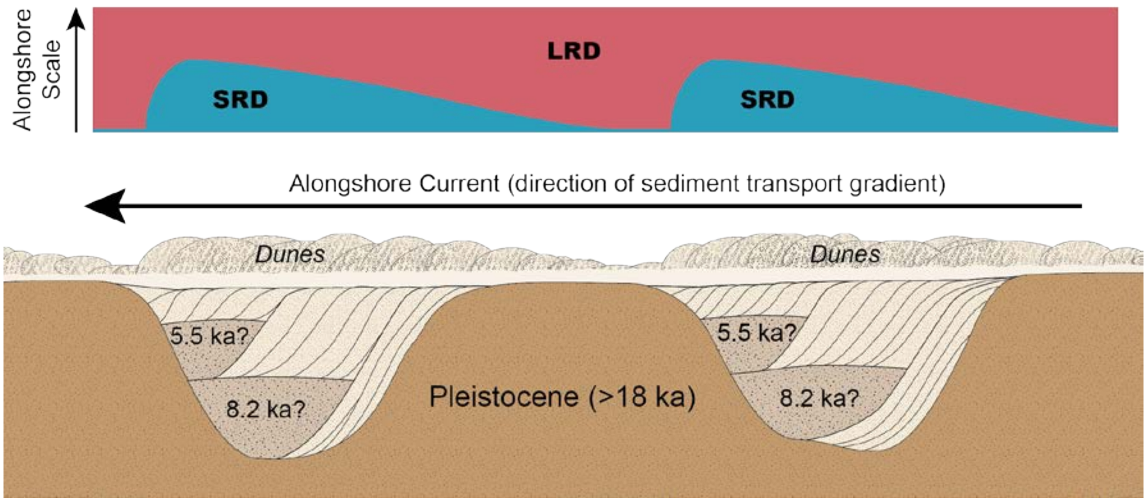

Figure IV.6 Conceptual model demonstrating how the framework geology, in conjunction with a persistent alongshore current, can set up asymmetries in coastal dune morphology.

The current paper is in agreement with previous research that demonstrates barrier island morphology is dissipative at broad spatial scales (Chapter 3; Lazarus et al, 2011). Long-range dependence is significant at very broad spatial scales in all island morphometrics with the exception of island width. Previous research also demonstrates that rhythmic undulations and isolated paleochannels can influence short-term shoreline change patterns (McNinch, 2004; Schupp et al, 2006; Lazarus et al, 2011) and beach and dune morphology (Houser et al, 2008; Houser and Barrett, 2010). This chapter presents new information supporting the hypothesis that paleochannels in the framework geology asymmetrically influence barrier island geomorphology. This asymmetry is likely caused by paleochannels acting as sediment sinks for sediment transported south by a prevailing southerly alongshore current during barrier island formation.

The alongshore distance that influences beach and dune morphology is dependent on paleochannel scale and orientation, relative to the average shoreline orientation. Long-range dependence plots of beach and dune morphometrics suggest that beach and dune morphology within the largest paleochannel dissecting the island, the ancestral Los Olmos, San Fernando, and Patronila Creeks, was influenced by beach and dune morphology up to 25 km north of the channel edge (Figure IV.3 and Figure IV.5). The large paleochannel identified by Fisk (1959) is slightly smaller in scale than the paleochannel forming Baffin Bay; however, the large Fisk (1959) channel intersects the coast at an oblique angle. Since the channel dissects PAIS at an oblique angle, the influence of this channel is more apparent on beach morphology than dune morphology. An oblique channel would have required more sediment to fill than a shore-normal channel. Subsequently, a wide beach and dunes would begin to form in the shore-normal paleochannel before the oblique paleochannel. In the oblique paleochannel the volume of sediment entering the channel would likely have been insufficient to build a wide beach to supply sediment for significant dune growth.

Paleocurrents during the Holocene were predominantly from north to south (Sionneau et al, 2008), which would have set up a southerly alongshore sediment transport gradient. Sediment transported from north to south along the coast would have nourished beaches updrift (*i.e.* north) of the channel. Consequently, nourished beaches updrift of the paleochannel had a greater sediment supply and increased fetch for aeolian transport inland to promote large dune development. While beach nourishment and dune growth continued updrift of the channel, excess sediment entering the channel was deposited along the updrift edge of the channel. Deposition on the updrift edge was caused by the increased accommodation space within the channel. Increasing the area that the alongshore current flows through (*i.e.* transitioning from a confined alongshore current to an open channel), while maintaining the alongshore current discharge, resulted in a decreased flow along the northern edge. Reducing alongshore current velocity caused sands to be deposited along the northern edge of the channel, while finer particles are transported farther into the channel and funneled offshore through the channel outlet. Given enough time, this preferential deposition would have built a spit into the channel. Sediment trapped in the paleochannel would be unavailable to the beach downdrift. The closest modern analogy to this alongshore sedimentation process is the formation and evolution of an alongshore spit forming a baymouth bar, where river valleys can become cut off by the elongating spit and build large dunes on the updrift side.

Directional dependencies in beach and dune morphology, initially set up by the interaction of framework geology with a dominant southerly alongshore current, persist through time due to preferential overwash reinforcing pre-existing alongshore variation in dune height. Areas of the island with limited or no dune development are preferentially overwashed by elevated water levels during a storm. Conversely, areas with taller dunes resist storm overwash/inundation and recover more rapidly following a storm. Alongshore variations in the barrier island morphometrics, such as dune height, persist through time because these patterns are re-enforced by episodic overwash of small dunes during storms.

The apparent disconnect between long-term shoreline change and framework geology is due to the cumulative influence of waves interacting with the coast daily. This disconnect is further highlighted by the lack of storms impacting PAIS. Long-term shoreline change rate is the result of waves moving sediment along the coast on a daily basis. While short-term variations in shoreline position caused by storms are feasible, PAIS has not been significantly impacted by a storm since Hurricane Bret in 1999. Any short-term undulations in shoreline position are likely to disappear over longer-time scales, especially since no storm has hit the island to cause significant localized shoreline erosion. Therefore, long-term shoreline change rate LRD is unlikely to exhibit substantial variation alongshore. Beach, dune, and island morphology do show significant variation in patterns of LRD along PAIS because the initial barrier island morphology was set up by the framework geology. Predicting future changes to barrier island geomorphology requires a comprehensive knowledge of how the framework geology affected initial variation in the beach and dunes.

Variations in the barrier island morphology influence patterns of vulnerability, which are caused by the interaction of wave run-up with beach width and dune height. Ultimately, alongshore variations in the barrier island vulnerability will control the patterns and rates of barrier island transgression. Areas with persistent low dune crest elevations are more likely to be overwashed or completely inundated during a storm, while areas with higher dune crest elevations are more likely to persist through a storm. Sediments in overwashed or inundated parts of the coast are more likely to be transported inland and become unavailable for post-storm dune recovery. The net landward flux of sediment in areas of low dunes will result in shoreline retreat along adjacent areas of the coast. Effective short- and long-term management of coastal resources requires understanding how alongshore variation in overwash vulnerability is set up by the framework geology.

Understanding how the framework geology influences barrier island geomorphology has important implications for understanding how barrier islands are likely to recover following a storm or series of storms. While many models of barrier island recovery focus on spatio-temporal models of change, Parmentier et al (2017) demonstrated that spatial autocorrelation outperformed temporal autocorrelation (*e.g.* “space-beats-time”, SBT) when predicting the recovery of vegetation following Hurricane Dean. Since vegetation recovery and dune geomorphic recovery are related (Houser et al, 2015), it follows that spatial autocorrelation in beach and dune features is essential to predicting future changes to barrier island geomorphology. The current paper demonstrates that framework geology influences barrier island geomorphology unevenly along the coast (Figure IV.6), which, in context of SBT theory, controls barrier island evolution as a whole. Accurately predicting future barrier island change is predicated on comprehensively understanding what processes influenced its initial formation and what processes continue to influence island morphology.

Given that framework geology influences beach and dune morphology along the coast, the methods and results of this chapter represent an opportunity for managers to improve coastal nourishment projects. Sediment budget imbalances set up by the framework geology dictate long-term barrier island trajectory. Utilizing ARFIMA models to evaluate the alongshore beach and dune morphology can provide valuable insight into the coast is likely to change naturally in the future. In order to reduce waste by coastal nourishment, future projects should seek to first comprehensively understand how the paleo-topography of an area continues to affect coastal processes and morphology. By understanding the long-term influence of framework geology, coastal nourishment projects can more effectively balance how a project focused on the near-future coastal morphology with long-term natural changes. Although there is no single solution to managing coastal resources, effective long- and short-term management of coastal resource should seek to balance societal pressure with natural long-term behavior in order to minimize economic and environmental loss.

Conclusion

This chapter quantitatively demonstrates that variation in the framework geology influences patterns of beach and dune morphology along a barrier island. Understanding what controls beach and dune morphology and barrier island development is integral to predicting future changes to barrier island geomorphology and island transgression caused by storms and sea level rise. Storm impact and barrier island transgression patterns are controlled by beach slope, dune height, and wave run-up. Given a persistent alongshore sediment gradient, paleochannels in the framework geology at PAIS likely acted as sediment sinks during island development. While wide beaches and, subsequently, large dunes are nourished with sediment updrift of the channel, excess sediment can become trapped in the channel. These channels trap sediment, starving sediment from downdrift portions of the coast. The result of this asymmetry in sediment supply is large dunes updrfit of the paleochannel and small dunes downdrift of the paleochannel. Effectively managing a barrier island underlain by a variable framework geology should seek to balance short-term societal pressures in context of long-term natural change (*i.e.* framework geology).

CHAPTER V

INTEGRATING FRAMEWORK GEOLOGY IN THE DEVELOPMENT OF A TEXAS BARRIER ISLAND

Synopsis

Barrier island formation and evolution depends on the initial variation in coastal morphology in context with storms and sea level rise. Predicting future changes to island morphology is predicated on accurately and comprehensively understanding how the combination of past morphology interacts with modern coastal processes. The currently accepted theory of formation for Padre Island National Seashore (PAIS) only minimally accounts for forcing by framework geology, despite recent evidence from demonstrating that framework geology has a directional influence on PAIS initial nearshore, beach, and dune morphology. This chapter re-evaluates the development of PAIS in context of framework geology. Surface morphometrics were extracted alongshore in conjunction with mutli-frequency electromagnetic induction (EMI) and 100 MHz ground-penetrating radar (GPR) surveys were used to map the subsurface framework geology. An undulating contact present in GPR profiles confirms the presence of paleochannels along PAIS, and stratigraphy of the overlying sediment demonstrates that the paleochannels were infilled by a combination of alongshore sediment transport processes and fluvial sedimentation. Downlapping reflectors on the northern edge of the paleochannels suggest that sediment transported south via alongshore currents was deposited on the updrift margin of

paleochannels as an elongating spit. The preferential deposition on the northern edge of the paleochannels represents an asymmetry in barrier island morphology, which has persisted in the modern barrier island morphology. Initial patterns in the beach and dune morphology were affected by paleochannels in the framework geology, which likely affected barrier island transgression patterns.

Introduction

Sustainably managing coastal resources requires knowledge of how the modern coastal morphology developed in order to predict how it is likely to change in the future. Since the modern beach and dune morphology is the result of coastal processes modifying pre-existing morphology through time, contemporary models of coastal morphology aim to integrate spatial and temporal dependencies. Parmentier et al (2017) recently demonstrated that spatial correlation models outperformed temporal correlation models in predicting resiliency of coastal vegetation following Hurricane Dean. Based on this "space-beats-time" (SBT) model of coastal resiliency, it is more important to understand how initial patterns arise along the barrier island coast. Spatial variation in the modern nearshore, beach, and dune morphology are derived from variations in the paleolandscape and will continue to influence future barrier island morphology by affecting modern coastal processes. In other words, the modern landscape inherits morphology from previous landscape configurations.

Pre-existing alongshore patterns in the nearshore morphology will affect alongshore sediment transport gradients, thereby controlling beach sediment supply. Since dunes develop from sand transported from the beach, it follows that alongshore variations in beach morphology are reflected in alongshore variation in the dune morphology. Large dunes are more likely to develop downwind of a wider beach because there is more sediment available for aeolian transport landward, while a narrower beach can only supply a limited volume of sand for small dune growth. During a storm, wave runup exceeding the dune height will cause sediment to be overwashed (*e.g.* eroded) from the dune and transported landward. Areas with small dunes are easily overwashed, while areas with large dunes are more resistant and persistent through time. Since initial patters in the framework geology can set up patterns in the nearshore, beach, and dune morphology that persist through time, it is important to quantitatively understand how the framework geology varies alongshore in order to accurately predict future changes to barrier island geomorphology.

Previous studies demonstrate that variations in the subsurface and offshore framework geology influence patterns of coastal vulnerability (Riggs et al, 1995; McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lentz and Hapke, 2011; Houser, 2012; Schwab et al, 2013; Schwab et al, 2014; Houser et al, 2015). Used here, framework geology is any variation in geologic structure, where geologic structure can be caused by variations in sediment type (*i.e.* sand vs. silt), differences in compaction, or significant changes in the subsurface organic content or mineralogy. This term encompasses the subsurface and offshore geologic structure, which may include rhythmic bar and swale structures (Houser and Mathew, 2011; Houser, 2012; Houser et al, 2015), shoreface attached sand ridges (SASR) overlying offshore glacial outwash headlands

(Hapke, Lentz, et al, 2010; Schwab et al, 2013), or buried infilled paleochannels (Fisk, 1959; McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Simms et al, 2010; Anderson et al, 2016). Previous research focuses on areas where the framework geology is relatively simple, such as an isolated paleochannel (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011), rhythmic ridge and swale complexes (Houser et al, 2008; Hapke, Lentz, et al, 2010; Houser and Barrett, 2010; Lentz and Hapke, 2011; Houser, 2012; Schwab et al, 2014; Houser et al, 2015), or a submerged glacial outwash headland (Hapke, Lentz, et al, 2010; Lentz and Hapke, 2011; Schwab et al, 2013; Schwab et al, 2014), although recent research on Padre Island National Seashore (PAIS), Texas provides insight into how a complex framework geology can influence barrier island geomorphology.

While many contemporary models of barrier island change attempt to encapsulate variations in vegetation dynamics and alongshore sediment transport, no current change models account for the influence of framework geology. In other words, current models of island evolution are more heavily focused on 'free' barrier island systems, and neglect 'forced' behavior. In a free system changes in nearshore, beach, and dune morphology are not structurally controlled by any underlying factor. Forced systems, on the other hand, are those where alongshore patterns in the coastal morphology are structurally controlled by an underlying variable. The concept of a free versus forced system provides a valuable approach to examine coastal geomorphology, although it is highly unlikely that a single system is completely free or completely forced. Rather, it is more likely that barrier island geomorphology and evolution lies somewhere on a continuum between free and forced.

Padre Island National Seashore (PAIS) is located in Texas along the Gulf of Mexico (Figure V.1) and is part of the longest barrier island in the world. The currently accepted theory of PAIS island formation accounts primarily for free behavior, with little focus on forced behavior. The theory argues that the island begins to form during the last glacial maximum (LGM) when river channels were actively being incised into the paleo-landscape (*i.e.* Pleistocene ravinement surface). At this same time, a series of barrier islands were proposed to be located along the paleo-shoreline, approximately 80 kilometers offshore of the modern shoreline (Figure V.2; Weise and White, 1980). Rapid collapse of the continental glaciers beginning approximately 18 thousand years ago (ka) resulted in rapid sea level rise until approximately 6 ka. The developmental history of PAIS remains unclear during this period of rapid sea level transgression, but it is accepted that the island reappeared near its modern position as a series of disconnected subaqueous shoals approximately 6 ka (Figure V.2). Around this time there was a substantial shift in the south Texas climate towards a cooler and wetter period (Sionneau et al, 2008).

Increased precipitation across south Texas in the mid-Holocene, coupled with the highly erodible south Texas landscape, resulted in significant amounts of sediment flux from the mainland into paleo-river systems. Eroded sediment transported toward the coast was deposited along the subaqueous shoals, eventually depositing enough material on top of the shoals to form a series of disconnected barrier islands (Figure V.3). Continued alongshore currents re-distributed excess sediment between the disconnected islands, eventually causing the islands to coalesce into the continuous barrier island present today (Figure V.3).

Previous research by Fisk (1959), Simms et al (2010), and Anderson et al (2016) document a series of paleochannels dissecting the island (Figure V.1). These paleochannels were incised into the then-exposed MIS II surface and vary in scale and orientation. The smallest paleochannels dissecting the island are oriented perpendicular to the coast and are only ~7.5 m deep (Fisk, 1959). Immediately north of these small channels in south-central PAIS is a very large paleochannel (~50 m deep) that dissects the island at an oblique angle (Fisk, 1959). Paleochannels in the MIS II surface along central PAIS were based on a series of sediment cores and two seismic profiles (also perpendicular to the island) collected in the 1950s. As a result, it is feasible that the true locations of the channels may very slightly due to minor errors in surveying. Another large paleochannel dissecting PAIS is adjacent to Baffin Bay and represents the ancestral Los Olmos, San Fernando, and Patronila Creeks (Simms et al, 2010; Anderson et al, 2016). The Baffin Bay paleochannel is oriented perpendicular to the island and is approximately 64 m deep. Previous research demonstrates that these paleochannels are asymmetrically related to alongshore patterns in the beach and dune morphology.

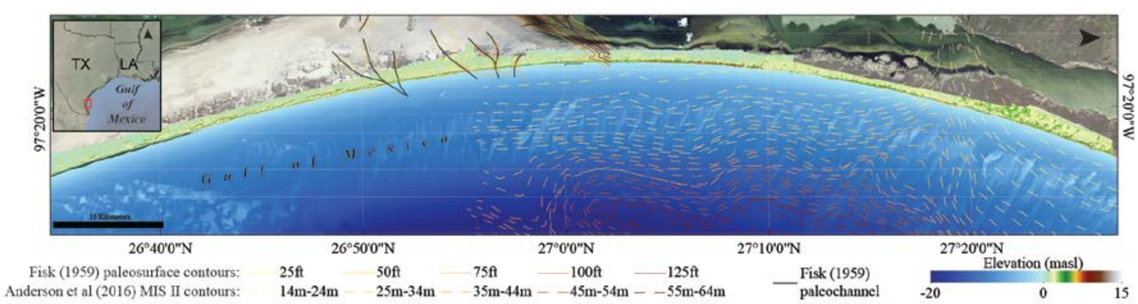

Figure V.1 Previous research has documented significant variation in the MIS II surface structure (Fisk, 1959; Anderson et al, 2016).

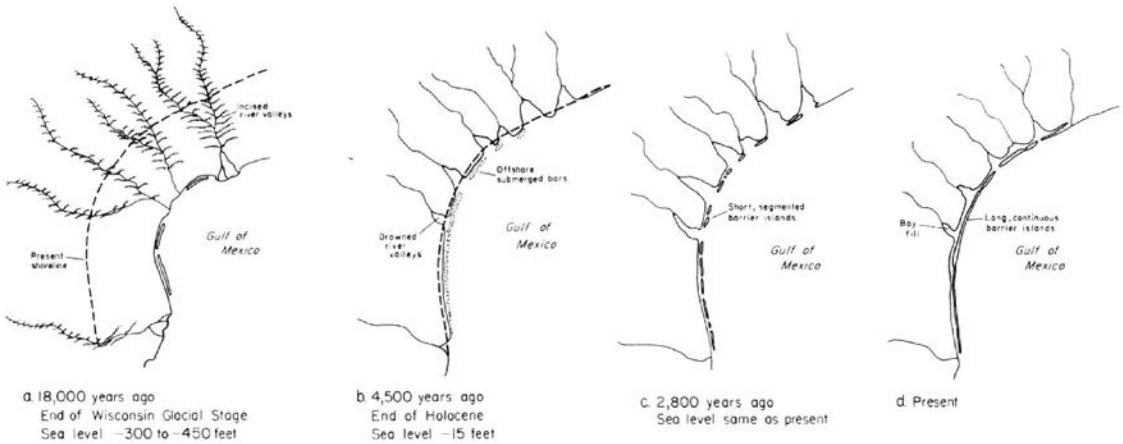

Figure V.2 The currently accepted theory of formation for Padre Island National Seashore. Modified from Weise and White (1980).

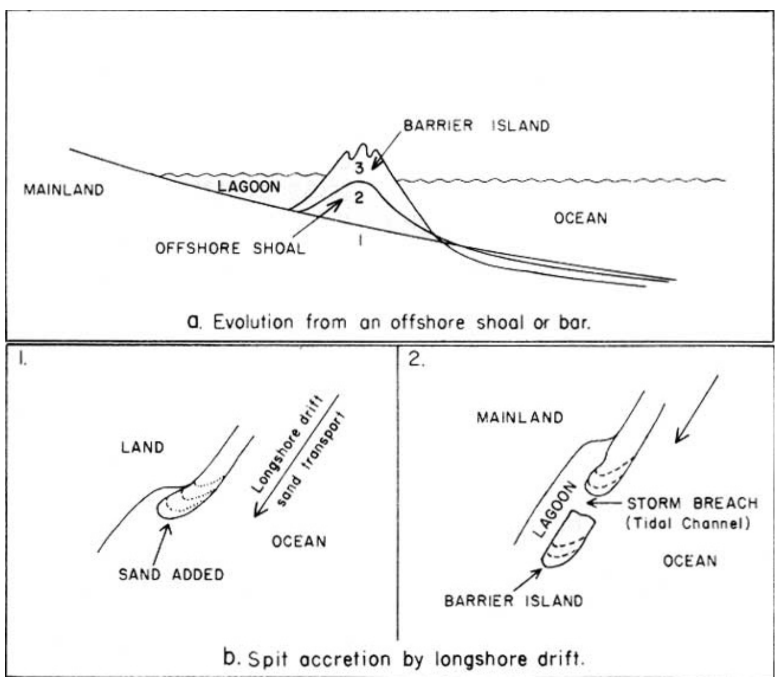

Figure V.3 The currently accepted model of PAIS formation states that (a) PAIS vertically aggraded between ~4.5 ka and ~2.8 ka, to become subaerially exposed as a series of disconnected barrier islands. Since ~2.8 ka, (b) the island has coalesced through alongshore spit elongation. Modified from Weise and White (1980).

The purpose of this chapter is to re-examine the accepted model of formation for PAIS in context of new information about how the complex framework geology likely affected barrier island geomorphology. The currently accepted theory of formation neglects the framework geology as a significant driver of barrier island transgression (Weise and White, 1980). Chapter 4 demonstrates that paleochannels and shore-oblique ridges and swales in the framework geology along PAIS asymmetrically influenced barrier island morphology. Managing barrier islands for short- and long-term environmental and economic sustainability requires a comprehensive understanding about how initial alongshore patterns in the nearshore, beach, and dune morphology likely influenced barrier island development in the past and how these patterns are likely to influence barrier island morphology in the future.

Methods and Data Sources

Alongshore patterns and relationships were evaluated from a seamless topobathymetric (*i.e.* “topobathy”) digital elevation model (DEM). The 1 m resolution topobathy DEM was derived from a LiDAR DEM fused at the shoreline with a National Geophysical Data Center (NGDC) coastal relief model (CRM). Beach, dune, and island morphometrics were extracted every 1 m in the alongshore direction using an automated multiscale approach (Wernette et al, 2016). Offshore bathymetric surface profiles were extracted every 1 m from the topobathy DEM resulting in multiple spatial data series along the island.

Mapping the broad-scale subsurface framework geology of PAIS was accomplished using a portable multi-frequency GSSI EMProfiler 400. The apparent conductivity of the halfspace was measured every 10 m at 3 kHz, 10 kHz, and 15 kHz, corresponding to ~5.1 m depth of investigation (DOI), ~2.8 m DOI, and ~2.3 m DOI, respectively. Portable electromagnetic induction (EMI) surveys are valuable for mapping broad-scale variations in the subsurface geology because they are very efficient to collect and process. EMI measures the apparent conductivity of the subsurface half space, and the signal is hydrologically influenced at fine spatial scales and geologically controlled at broad spatial scales. Another factor influencing the elevation of investigation is topography. To reduce the influence of changing hydrology and changing elevation on apparent conductivity, EMI surveys were conducted on the dry backshore, between the shoreface and any dunes. Furthermore, it is highly unlikely that the EMI signal is significantly controlled by changing subsurface hydrology since yet unpublished hydrogeological surveys indicated the water table was below the computed EMI depth of investigation. Controlling for hydrology and topography is important when using EMI to map the subsurface framework geology.

Ground-penetrating radar (GPR) surveys are ideal for examining detailed subsurface geologic structure because GPR provides more continuous subsurface information than EMI. However, since GPR is more challenging to process on the fly, GPR surveys were used to examine subsurface geologic structure at a localized scale where infilled paleochannels had been identified by previous studies or were suspected based on EMI surveys (Figure V.4). A 100 MHz GPR system was used with a 0.50 m step size. To maximize the effectiveness of GPR along PAIS, surveys were collected during the summer when conditions were driest and/or during periods of extreme low tide. All GPR transects were collected along the dry backbeach to reduce the influence of hydrological changes on the subsurface conductivity.

Recent unpublished piezometer surveys along PAIS suggest that underlying variations in sedimentology and lithology are the dominant control on the EMI survey. Piezometer measurements were attempted up to 2 m deep were attempted along the dry back beach in November 2016. No water was evident in any of the attempted measurements, illustrating that the groundwater table is beyond the influence of the 15 kHz EMI survey. Since the 3 kHz, 10 kHz, and 15 kHz EMI survey measurements parallel each other, each of the three frequencies provides the same information about the subsurface geological structure along PAIS. The piezometer survey supports a geologic interpretation because it demonstrates that the alongshore variations are not likely due to variations in the hydrology.

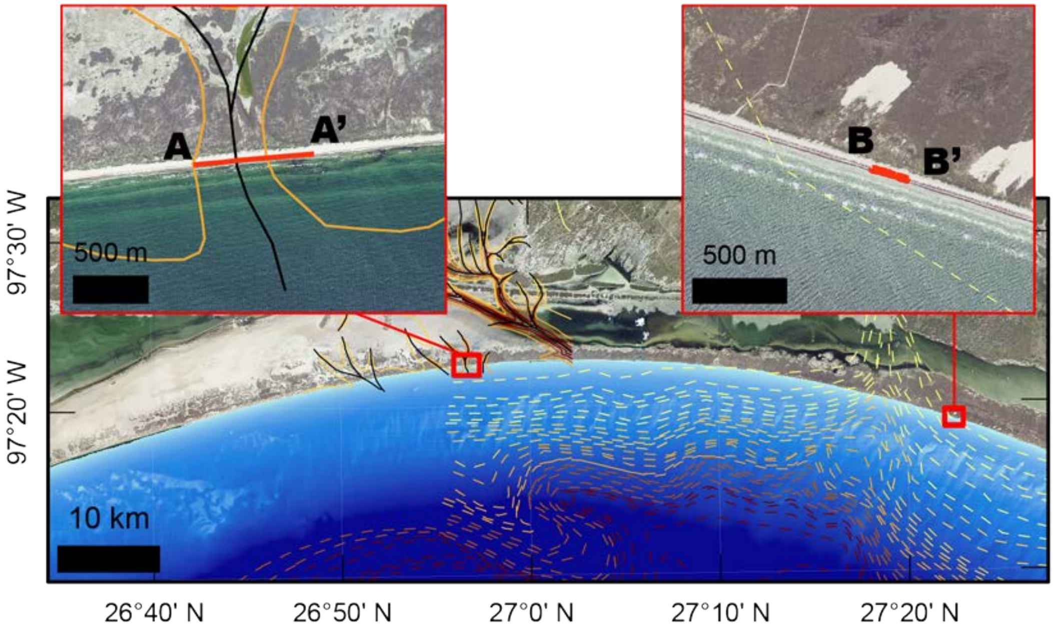

Figure V.4 Ground-penetrating radar surveys were conducted adjacent to two previously identified paleochannels using a 100 MHz system.

Results

A continuous and undulating surface in both GPR surveys support previous research documenting alongshore variation in the subsurface geologic structure (Figure V.5 and Figure V.6; Fisk, 1959; Simms et al, 2010; Anderson et al, 2016). Transect A-A' (Figure V.5) was collected within one of the relatively fine-scale paleochannels identified by Fisk (1959). Although the profile is moderately noisy, there is a continuous undulating reflector between ~5 m and 10 m deep (Figure V.5). Presumably, this strong reflector is the same MIS II surface mapped by Fisk (1959), who documented a paleochannel at this location with a depth of approximately 7.8 m. The GPR survey collected in August 2015 is in close agreement with the location and depth of the previously identified paleochannel, but this new survey provides more detailed information about the MIS II paleo-topography. The reflector is relatively strong because it is likely the impedance contrast between the muddy sediments of the MIS II surface and the overlying Holocene sand. Undulations in the MIS II surface suggests that the fine-scale paleochannel may have been a series of very fine-scale paleochannels, each only a few meters deep. Given the bifurcating and fine-scale of the paleochannel, it is feasible that this paleochannel represents an ephemeral stream system or a tributary of a larger offshore paleochannel.

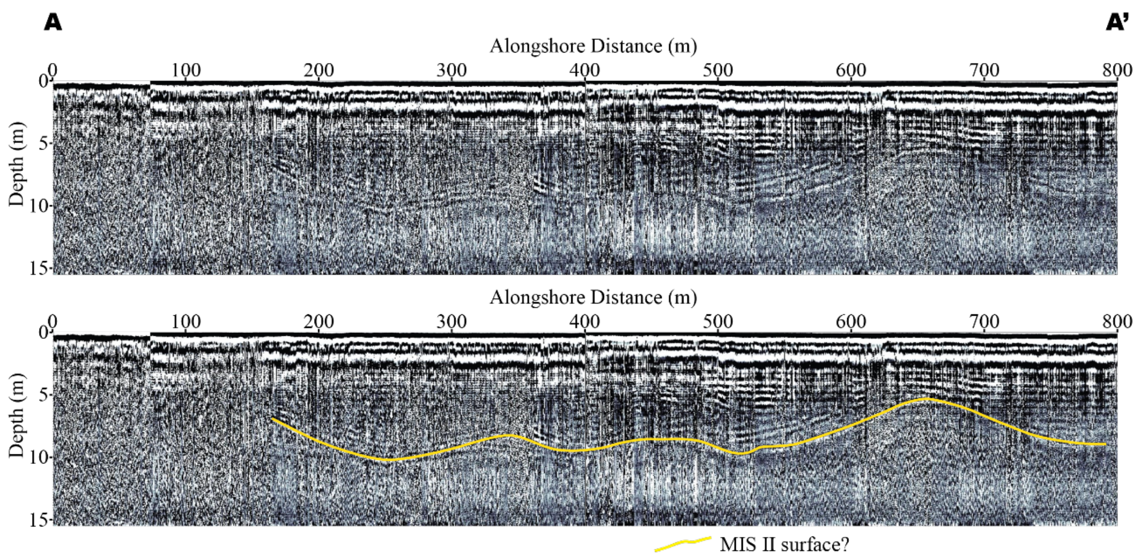

Figure V.5 Raw (top) and interpreted (bottom) GPR profile along transect A-A' (see Figure V.4 for location of the transect).

Since the MIS II surface has not been mapped immediately offshore of the fine-scale paleochannel present in GPR transect A-A', it is not possible to trace this channel to its main paleochannel. Internal stratigraphy within the paleochannel mapped along survey A-A' would, however, provide valuable insight into precisely how the paleochannel influenced barrier island development. Onlapping and downlapping reflectors would suggest that the channel filled preferentially in one direction. Unfortunately, due to noise in the GPR data, it is not possible to resolve any internal stratigraphy within the paleochannel that would provide more detailed insight into the influence of the fine-scale paleochannel mapped by survey A-A'.

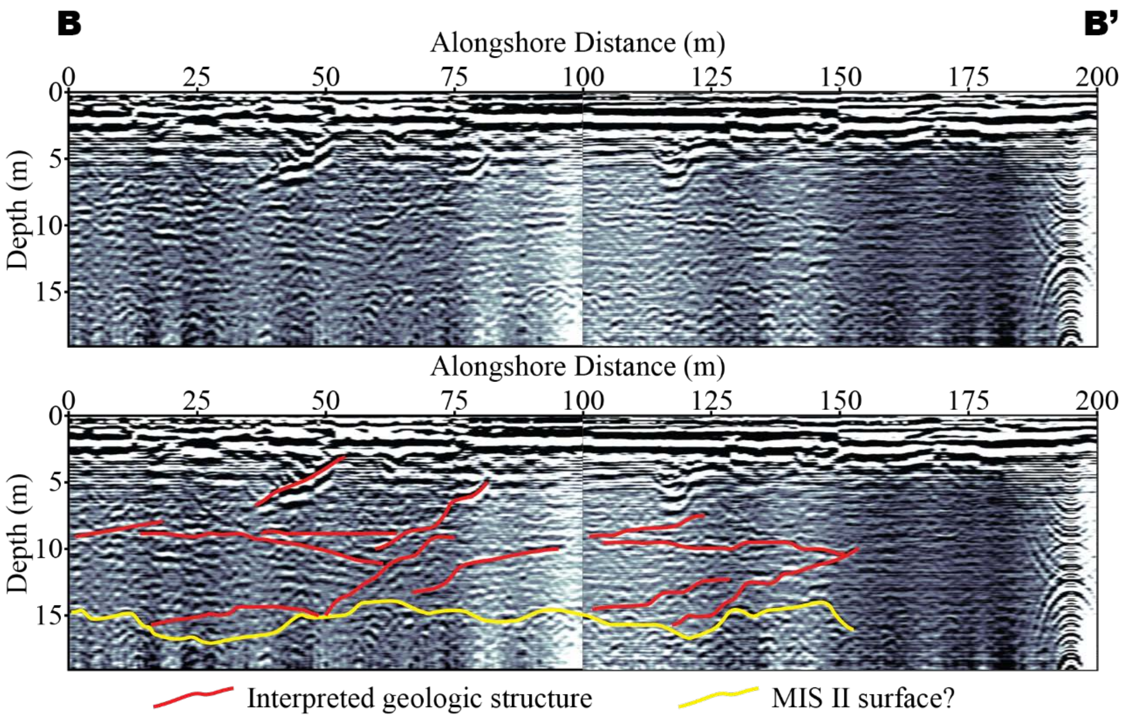

Figure V.6 Raw (top) and interpreted (bottom) GPR profile along transect B-B' (see Figure V.4 for location of the transect).

The B-B' GPR transect was located on the northern edge of the Baffin Bay paleochannel (Figure V.4). Collected in November 2016, this GPR survey exhibits less noise than the A-A' survey and provides more detailed insight into the subsurface geologic structure. The B-B' transect was collected in an attempt to corroborate the paleochannel location mapped by Simms et al (2010) and Anderson et al (2016) and further explore barrier island development. The MIS II contact is present near the bottom of the profile as an undulating reflector approximately 15 m below the surface. This depth is in ageement with previous studies mapping MIS II paleochannels (Simms et al, 2010; Anderson et al, 2016), providing further evidence that the interpreted contact is the MIS II paleosurface.

Stratigraphy overlying the MIS II surface suggests that paleochannel fill is derived from alongshore sediment transport gradients and fluvium from the ancestral Los Olmos, San Fernando, and Patronila Creeks (Figure V.6). Subsurface reflectors in the northern two-thirds of transect B-B’ dip to the south and downlap onto the MIS II contact. Downlapping reflectors in this area are interpreted as periods where the paleochannel was actively being infilled with sediment from along the coast. A spit likely formed on the downdrift edge of an updrift island, depositing sediment along the northern edge of the paleochannel.

An abrupt shift to near-horizontal reflectors in sediment immediately overlying the MIS II contact in the southern ~65 m of transect B-B’ represents a shift to a fluvial dominated system (Figure V.6). It is plausible that this shift in sedimentation occurred approximately 8.2 ka, when sea-level increased rapidly by 0.5 m to 1.0 m (Kendall et al, 2008). The rapid increase in sea level associated with the 8.2 climate event would have resulted in a greater accomodation space for fluvial sediment to accumulate within the channel itself. As a result of sediment being deposited within the paleochannels, less sediment would be transported alongshore for spit growth. A similar ‘flooding surface’ has been documented in estuaries throughout the Gulf of Mexico (Simms et al, 2006;

Simms et al, 2010; Anderson et al, 2016), demonstrating that the shift in sedimentation patterns is not an isolated case at the ancestral Los Olmos, San Fernando, and Patronila Creeks.

Following this large accumulation of fluvial sediment, reflectors downlapping on the fluvial sediments suggest that alongshore sediment transport became the dominant process affecting paleochannel sedimentation. This shift is marked by reflectors in the southern 65 m of transect B-B' (Figure V.6). As the accomodation space within the paleochannels decreased, the ancestral river systems began discharging more sediment along the Gulf of Mexico. The persistent southerly alongshore current transported sediment from the updrift ancestral Nueces River to the Los Olmos, San Fernando, and Patronila Creeks paleochannel. This pattern of alongshore sedimentation and downlapping reflectors is present throughout the uppermost portion of the southern 65 m of transect B-B'.

Discussion

A series of paleochannels dissect PAIS, varying in scale and angle of intersection. Several fine-scale (~7.5 m deep) paleochannels dissect south-central PAIS perpendicular to the shoreline, and a substantially deeper (~38 m deep) paleochannel crosses PAIS immediately to the north at an oblique angle (Fisk, 1959). More recent studies by Simms et al (2010) and Anderson et al (2016) utilized a network of existing geophysical surveys throughout the Gulf of Mexico and new geophysical surveys throughout Baffin Bay to map the MIS II paleosurface.

Many of the bays along the Texas coast are ancestral river valleys that were formed into the paleotopograhic surface during MIS II, including Baffin and Corpus Christi Bays (Anderson et al, 2016). Baffin Bay is formed by the ancestral Los Olmos, San Fernando, and Patronila Creeks (Simms et al, 2010; Anderson et al, 2016), and Corpus Christi Bay is the ancestral Nueces River (Simms et al, 2010; Anderson et al, 2016). Although identified by Fisk (1959), the large paleochannel dissecting central PAIS at an oblique angle has not been attributed to a specific paleo-river system (Fisk, 1959). These rivers carried sediment from south Texas to the Gulf of Mexico during Holocene sea level transgression (Anderson et al, 2016).

Chapters 3 and 4, in conjunction with previous research along the Texas coast, suggest that the currently accepted theory of formation for PAIS is incomplete. The currently accepted theory of formation does not explicitly account for the effects of paleochannels on barrier island morphology and island transgression patterns. Similarly, it does not account for directional dependencies associated with a paleochannel interacting with alongshore sediment transport gradients. The current paper represents a re-examination of PAIS development and evolution in context of new information regarding paleotopographic inheritance along the coast.

Paleochannels incised into the MIS II surface likely influenced initial variations in beach and dune morphology during the last glacial maximum (LGM) when barrier islands were located approximately 80 km offshore. Areas of the island characterized by taller dunes would have been more likely to withstand large waves during storms, while areas with smaller dunes and gaps in the dunes would have been more likely to be eroded during a storm. Small dunes eroded during a storm would have been transported landward and deposited along the landward margin of the island. Erosion from the beach and dunes would result in a localized shoreline erosion hotspot. Post-storm waves would smooth out these localized erosional hotspots by eroding sediment from adjacent areas of the beach. In this way, the overall shoreline position would translate landward from its pre-storm location. Sediment deposited along the landward margin of the barrier island would be redistributed by backbarrier and lagoon currents. Since patterns of overwash are controlled by pre-storm patterns in the alongshore beach and dune morphology, it follows that barrier island paleotopography at the LGM would have influenced patterns of barrier island transgression by promoting dune development within paleochannels, increasing to the south (Figure V.7). These initial alongshore variations in dune morphology have persisted through time and exist today because episodic storm overwash limits dune development where dunes were initially small and vulnerable.

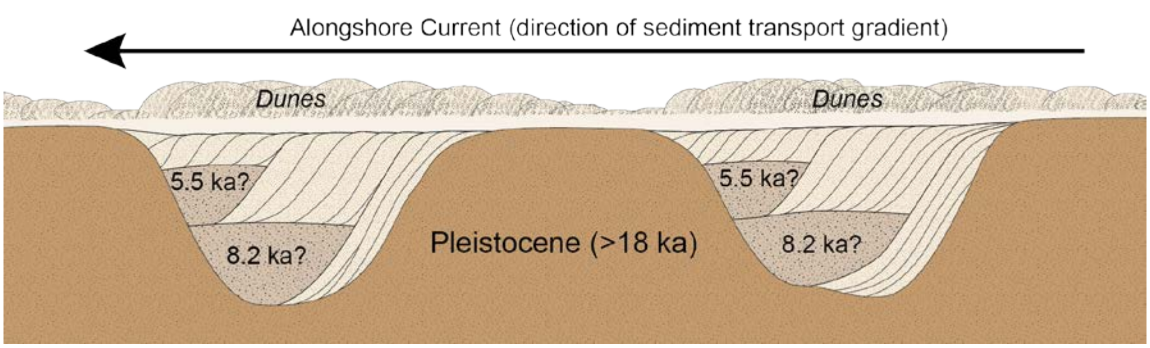

Figure V.7 Paleochannels in the framework geology along PAIS likely influenced barrier island geomorphology by setting up directional dependencies in the dune morphology that persist through time. This conceptual model represents a possible theory of formation for PAIS that is consistent with other research throughout the region and directly accounts for framework geology effects.

While it would be possible for the transgressing barrier island to fill in a paleochannel and transgress up the channel, the rate of sea level rise during the late Pleistocene and early Holocene was ~4.2 mm yr^{-1} (Milliken et al, 2008). Rapid sea level rise would have caused the accommodation space within the paleochannels to remain relatively high, limiting the ability of a transgressing barrier island to significantly fill in the channels. Given that barrier island transgression would keep pace with sea level rise, it is likely that the barrier islands would have transgressed landward along the path of least resistance and not fill in the paleochannels. In this way, paleochannels dissecting the continental shelf would have directly impacted the landward trajectory of the transgressing barrier islands.

Approximately 8.2 ka sea level along the Gulf of Mexico rapidly increased 0.5 m to 1.0 m (Simms et al, 2010). Known as the 8.2 ka climatic event, or Younger Dryas, this rapid increase in sea level actually slowed the overall pace of sea level rise, causing some barrier islands, such as Mustang Island, to stabilize in their modern location (Simms et al, 2006). Mustang Island is immediately north of PAIS and south of Corpus Christi Bay. Based on sediment cores and seismic surveys, Simms et al (2006) proposed that Mustang Island had stabilized in its modern location by 8.2 ka and proposed that it was nourished by sediment from the transgressive Colorado River deltas. Alongshore currents eroded sediment from the deltas and deposited it along the coast, thereby nourishing the coastal sediment supply. It is plausible that the areas of PAIS adjacent to the paleochannels were similarly influenced by updrift sediment sources, with the most likely sources being other ancestral paleochannels.

Ground-penetrating radar facies along PAIS suggest that sediment moving along the coast from north to south was deposited along the updrift edge of paleochannels. Steeply dipping, downlapping reflectors suggest that the depositional environment within the paleochannel was high energy and composed primarily of sand. Since finer particles are more likely to remain in suspension when entering a large paleochannel, it is likely that sand was preferentially deposited along the northern (updrift) flank of the paleochannels. Areas of the coast updrift of a paleochannel would receive sediment from the updrift paleochannel. A wider and higher volume beach updrift of the channel would provide a greater sediment supply for aeolian transport landward for dune development. As a result, paleochannels in the framework geology along PAIS asymmetrically affected beach and dune development, which likely influenced patterns of washover and barrier island transgression. The abrupt increase in sea level and subsequent slowing of sea level rise around 8.2 ka shifted sedimentation patterns within the paleochannels to fluvially dominated.

Vertical aggradation during sea-level rise, according to the currently accepted theory of PAIS development, would require sediment to accumulate faster than the rate of sea-level rise plus storm impacts. Assuming PAIS transgressed landward with sea level transgression and regular storms, it is highly unlikely that the island was a series of subaqueous shoals. In order for the shoals to aggrade and become subaerially exposed, sediment input to the system would have to be considerable and consistent. The large and constant sediment supply would have to coincide with a significant period of decreased storm activity since large waves during a storm can significantly erode the beach and dunes. Large dunes would have to develop very rapidly or gradually during a prolonged period without storms, otherwise the island would be regularly overwashed and inundated. The closest modern analog to this issue is the Chandeleur Islands offshore of Louisiana, where Hurricane Katrina significantly eroded dunes along much of the island, limiting post-storm recovery along the island.

Conclusion

This chapter demonstrates that paleochannels in the PAIS framework geology directionally influenced barrier island development by affecting alongshore sedimentation patterns. A persistent alongshore currents transported sediment discharged from ancestral rivers along the coast from north to south. Given the directionality of sediment transport, paleochannels acted as sediment sinks in the alongshore sediment budget. Alongshore spits developed on the updrift edges of paleochannels that were nourished from other paleochannels farther up the coast. Areas of the coast updrift of these paleochannels characterized by Beach and dune morphometrics are greater on the updrift side of the paleochannels, providing further evidence that the modern barrier island morphology was affected by initial variation in the framework geology. Reflectors in alongshore GPR surveys downlap onto the MIS II contact surface and dip to the south. The abrupt shift to near-horizonal reflectors in the southern end of a GPR survey suggests fluvial sedimentation was dominant for a period of island development. Future research incorporating sediment cores and OSL dating is required to more precisely refine the geochronological history of PAIS. Managing coastal resources for short- and long-term environmental and economic sustainability requires complete and accurate information about how PAIS developed. Predicting likely future changes to island morphology is predicated on this comprehensive understanding.

CHAPTER VI

CONCLUSION

Extreme storms, hurricanes, nor'easters, and tropical depressions, can cause widespread erosion and washover on barrier islands, and threaten coastal communities. The strong winds and waves of these storms can erode the beach and dunes, causing significant damage to coastal infrastructure and threatening human lives (Elko et al, 2016). Coastal vulnerability and resiliency depends on the coastal morphology (*i.e.* nearshore, beach, and dune morphology) in conjunction with storminess (*i.e.* storm frequency and magnitude) and the rate of sea level rise. Variations in the initial coastal morphology, such as undulations in dune height, can propagate through as heterogeneity in the modern barrier island morphology. Given that the modern landscape can inherit features and patterns of variability through time (Taylor Perron and Fagherazzi, 2012), it is important to understand what factors influenced the initial coastal morphology in order to more accurately predict future changes in response to storms and sea level rise. Improving the accuracy of future change models requires that we more accurately understand how a multitude of coastal processes interact to change the coastal geomorphology.

Previous field-based studies demonstrate that patterns and variation in the framework geology can influence barrier island morphology by affecting patterns of wave refraction and sediment transport gradients (Houser and Barrett, 2010; Houser, 2012). It is important to recognize, however, that previous research has focused on areas with relatively simple framework geology, such as isolated paleochannels (McNinch, 2004; Browder and McNinch, 2006; Schupp et al, 2006; Lazarus et al, 2011), rhythmic shore-oblique ridges and swales (Houser and Barrett, 2010; Houser and Mathew, 2011; Houser, 2012), or a submerged glacial outwash headland (Hapke, Lentz, et al, 2010; Schwab et al, 2013; Schwab et al, 2014). Complex patterns in the framework geology have the potential to significantly affect wave refraction and reflection patterns along the coast, thereby influencing beach and dune morphology and overall patterns of barrier island resiliency.

Current coastal morphodynamic models (*i.e.* Plant and Stockdon, 2012; Sherwood et al, 2014; Wilson et al, 2015) do not explicitly account for the influence of framework geology, despite increasing evidence that framework geology is a driver of coastal geomorphology at broad geographic scales (Elko et al, 2016). Incorporating the effects of framework geology into current models requires that we first quantitatively understand how variations in the framework geology influence coastal geomorphology both spatially and temporally. This dissertation examined the influence of a spatially complex framework geology on barrier island geomorphology.

This dissertation utilized a combination of field-based surveys and public DEM data to: (1) extract beach, dune, and island morphometrics using a multiscale relative relief approach (Chapter 2), (2) quantitatively demonstrate that paleochannels in the framework geology interact with daily wave reflection and refraction patterns to influence the modern barrier island (Chapter 3), and (3) demonstrate that paleochannels in the framework geology can have an asymmetric influence on the barrier island morphology, given a persistent alongshore sediment transport gradient (Chapter 4). Chapters 2 through 4 present new evidence about the effects of framework geology on barrier island evolution, suggesting the currently accepted theory of formation for PAIS is incomplete and should be re-examined in context of the framework geology.

Spatial variations in the framework geology, such as complex paleochannel networks, influence the nearshore bathymetry. The oblique ridges and swales along southern PAIS may have been derived from Rio Grande paleo-delta, similar to ridges and swales along Fire Island, NY (Lentz and Hapke, 2011; Schwab et al, 2013; Schwab et al, 2014; Warner et al, 2014). Ridges and swales along southern PAIS continue to influence modern patterns of wave refraction around ridges and swales, resulting in a variable alongshore beach and dune morphology. The interaction of framework geology with finer-scale patterns of wave refraction and reflection patterns is evident in the bicoherence hotspots in multiple beach and dune morphometrics (Chapter 3). Wave refraction and reflection influence alongshore sediment transport gradients and affect the volume of sediment available at any one location along the beach. Beach width will directly impact the amount of sediment available for aeolian transport. Sand from the beach is transported inland via onshore winds, causing dunes to form and grow. While vegetation distribution and expansion patterns do influence dune morphology (Duran et al, 2008; Judd et al, 2008; de M. Luna et al, 2011; Duran and Moore, 2013; Houser et al, 2015; Goldstein et al, 2017), continuous wavelet transformation (CWT) and wavelet coherence (WTC) analyses of alongshore variables support the hypothesis that broad-scale variations in sediment supply are ultimately set-up and reinforced by initial variations in the framework geology.

The paleochannels along PAIS not only influence beach and dune morphology within the channel edges. Chapter 4 presents evidence from ARFIMA modelling that paleochannels can asymmetrically influence beach and dune morphology. Areas updrift of the paleochannels exhibit greater long-range dependence (LRD) than downdrift areas. This asymmetry is likely due to paleochannels interrupting the alongshore sediment transport gradient and acting as sediment sinks, thereby starving parts of the beach downdrift of the paleochannel. Sediment moving from north to south, with the dominant alongshore current, nourishes the beach updrift of the channel, resulting in a generally wider beach. The greater effective fetch caused by the wider beach provides more sand for aeolian transport inland and foredune growth, resulting in larger dunes updrift of the paleochannel. This pattern continues alongshore until reaching a paleochannel, where flow velocity will decrease as the accommodation space increases within the channel and flow decreases. Increased accommodation space and decreased flow velocity within the channel will cause sediment to be deposited along the updrift edge of the channel. Sands are preferentially deposited along the updrift edge of the paleochannel and extend downdrift as a spit, similar to the formation of a baymouth bar, while finer particles moving alongshore would be transported offshore by water exiting through the channel outlet. Because the alongshore sediment transport gradient is dominantly southerly, the influence of paleochannels on beach and dune morphology is directional and not necessarily symmetric.

This dissertation demonstrates that framework geology is a significant driver of barrier island evolution by setting up initial variation in the beach and dune morphology and modifying normal conditions and coastal processes. Future work should seek to further refine PAIS geochronology through a combination of nearshore seismic surveys, sediment cores, optically stimulated luminescence (OSL) dating. Since landscapes can inherit morphology from the paleo-landscape, accurately predicting future changes to barrier islands requires a comprehensive understanding of how the framework geology can influence coastal processes and initial patterns in the barrier island geomorphology. Framework geology exerts structural control on nearshore, beach, and dune morphology, which drives patterns of barrier island transgression.

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