Sedimentary Geology 321 (2015) 11–24

Contents lists available at ScienceDirect

Sedimentary Geology

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

Review

Review of electromagnetic induction for mapping barrier island framework geology

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ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form 4 March 2015
Accepted 7 March 2015
Available online 17 March 2015

Editor: Dr. J. Knight

Keywords:
Electromagnetic induction
Coastal geomorphology
Barrier islands
Geologic framework
Groundwater dynamics
Near-surface applied geophysics

ABSTRACT

The geologic framework controls on modern barrier island transgression and the relationship of these controls to subsurface structure, hydrology and island geomorphology are not well understood. Recent evidence suggests that alongshore variations in pre-Holocene geology of barrier islands modify nearshore hydrodynamic processes and sediment transport, ultimately affecting how barrier islands will respond to relative sea-level rise. Explorations of Holocene barrier island geology are usually based on cores to supplement bathymetric, onshore/offshore seismic and/or ground-penetrating radar (GPR) surveys. The advantages and limitations of these methods with respect to barrier island investigations are briefly described in this review. Alternative near-surface geophysical methods including electromagnetic induction (EMI) sensors are increasingly being used for coastal research because they are non-invasive, provide continuous subsurface information across a variety of sub-environments, and are capable of characterizing large areas in a short time. Although these EMI sensors have shown promise in coastal applications, a number of issues primarily related to subsurface hydrology need to be addressed to fully assess the limitations of this technique. This paper reviews the theory, methodology and applications of EMI in support of geologic framework studies with particular reference to barrier islands. Resolution of these issues will allow EMI sensors to complement and offer significant advantages over traditional methods in support of an improved understanding of large-scale barrier island evolution.

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1. Introduction

Along sandy coastlines, stratigraphically-controlled bathymetric features modify hydrodynamic processes on the inner shelf and nearshore, in turn affecting beach morphodynamics along the adjacent shoreline (Riggs et al., 1995). This geologic framework has been suggested to play a considerable role in determining how barrier island systems evolve during storms and in response to local sea-level rise (e.g., Hoyt, 1967; Kraft, 1971; Kraft and John, 1979; Kraft et al., 1982; Belknap and Kraft, 1985; Riggs et al., 1995; Dillenburg et al., 2000; Honeycutt and Krantz, 2003; Harris et al., 2005; Lentz and Hapke, 2011). Processes in the nearshore environment including waves, currents and sediment transport exert important controls on nearshore and beach morphology (McNinch, 2004). However, antecedent geology has also been suggested to exert a first-order control on nearshore morphology (e.g., sandbars), which can modify surf zone dynamics and influence beach morphology (McNinch, 2004; Schupp et al., 2006).

The geology of a barrier island represents a time-integrated net depositional record of past coastal forcing, the sequence of which can be reconstructed using traditional geologic principles (Riggs et al., 1995; Woodroffe, 2002). Most barrier island systems along the passive continental margins of the U.S. east and Gulf coasts are underlain by Pleistocene (or older) morphostratigraphic features such as incised river valleys (Schupp et al., 2006), inlet channels (FitzGerald et al., 2012) and relict transgressive features (Houser, 2012). These inherited features, in part, affect the exchange of sediment amongst the nearshore, beach and dune, and therefore determine how the island responds to individual storms (Riggs et al., 1995; Schupp et al., 2006; Houser et al., 2008). For example, evidence from Santa Rosa Island, Florida, suggests that ridge and swale bathymetric features along the shoreface are transgressive features that reinforce alongshore variations in dune height and storm response (Houser, 2012). In this respect, the position and distribution of subsurface structures have significant implications for beach and dune morphology, which is a primary control on net barrier island response to rising sea level (Riggs and O'Connor, 1974; Riggs, 1979; Reinson, 1992; Jackson et al., 2005; Houser, 2012). Specifically, alongshore variations in beach–dune morphology not only control storm impacts (i.e., the ratio between wave runup height and dune height), but also determine which areas across the island are most likely

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http://dx.doi.org/10.1016/j.sedgeo.2015.03.005
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to experience overwash and/or blowouts, ultimately governing large-scale barrier transgression (Sallenger, 2000; Morton, 2002; Houser et al., 2008; Houser, 2013; Masselink and van Heteren, 2014). Therefore, an assessment of antecedent geology (i.e., geologic framework) is critical for coastal management and risk assessment for anthropogenically-modified barrier islands (Hapke et al., 2010; Lentz and Hapke, 2011; Lentz et al., 2013).

Studies investigating the geologic framework controls on barrier island evolution have primarily focused on a specific sub-environment within the barrier island system (Table 1). The cross-shore sequence of morpho-sedimentary sub-units was defined as a *coastal tract* by Cowell et al. (2003) and represents the continuum of mutually dependent morphological units. In the offshore direction, the barrier system consists of inner-shelf, nearshore, beach, barrier and lagoon backbarrier sub-environments (Cowell et al., 2003; Van Heteren, 2014). Conversely, the sub-environments in the alongshore direction include the barrier island system, tidal inlets and subtidal deltas. In the analysis of large-scale coastal evolution, the data collection techniques available force an arbitrary compartmentalization of each sub-environment within the barrier island system. Inner-shelf (e.g., Riggs, 1979; Foyle and Oertel, 1997; Schwab et al., 2000; Rodriguez et al., 2001) and nearshore (e.g., Evans et al., 1985; Riggs et al., 1995; McNinch, 2004; Browder and McNinch, 2006) studies mainly use bathymetric and seismic surveys, respectively, because these methods are best suited for shallow water and offshore environments. Conversely, beach and barrier studies (e.g., Otvos, 1970; Riggs et al., 1995; Fitzgerald and Van Heteren, 1999; Morton, 2002; Jackson et al., 2005; Mallinson et al., 2010; Cooper et al., 2012) have tended to use coring and/or remote sensing techniques. It is important to note that the various methods listed above are used for different aims. For example, seismic imaging provides information about structure but cannot be used for dating sediments and/or events. A more detailed discussion of the traditional methods for barrier island research, their benefits and limitations is given in Section 3.

Despite the utility of these methods, coring provides only point-source information and in many cases limited penetration depth, whereas the seismic method is not well suited for land-based surveys in unconsolidated, sandy sediments (Leatherman, 1987; Smith and Sjogren, 2006; Schrott and Sass, 2008). Thus, coastal researchers began to turn to other geophysical techniques such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR). Used since the 1980s, GPR techniques provide high-resolution imagery of subsurface stratigraphy, thereby improving interpretations of geologic controls on barrier island evolution (e.g., Leatherman, 1987; Van Heteren et al., 1994; Jol et al., 1996; Bristow et al., 2000; Neal and Roberts, 2000; Buynevich and Fitzgerald, 2003; Mallinson et al., 2010). Over the past decade, ERT has become an increasingly used method for time-lapse monitoring of saltwater intrusion dynamics (e.g., Bauer et al., 2006; Adepelumi et al., 2009; Martinez et al., 2009; Zarroca et al., 2011) and migration of contaminant plumes in coastal aquifers (e.g., Cassiani et al., 2006). Collectively, some of the strengths and weaknesses of each method used for barrier island studies are summarized in Table 2. Because each method is best suited for a particular sub-environment, only a few studies have integrated multiple methods to explore the role of geologic inheritance on large-scale barrier island evolution (see Fisk, 1959; Evans et al., 1985; Williams et al., 1991; McBride et al., 1995; Harris et al., 2005; Kulp et al., 2005; Mallinson et al., 2010).

All geophysical techniques are ultimately constrained by subsurface hydrology including saltwater intrusion and groundwater table position. The relationship between subsurface geologic structures and hydrologic processes in barrier islands is not well known (Horn, 2002). Most coastal hydrology studies have focused either on nearshore/swash zone hydrodynamics (e.g., Lanyon et al., 1982; Nielsen, 1990; Hegge and Masselink, 1991; Gourlay, 1992; Turner, 1993; Oh and Dean, 1994; Horn, 2002) or hydrologic processes in backbarrier/lagoon environments (e.g., Amdurer and Land, 1982; Kocurek et al., 1992; Nielsen, 1999; Stevens et al., 2009). With the notable exceptions conducted by Nielsen and Kang (1996), Reide Corbett et al. (2000), and Ruppel et al. (2000), there is a paucity of information regarding groundwater dynamics throughout barrier island systems. Most coastal

Table 1
A summary of the coastal sub-system, methods and scientific applications for each of the publications investigating geologic controls on modern barrier island evolution discussed in this review.

Coastal sub-system investigated	Methods used	Applications	Relevant studies
Inner shelf	Seismic surveys, CSEM, sidescan-sonar, cores, and sediment samples	Influence of antecedent geology on barrier island development and evolution	Swift (1975), Field and Duane (1976), Foyle and Oertel (1997), Evans et al. (2000), Schwab et al. (2000)
Inner shelf/nearshore transition	High-resolution bathymetry, sidescan-sonar, subbottom profiles, vibracores, shoreline change analysis, radiocarbon dating, and computer modeling	Influence of antecedent topography and geologic framework on barrier evolution, shoreline change, sediment budget, and shoreface equilibrium	Thieler et al. (1995), Dillenburg et al. (2000), Rodriguez et al. (2001), Hapke et al. (2010)
Nearshore	Seismic, sidescan-sonar, swath/chirp bathymetry, acoustic backscatter, vibracores, and historical shoreline positions	Geologic controls on nearshore morphodynamics, preservation potential, shoreline change, and implications for coastal management	Belknap and Kraft (1985), Honeycutt and Krantz (2003), McNinch (2004), Browder and McNinch (2006), Schupp et al. (2006)
Nearshore/beach transition	Bathymetric surveys, shoreline position surveys, numerical modeling	Importance of geological framework related to the ability of the Bruun rule for hindcasting/forecasting rates of coastal shoreline erosion	List et al. (1997)
Beach	LiDAR, RTK (GPS), aerial photography, observation, and beach profiles	Geologic controls on morphodynamic beach state, and shoreline change	Jackson et al. (2005), Lentz and Hapke (2011), Lazarus et al. (2011), Lentz et al. (2013)
Beach/barrier transition	GPR, vibracoring, drill cores, observation, and aerial photography	Role of geologic framework in determining barrier formation, morphology and shoreface dynamics, storm impacts, and barrier classification	Otvos (1970), Riggs et al. (1995), Fitzgerald and Van Heteren (1999), FitzGerald et al. (2012), Morton (2002), Mallinson et al. (2010), Cooper et al. (2012)
Barrier	Seismic surveys, GPR, EM surveys	Controls on freshwater lens morphology in small barrier islands	Schneider and Kruse (2003)
Barrier/lagoon transition	Cores, geophysical logs, and radiocarbon dating	Geologic controls on transgressive and regressive barrier sequences	Kraft and John (1979)
Lagoon	Cores, probe samples, drill holes, radiocarbon dating	Geologic controls on barrier island transgression	Kraft (1971)
Entire barrier system	Seismic surveys, drive sampler and rotary core borings, vibracores, trenching, radiocarbon dating, and digital shoreline plots	Geologic controls on the formation and evolution of barrier island systems, erosion and sediment availability, and coastal restoration/management	Fisk (1959), Evans et al. (1985), Williams et al. (1991), Harris et al. (2005), Kulp et al. (2005), Mallinson et al. (2010)

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