Continental Shelf Research 144 (2017) 80–97

Contents lists available at ScienceDirect

Continental Shelf Research

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

Sand ridge morphology and bedform migration patterns derived from bathymetry and backscatter on the inner-continental shelf offshore of Assateague Island, USA

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ABSTRACT

The U.S. Geological Survey and the National Oceanographic and Atmospheric Administration conducted geophysical and hydrographic surveys, respectively, along the inner-continental shelf of Fenwick and Assateague Islands, Maryland and Virginia over the last 40 years. High resolution bathymetry and backscatter data derived from surveys over the last decade are used to describe the morphology and presence of sand ridges on the inner-continental shelf and measure the change in the position of smaller-scale (10–100 s of meters) seafloor features. Bathymetric surveys from the last 30 years link decadal-scale sand ridge migration patterns to the high-resolution measurements of smaller-scale bedform features. Sand ridge morphology on the inner-shelf changes across-shore and alongshore. Areas of similar sand ridge morphology are separated alongshore by zones where ridges are less pronounced or completely transected by transverse dunes. Seafloor-change analyses derived from backscatter data over a 4–7 year period show that southerly dune migration increases in magnitude from north to south, and the east-west pattern of bedform migration changes ~ 10 km north of the Maryland-Virginia state line. Sand ridge morphology and occurrence and bedform migration changes may be connected to observed changes in geologic framework including topographic highs, deflated zones, and sand availability. Additionally, changes in sand ridge occurrence and morphology may help explain changes in the long-term shoreline trends along Fenwick and Assateague Islands. Although the data presented here cannot quantitatively link sand ridges to sediment transport and shoreline change, it does present a compelling relationship between inner-shelf sand availability and movement, sand ridge occurrence and morphology, geologic framework, and shoreline behavior.

1. Introduction

Sand ridge and swale topography dominates the seafloor landscape along much of the US Atlantic continental shelf (Duane et al., 1972; Uchupi, 1968). Morphology of storm-dominated continental shelves like the Delaware-Maryland-Virginia (Delmarva) Peninsula has been characterized as having sand ridges 1–10 m in height with widths between 1 and 5 km, lengths that can extend for several km, spacing of 2–10 km, migration rates of 1–10 m/yr, and orientations between 5 and 50 degrees oblique to the shoreline (McKinney, 1975; Swift and Field, 1981; Figueiredo et al., 1981; Stubblefield et al., 1984).

Hypotheses on the origin of these prominent seafloor features generally fall into 2 broad categories (McBride and Moslow, 1991; Trowbridge, 1995; Goff et al., 1999). The first category suggests that these sedimentary structures are formed from relict features of the Holocene transgression, such as deltas, estuarine shoals, and cape-associated shoals, which became stranded, reworked, and then eventually submerged (Veatch and Smith, 1939; McClennen and McMaster, 1971). Furthering this approach, McBride and Moslow (1991) more recently put forth a mechanism for sand ridge formation that attributed the increase in the number of sand ridges along wave-dominated coasts to lateral inlet migration, ebb-tidal delta reworking then stranding, and shoreline retreat. In contrast to this stranding approach, the second category of hypotheses attributes ridge formation and maintenance to post-transgressive (modern) oceanographic processes, including bedform evolution, linear instability, edge waves, infragravity waves, helical flow structures, and coastal boundary effects (Swift and Freeland, 1978; Dolan et al., 1979; Huthnance, 1982; Hulscher, 1996; Boczar-Karakiewicz and Bona, 1986; Trowbridge, 1995). Improvements to the Trowbridge (1995) storm-driven instability model have added complexity (i.e. Coriolis effect, bed load and suspended load transport) and demonstrated the ability of morphodynamic models to generate updrift-rotated, shoreface-connected sand ridges that are consistent with field observations along Fire Island, NY

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http://dx.doi.org/10.1016/j.csr.2017.06.021
Received 18 July 2016; Received in revised form 15 May 2017; Accepted 19 June 2017
Available online 28 June 2017

(Falqués et al., 1998; Calvete et al., 2001a, 2001b; Warner et al., 2014; Walgreen et al., 2003; Vis-Star et al., 2007). These studies have shown that shoreface-connected sand ridges form from an instability mechanism over seaward-sloping shorefaces. Ridges that form in a preferred state will then grow and achieve long-term stability as a result of the offshore deflection of currents over the ridge crests and a landward deflection in the troughs. As the currents veer seaward on the ridge crests, their sediment carrying capacity will diminish and promote deposition on the ridge crest, enhancing the preferred self-sustaining state. Nnafie et al. (2014) added sea-level rise and shelf slope variations to the nonlinear morphodynamic model, which confirmed assertions from Swift et al. (1973), Figueiredo et al. (1981), Field and Duane (1976), McBride and Moslow (1991) that sand ridge formation, growth, migration, and eventual drowning is the result of geologic (i.e. sea-level rise and shoreline transgression) and oceanographic processes (i.e. storms and offshore-directed currents), and a robust model that explains the presence of sand ridges across the shelf needs to account for both. Factors such as sediment supply and the role of antecedent geology are not currently well established in morphodynamic models, but are essential to explaining the distribution, evolution, and varying morphology of sand ridges on storm-dominated shelves.

The formation and evolution of large-scale sedimentary structures like sand ridges occur on time-scales that are difficult to confirm with models and field observations (Oreskes et al., 1994), which is why there is over 70 years of research devoted to sand ridge origin, beginning with the work of Veatch and Smith (1939). In some cases smaller-scale bedforms can be observed and measured as a proxy for net bedload transport direction (Langhorne, 1982; Kubo et al., 2004; Knaapen et al., 2005: Barnard et al., 2010), such that orientation and migration of medium to large dunes may be used to infer local across-shore and alongshore sediment pathway changes that may contribute to sand ridge occurrence and morphology. Sand ridges are thought to play a key role in maintaining long-term shoreline stability along Fire Island, NY (Hapke et al., 2010a; Schwab, 2013). Sand ridges in southeast Virginia and northeast North Carolina are known to coincide with outcropping relict channels, gravel deposits at the seafloor, and shoreline erosional hotspots (Browder and McNinch, 2006; McNinch, 2004). Thus, identifying changes in sand ridge occurrence and morphology and bedform migration could lead to a clearer understanding of their contribution to long-term shoreline behavior, sediment pathways, and geologic framework on the inner-shelf.

This study builds on findings from Swift and Field (1981), which identified a change in sand ridge morphology across the shelf from the shoreface to the offshore along the Delmarva Peninsula. We revisit some of the cross-shelf metrics of ridge morphology and identify an alongshore change in morphology that occurs from Fenwick Island to the southern end of Assateague Island. Additionally, migration rates of small- scale (10–100 s of meters wavelength) bedforms, identified in time series bathymetric and backscatter datasets and associated with the ridge and swale topography, are measured to determine local changes in bedform and sand ridge migration patterns in the alongshore and cross-shore. Changes in sand ridge morphology and distribution on the shelf can be explained when bedform migration patterns, sand availability, and geologic framework are considered. The work presented here is part of a larger effort to ultimately understand the relationship between geologic framework and coastal vulnerability along the Delmarva Peninsula.

2. Geologic setting

Assateague and Fenwick Islands lie within the Delmarva coastal compartment of the Delmarva Peninsula (Fig. 1). Fisher (1967, 1982) and Oertel and Kraft (1994) described four major geomorphic elements of the Delmarva Coast, which are bounded by Delaware Bay to the north and Chesapeake Bay to the south. The major elements include a cuspate spit (Cape Henlopen), an eroding headland (Bethany and Rehoboth Beach), a wave-dominated spit and barrier (Fenwick and Assateague Islands, respectively), and mixed-energy to tide-dominated barriers (the barrier islands of Virginia). Updrift rotated, shoreface-attached ridges start to appear at Bethany Beach near the littoral drift fulcrum identified by Fisher (1967). According to McBride and Moslow (1991) sand ridges are most prevalent along wave-dominated barrier coasts like Fenwick and Assateague Islands, which have the highest density and most-well developed sand ridges of the entire US Atlantic coast.

On the shelf offshore of Assateague Island, a Holocene to pre-Holocene unconformity mapped and cored by Field (1976); (1980), Toscano et al. (1989); Toscano and York (1992), Wells (1994) indicates the majority of the overlying sedimentary deposit is patchy, transgressive sand ridges with no Holocene barrier island or back barrier deposits found below 12-m MSL (Toscano and York, 1992). Ravinement processes and slow sea-level rise rates over the last 7000 years are responsible for the removal of the majority of the Holocene depositional sequence on the shelf out to 30 m below MSL (Toscano and York, 1992). The sand ridge sediments are thought to be sourced from the erosion and reworking of the underlying pre-Holocene deposits similar to the sand ridges off Fire Island, NY described by Schwab et al. (2014). The Wisconsinan-age paleo-St. Martin fluvial system and numerous outcropping tidal channels incised into the pre-Holocene deposits have been identified in seismic-reflection data on the inner continental shelf (Field, 1976, 1980; Toscano et al., 1989; Toscano and York, 1992; Wells, 1994). Paleochannels have been associated with gravelly deposits, sorted bedforms, and erosional hotspots along the shoreline in North Carolina and Virginia (Riggs et al., 1995; McNinch, 2004; Browder and McNinch, 2006).

Storm-dominated coasts such as Fenwick and Assateague Islands, are classified as such because storms from late fall to early spring are thought to drive the net alongshore and cross-shore sediment transport within the region. Mean winter wave heights calculated by Komar and Allan (2008) using NGDC wave data offshore of Cape May, NJ are 2.5 m, while mean summer wave heights are around 1.3 m over a 30 year period. The dominant summer wave direction is from the east and southeast whereas the winter wave direction is from the northeast and east. The net southerly alongshore transport of sediment on the inner-shelf within the study area is the result of storm-driven flow. The spring tide range at Ocean City, MD is 0.75 m according to NOAA tides and currents (https://tidesandcurrents.noaa.gov/), resulting in a microtidal shelf with weak tidal currents.

Long-term shoreline change varies significantly within the region. There is no sand contribution from rivers (Meade, 1969), so alongshore transport of sand through updrift erosion of headlands and cross-shore exchange with the inner-shelf are the only potential sources of sediment to beaches. Hapke et al. (2010b) produced long-term (century-scale) and short-term (decadal-scale) shoreline change rates for the region, which show that Fenwick Island is slightly erosional to stable over the last century. Assateague Island is erosional at the northern end, south of the Ocean City Inlet, and has retreated more than 500 m since the inlet was stabilized in the 1930s. Central Assateague is stable over the long-term, and the southern end of Assateague Island is primarily accretionary as a result of spit progradation processes (Hapke, 2010b).

3. Methods

3.1. Data sources

Between 1975 and 2014, 28 hydrographic and geophysical datasets were collected on the inner-continental shelf of the Delmarva Peninsula (Table 1; Fig. 2). These data can be broken into 3 groups. The first group of data consists of 17 National Oceanic and Atmospheric Administration (NOAA) hydrographic surveys collected by Leidos