Marine Geology 398 (2018) 151–162

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

# Influence of a spatially complex framework geology on barrier island geomorphology

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ARTICLE INFO

Editor: E. Anthony

*Keywords:*
Coastal geomorphology
Coastal processes
Framework geology
Electromagnetic inductance
Geographic information science (GIS)
Wavelet analysis

ABSTRACT

Barrier island response and recovery to storms, and island transgression with relative sea level rise, can be influenced by the framework geology. The influence of framework geology on barrier island geomorphology has previously been examined in areas where the framework is rhythmic alongshore or consists of an isolated paleo-channel or headland. The purpose of this paper is to examine the influence of framework geology on beach and dune geomorphology at Padre Island National Seashore (PAIS), Texas, USA, where the framework geology is variable alongshore. Alongshore beach and dune morphometrics and offshore bathymetric profiles were extracted from a combined topography and bathymetry digital elevation model (DEM) using an automated approach along the ~100 km study area, and an electromagnetic induction (EMI) survey was used to map the subsurface framework geology. Wavelet decomposition, Global Wavelet (GW), and bicoherence analyses were used to test for spatial relationships between and within the extracted alongshore metrics. GW trendlines demonstrate that beach and dune morphometrics are structurally controlled. Hotspots in wavelet coherence plots between framework geology and alongshore island morphometrics indicate that the paleo-channels dissecting the island influence beach and dune morphology, with large dunes found in the area directly landward of the paleochannels. Bicoherence analysis of alongshore beach and dune morphometrics indicates that low-frequency oscillations due to framework geology interact with higher-frequency oscillations, with greater small-scale variability in the dune line directly landward of the paleo-channels. These results suggest that the paleo-channels of PAIS non-linearly influence beach and dune morphology, which in turn alters the response of the island to storms and sea level rise. It is argued that an understanding of the framework geology is key to predicting island response to sea level rise and framework geology needs to be included in barrier island models. This paper demonstrates that an irregular framework geology influences small-scale coastal processes, and creates interactions across scales that influence beach and dune morphology and affects barrier island response to storms and sea level rise.

## 1. Introduction

Barrier island morphology is the product of modern processes (*e.g.* alongshore sediment transport, wave action) interacting with pre-existing topography and bathymetry formed by past processes or in response to past storms, changes in sediment supply and sea level rise. 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 defined by variations in sediment type (*i.e.* sand *vs.* silt *vs.* clay), 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 paleo-channels (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006), mud-core ridges (Houser and Mathew, 2011; Houser, 2012; Houser et al., 2015), shore-

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https://doi.org/10.1016/j.margeo.2018.01.011
Received 28 June 2017; Received in revised form 2 December 2017; Accepted 25 January 2018

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). Studies of barrier islands along the U.S. Atlantic and Gulf of Mexico coasts demonstrate that subsurface geology can influence 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; Hapke et al., 2016), although these studies were focused on coasts with rhythmic geology, simple paleo-channels (*i.e.* limited bifurcation), or a single submerged headland. In many other environments, including the Outer Banks of North Carolina (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006) and parts of the Texas coast (Fisk, 1959; Anderson et al., 2014; Anderson et al., 2016), the framework geology is dominated by an irregular subsurface and offshore structure of varying size and sediment texture. The influence of framework geology on barrier island geomorphology is often overlooked or in some cases has been discounted as important when predicting future change and managing coastal resources (Duran and Moore, 2013; Murray et al., 2015; Goldstein and Moore, 2016; Goldstein et al., 2017).

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 (Stockdon et al., 2006; Plant and Stockdon, 2012; Gutierrez et al., 2015), 2) improving long-term coastal change assessments (Hapke et al., 2016), and 3) understanding coastal vulnerability to climate change and sea-level rise (Anderson et al., 2014; Wallace and Anderson, 2013; Dai et al., 2015). A Bayesian Network (BN) approach has recently been used to predict and assess the vulnerability of islands to sea level rise based on expert knowledge of hydrodynamic forcing, modern geomorphology and geologic constraints (Stockdon et al., 2006; Plant and Stockdon, 2012; Long et al., 2014; Wilson et al., 2015). The BN approach has been shown to be a valuable approach to predicting future changes, but there remains uncertainty about how the framework geology affects the hydrodynamic forcing, beach, and dune morphology. Improving model performance requires further study of how the framework geology influences beach and dune morphology through variations in wave energy or sediment supply and texture (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Houser, 2012; Schwab et al., 2013; Schwab et al., 2014; Warner et al., 2014).

As noted, the framework geology can range from rhythmic features to irregular and complex structures. Semi-regular offshore shore-oblique bar and trough structures have been documented at South Padre Island, Texas (Houser and Mathew, 2011), Santa Rosa Island, 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 (Houser and Mathew, 2011). An opposite pattern is observed at Santa Rosa Island, where the ridge and swale bathymetry offshore of Santa Rosa Island creates quasi-regular littoral cells (Stone, 1991), and an alongshore variation in beach and dune morphology that determines island response to storms and island transgression (Hyne and Goodell, 1967; Stone, 1991; Houser, 2012). Similar structures are present along portions of the southeastern U.S. Atlantic coast and are related to irregular and non-repeating relict subsurface paleo-channels infilled during Holocene sea-level transgression (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006). Shoreface attached sand ridges also alter beach and dune processes at Fire Island, NY (Hapke et al., 2010; Lentz and Hapke, 2011; Schwab et al., 2013; Hapke et al., 2016), where they are believed to be formed and maintained by oceanographic processes reworking a sandy submerged headland (Schwab et al., 2014; Warner et al., 2014).

Regardless of how these different shore-oblique bar and trough features developed, their location and morphology can influence beach and dune morphology. Shoreline variability and erosional hotspots along the southeastern U.S. coast have also been linked to shore-oblique bars and infilled paleo-channels in the framework geology (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Lazarus et al., 2011), where relict infilled paleo-channels 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, surf-zone currents are identified as the dominant driver of coastal geomorphology at alongshore length scales ranging from 30 m to 500 m, but that wave propagation over complicated bathymetry, as reflected by persistent kilometer-scale bedforms, begins to influence coastal geomorphology at an alongshore length scale of ~300 m. At the largest alongshore length scales analyzed, it was hypothesized that the dominant driver of coastal geomorphology are gradients in the wave-driven alongshore current associated with island curvature, 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 and does not account for the influence of framework geology or interaction between broad- and fine-scale processes. Cross-scale interactions between framework geology and localized processes has been suggested in shoreline change studies (Hapke et al., 2016) and beach-dune morphology (see Houser, 2012) in areas where the framework geology exhibits a regular alongshore variation. While alongshore shoreline behavior may be dissipative, variations in the dune morphology are reinforced by washover (Houser, 2012; Weymer et al., 2015a), which occurs on shorter timescales than the recovery of the dune through the expansion of dune-building vegetation (Houser et al., 2015).Shoreline behavior may become disconnected from beach morphology and behavior, and beach morphology may become disconnected from dune morphology and behavior, a process referred to as 'process decoupling' (Houser, 2009; Hapke et al., 2016).

The purpose of this paper is to test the hypothesis that an irregular framework geology influences fine-scale coastal processes (< 1000 m), and creates interactions across scales that influence beach and dune morphology and island response to storms and sea level rise. Previous studies of barrier island geomorphology have tended to focus on shoreline change at discrete alongshore length scales (Lazarus et al., 2011), but there is evidence that the framework geology influences broad-scale coastal processes, which in turn non-linearly influence filer-scale coastal processes responsible for changes in shoreline position, beach morphology, and dune morphology (Hapke et al., 2016). In this respect, the interaction between broad- and fine-scale coastal processes resembles a feedback mechanism, which is examined in the current study through wavelet decomposition, bicoherence analyses, and wavelet coherence. Wavelet decomposition provides valuable insight into structural patterns within a single morphological variable (see Lazarus et al., 2011), while bicoherence analyses help identify non-linear interactions (see Elsayed, 2006a, 2006b) between long-term (broad-scale) coastal processes (*i.e.* island transgression patterns and framework geology influences) and short-term (fine-scale) coastal processes (*i.e.* swash and surf zone processes). An extension of wavelet decomposition, wavelet coherence provides information about phase relationships between two variables. The analytical approaches used in this paper provide insight into process decoupling of shoreline, beach, and dune behavior at different spatial and temporal scales. Understanding and