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Natural Maintenance of Sand Ridges and Linear Shoals on the U.S. Gulf and Atlantic Continental Shelves and the Potential Impacts of Dredging

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ABSTRACT

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Ridge and swale topography is exceptionally well developed on the continental shelves of the Mid-Atlantic Bight and the northeastern Gulf of Mexico. In both cases, these linear ridges are oriented parallel to the predominant wave approach direction, suggesting a common process for both their origin and maintenance. Most researchers have concluded that ridges were derived from shorefaces of barrier islands as they retreated across the shelf in response to rising sea level and tides or storm-driven currents maintain them.

The widely cited ridge formation theory of HUTHNANCE (1982) requires a sufficient sand source, currents to move the sand, and an irregularity on the sea floor around which the ridges are initiated. MCBRIDE and MOSLOW (1991) postulated that one of the initial irregularities is a segment of an ebb-tidal delta abandoned by inlet migration. However, the search for other precursors continues. These theories of origin provide little information on how these features maintain their form once they are detached from the shore yet remain in a zone of active wave attack (*i.e.* in depths less than 20 m). SNEDDEN *et al.* (1999) indicate that shoals in water depths less than approximately 20 m are migrating shoreward through the influence of Stokes Drift under fair-weather waves based on the work of MCHONE (1973). However, this model does not explain the maintenance of the form of linear shoal and ridge features.

To assess the impacts of dredging on these features it is essential that a better understanding of the processes that maintain these features be developed. A new conceptual model presented in this paper demonstrates how waves shoaling and refracting up either side of a ridge off the coast of Maryland and Delaware result in convergence of sand transport over the crest of the ridge, thus maintaining the ridge even after it is detached from shoreface processes.

The possibility that these ridges might deflate or disappear as a consequence of dredging, resulting in dramatic changes in wave conditions along the shore, is a major concern. The application of a spectral or phase-resolving wave model combined with two-dimensional hydrodynamic and sand transport models as applied in this paper represents a method to evaluate this potential impact of dredging.

ADDITIONAL INDEX WORDS: *Wave refraction, sand transport, non-linear wave orbital velocity, shoal evolution, shoal persistence.*

INTRODUCTION

A growing demand exists for good quality sand to support beach nourishment projects along the Gulf and Atlantic coasts of the United States. As a result of dwindling supply of suitable quality sand in State waters that can be extracted without significant physical and biological impacts, Outer Continental Shelf (OCS) deposits, under the federal jurisdiction of the Minerals Management Service (MMS), are now being dredged and widely considered as a primary source of sand. In response to this demand, the MMS has completed a range of investigations including several environmental studies of individual deposits on the OCS. In addition, the MMS commissioned a study to design a long-term monitoring program that would evaluate the physical and biological changes that might occur as a result of Federal OCS sand mining (NAIRN *et al.,* this volume). The outcome of this project was the development of monitoring protocols for dredging OCS sand. A component of these protocols will address the long-term response of shoal morphology. Any significant changes to the shoal form that are triggered by removal of sand could result in a range of indirect physical and biological impacts.

During development of the monitoring protocols, the types of OCS sand deposits that have been dredged or targeted for dredging were reviewed and classified. Many of these features had the form of ridge and swale complexes or similarly shaped shoals and were found in water depths of 5 to 15 m in a zone of active wave action. A concern exists that repeated dredging of these shoals may eventually result in the "deflation" of the features by permanently altering natural processes that maintain shoal form. Recognizing that the potential for these shoal-type features to be altered in form may result in significant biological and physical impacts, a review of the characteristics, origin and maintenance of these features was undertaken. A new conceptual model for mainte-

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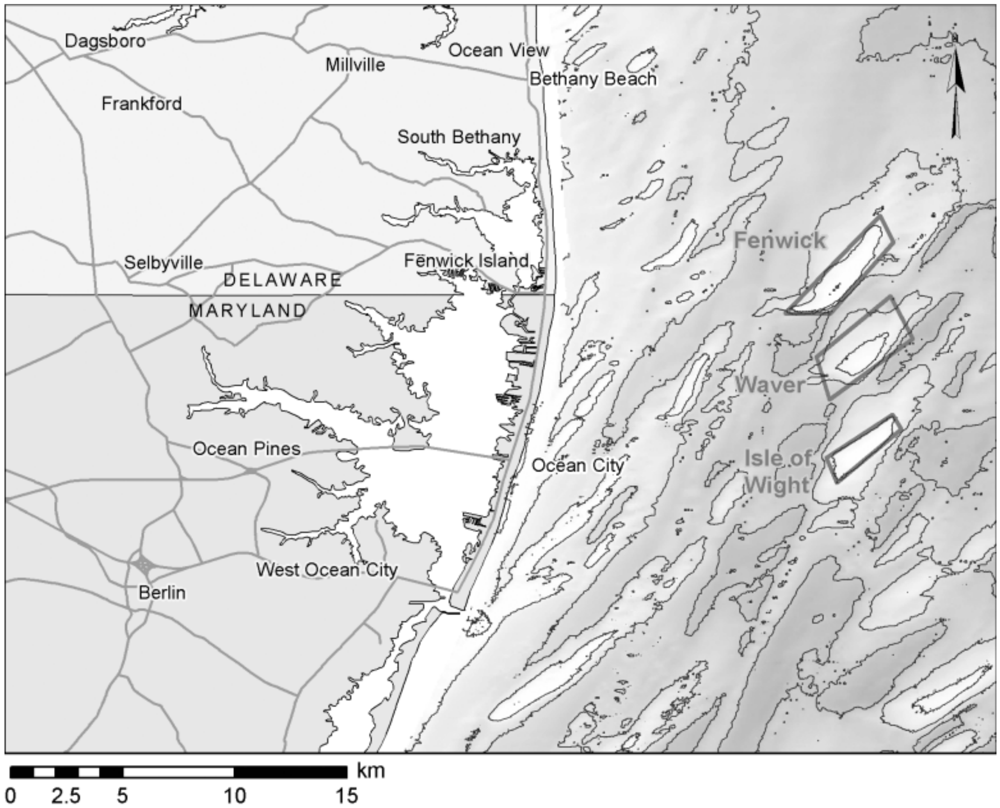

Figure 1. Example of ridge and swale topography typical of the Mid-Atlantic Bight region. Note detailed bathymetry (VIMS, 2000).

nance of continental shelf shoal features by wave action is presented. Finally, the potential physical and biological impacts of dredging these features are summarized.

The specific objective of this paper is to determine how ridge and linear shoal features are maintained in order to develop a method to assess the impact of dredging on shoal "maintaining" processes. The definition, occurrence, and origin of these features are reviewed for the purpose of deriving an understanding of processes that maintain these features in their observed form within the active wave zone. Much more comprehensive literature reviews are presented by McBride and Moslow (1991) and Snedden *et al.* (1999). The primary focus is on a review of the processes that maintain these features and ultimately the development of a new conceptual model to explain how these features are maintained.

DEFINITION AND OCCURRENCE

Several kinds of sand bodies exist on the continental shelves of the USA, but this discussion will focus primarily on sand ridges and swales that are located on the inner/upper continental shelf and oriented parallel to the predominant or prevailing wave approach direction (*i.e.,* ridges that are oriented shore-oblique). One of the first comprehensive descriptions of these occurrences on the continental shelf off the east coast of the USA was by Uchupi (1968). These features, which he termed sand swells, were described as follows: radiating clusters near the mouths of estuaries; arcuate, seaward convex ridge systems near cuspate forelands; shoreface ridge and swale systems; and broadly spaced ridges and swales on the open shelf. Ridges and swales will be emphasized in this discussion.

Other varieties of sand bodies preserved on the shelf that could provide sand for beach renourishment include: (1) overstepped barrier islands (*e.g.,* Ship Shoal off the Mississippi Delta); (2) active and inactive estuarine entrance shoals (*e.g.,* off St. Helena Sound, South Carolina); (3) large ebb-tidal deltas off major tidal inlets (*e.g.,* Mobile Bay); (4) delta lobes deposited at lower stands in sea level (*e.g.,* Santee Delta, South Carolina); (5) features associated with low-stand river valleys (*e.g.,* shelf off Texas and North Carolina); and (6) tidal sand ridges (*e.g.,* offshore New England and Alaska); and possibly others (see Table 3 in McBride and Moslow, 1991).

The best examples of ridge and swale topography on the North American continental shelf occur in the mid-Atlantic Bight (Figure 1), northeastern Gulf of Mexico (offshore Alabama and northwest Florida; Figure 2) and Sable Island Bank in eastern Canada (Figure 3).

In every case, the long axes of ridges are oriented directly into the predominant or prevailing storm wave approach direction. Waves approach from the northeast in the mid-Atlantic Bight (during "nor'easters"), from the southeast off Al-

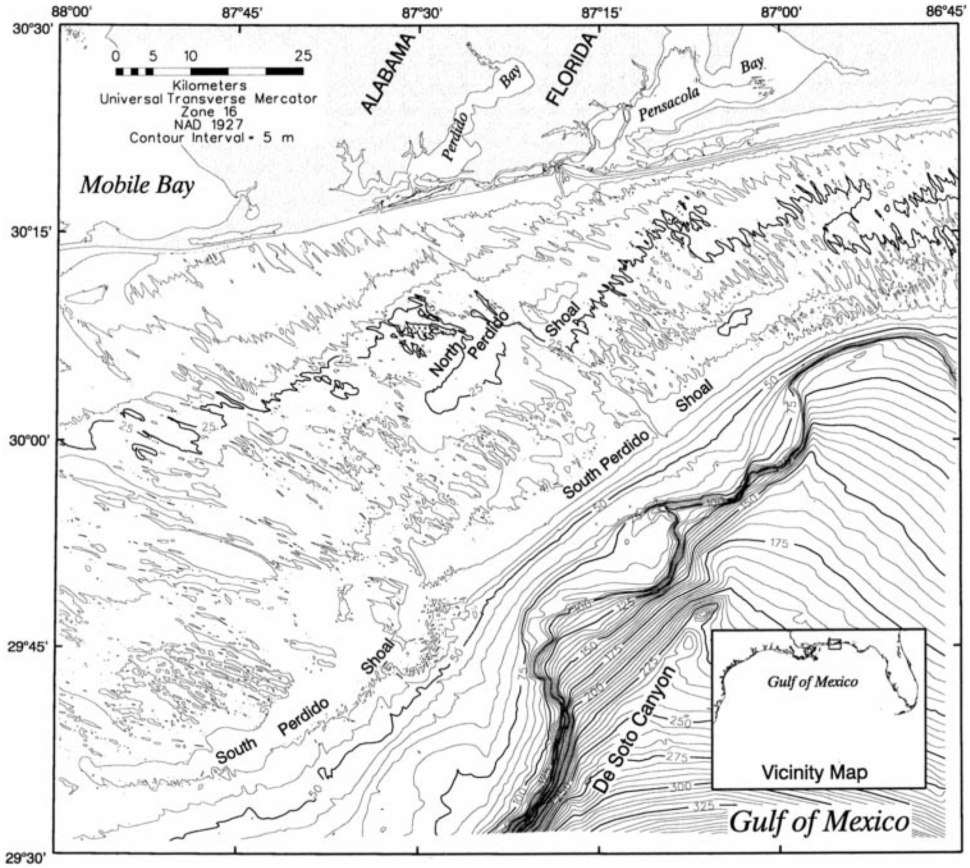

Figure 2. Continental shelf in the northeastern Gulf of Mexico showing detailed bathymetry at 5 m contour intervals. Thicker contours are at 25 m intervals. From McBride *et al.* (1999).

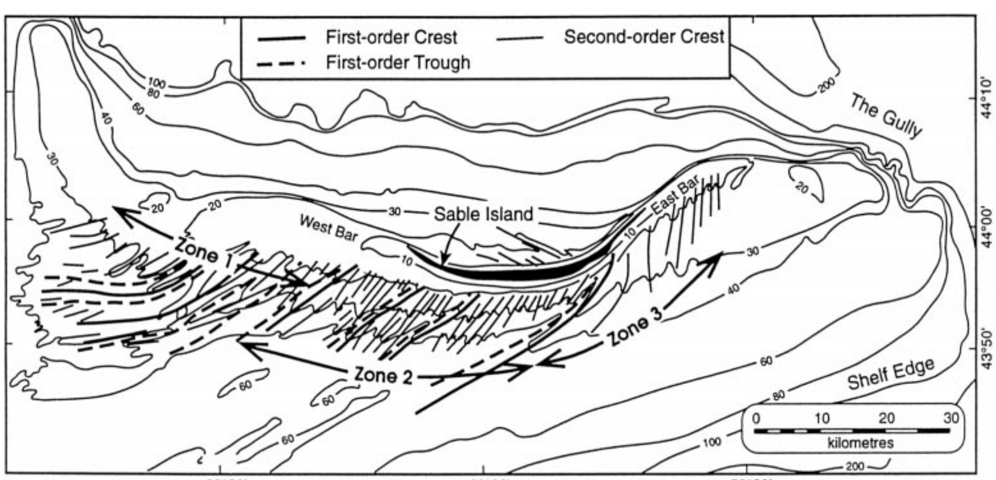

Figure 3. Bathymetry (in meters) of the area surrounding Sable Island, with crestline positions of the shoreface-attached ridges. From Hoogondoorn and Dalrymple (1986).

Table 1. *General characteristics of sand ridges summarized from the data for the Maryland shelf (slightly modified from SWIFT and FIELD, 1981) and for global sand ridges, including tidal sand ridges (from SNEDDEN and DALRYMPLE, 1999).*

Criteria	Maryland	Global
orientation	perpendicular to wave approach	flow-oblique
symmetry	asymmetrical near shore	asymmetrical
relief	3–12 m	5–40 m
horizontal width	0.9–2.8 km	0.7–8 km
spacing	1.5–11.1 km	—
maximum side slopes	0.2–7 degrees	<1–7 degrees
grain size	fine to coarse sand	fine to coarse sand
lateral trends (grain size)	stoss* side coarser than lee side	stoss side coarser
superimposed bedforms	ripples to sand waves	ripples to sand waves

* Stoss side faces the dominant current direction (or in the case of waves faces the dominant wave approach direction).

abama, and from the southwest on Sable Bank. This fact seems to suggest a common process, likely related to wave forces either directly or indirectly, for both the origin and maintenance of these features.

Table 1 lists the general characteristics of sand ridges. Grain size trends commonly observed on sand ridges off Sable Island and New Jersey show that coarsest sediments occur in the swales and on the shoreward flank of ridges (*i.e.,* northwest side of New Jersey ridges and west side of Sable Island ridges). This pattern appears to be typical for ridges in water depths of less than 20 m.

Based on the numerous studies conducted within the last two decades, it seems clear that, once formed, most ridges in depths of less than 20 m are maintained and even enlarged by present-day hydrodynamics (SNEDDEN and DALRYMPLE, 1999). It also seems clear that an evolutionary progression occurs in an offshore direction as the influence of waves diminishes. The contrast of storm and fair-weather conditions on ridges, in both nearshore and offshore areas, as envisioned by SNEDDEN *et al.* (1999), is given in Figure 4. The fair-weather onshore transport mechanism due to Stokes Drift was originally proposed by MCHONE (1973). Measurements of currents taken during a storm showed that storm-generated flows ran obliquely offshore and across the crest of a shoreface-attached ridge in New Jersey (Figure 5; from SNEDDEN *et al.,* 1994). It is noted that this ridge is much closer to shore than the ridges under consideration on the OCS.

GOFF *et al.* (1999) stated "in depths greater than 20 m, ridges have not continued to grow since transgression has brought them into the offshore hydrodynamic regime". Many studies have concluded that reworking occurs at the tops of the ridges located further offshore, but few imply that the ridges have been completely reformed.

THEORIES FOR ORIGIN AND MAINTENANCE

PENLAND *et al.* (1988) studied the evolution of Ship Shoal, a large transgressive sand body off the coast of Louisiana using vibracores, age dates, seismic profiles, and fossil assemblages. The shoal, located in water depths of 3 to 10 m, has a 5 m thick core that was interpreted as a barrier island

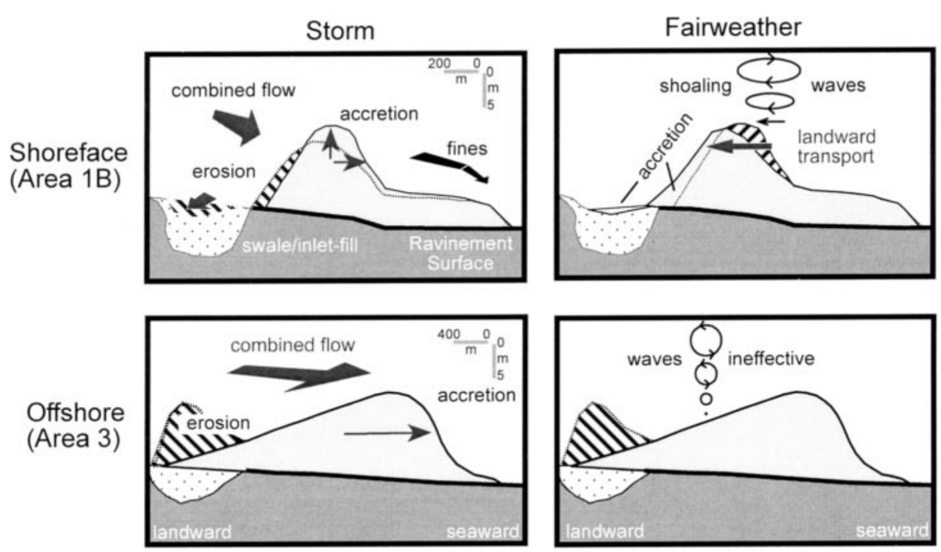

Figure 4. Storm and fair-weather dynamics and ridge migration in nearshore and offshore areas. Based on current meter data reported in SNEDDEN *et al.* (1994) and MCCLELLAND (1973) and bathymetric surveys of MCHONE (1973). From SNEDDEN *et al.* (1999).

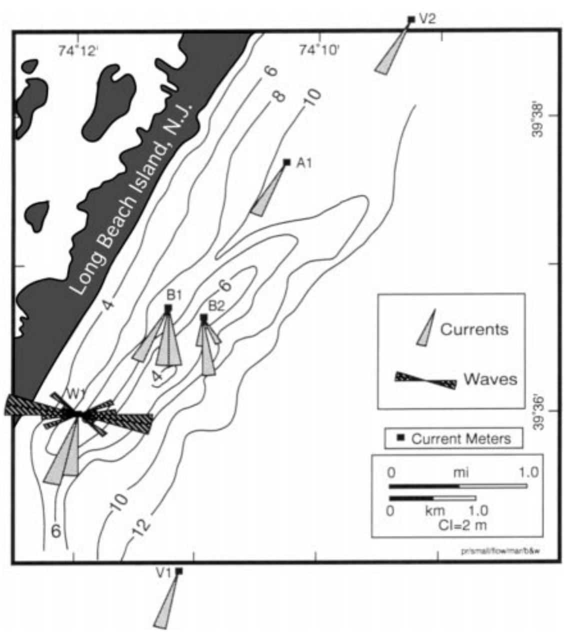

Figure 5. Orientation of near-bottom, peak storm current and wave motion 30–31 March 1985. Current meters V1 and V2, which are located outside map area, are shown for reference. From SNEDDEN *et al.* (1994).

deposit. Furthermore, the shoal is asymmetric landward, implying some modification and reworking by waves. Preservation of a relict barrier island of this magnitude can only occur on shorelines that are subsiding rapidly, which is the case for the abandoned Mississippi River delta lobe with which that barrier island was associated. On tectonically stable shelves, such as Maryland and Alabama, any such lowstand barrier islands that may have been present, owing to a stabilization of sea level for some period of time, would have been eroded away during the slow rise of sea level that followed formation of the islands. Some authors, such as STUBBLEFIELD *et al.* (1984), have concluded that remnants of relict barrier islands are still preserved on the middle continental shelf of the Mid-Atlantic Bight, but none have been proposed for depths as shallow as Ship Shoal, at least not in the more recent literature.

The development of ridge and swale topography of the type under discussion here appears to be favored by: a wide, sandy continental shelf with a moderately abundant sand supply, either from riverine sources, erosion of the shoreline as the sea level rises, or from sediment brought to the shelf during periods of glaciation and/or ice melt; rising sea level over a widening shelf; and bathymetric irregularities that act as nuclei for the ridges.

Ridges and swales do not occur on prograding delta fronts or other intensely prograding areas, especially those with high rates of mud deposition. Based on a literature search, ridges and swales do not occur on macrotidal coasts, but apparently some occur off the mesotidal coast of the North Sea (HUTHNANCE, 1982). The center of the Georgia Bight, which has the largest tides along the east coast of the USA south of Maine, as well as a source for abundant muddy sediments, does not have near the number of ridges that occur in the Mid-Atlantic Bight area.

Early researchers of the Mid-Atlantic Bight recognized a need to explain the puzzling fact that ridges are parallel to each other, seeming to mimic earlier ridges in deeper water, and that their long axes are oriented directly into the dominant northeasterly wave approach direction. SWIFT *et al.* (1973) and later authors concluded that ridges were derived from the shoreface of barrier islands as they retreated across the continental shelf in response to rising sea level. Over time, these new shoals became disconnected from the barrier islands and retreated to the southeast as the barrier island continued to migrate landward. To explain how the ridges were maintained, these authors relied on storm-generated helical secondary flow structure and storm wave surge, which resulted in converging bottom currents that aggraded the ridge crests.

Numerous other formation theories have been proposed, none of which dispute the importance of rising sea level and an abundant sand supply. One of the more controversial theories was proposed by BOCZAR-KARAKIEWICZ and BONA (1986). It states that a mechanism that may account for systems of sand ridges on wave-dominated shelves is associated with the development of infragravity waves. These waves have periods ranging from 30 seconds to 5 minutes. This theory does seem to account for the number and parallelism of the ridges. However, even the authors admit that mechanisms leading to the development and form of ridges are not explained by this concept.

One of the more widely cited theories of origin and maintenance of these features is that of HUTHNANCE (1982). Based on observations of tidal currents and sand transport for linear sand banks offshore Norfolk, UK on the North Sea, CASTON (1972) found that the direction of the tidal currents progressively turned towards the crest of the shoal feature in shallower water, thereby maintaining the feature. HUTHNANCE (1982) developed his model to provide a theoretical explanation for the observations of CASTON (1972) and ultimately for the formation, growth, maintenance, and equilibrium of tidal sand ridges.

The HUTHNANCE (1982) model is based on the solution of continuity of mass and momentum equations for depth-averaged flow. This hydrodynamic model was coupled with the sediment transport formulation of BAGNOLD (1956) to predict sediment transport patterns in the two horizontal dimensions. When a perturbation or irregularity is introduced to the seafloor, tidal flows moving over the feature will tend to turn toward the crest of the feature as a result of the influence of increased friction slowing currents in shallow water. The influence of wave action was introduced to the model to suppress growth above a certain crest elevation (*i.e.,* above a certain depth wave action acts to suspend sediment and prevent additional deposition). The influence of non-linearity of the oscillatory wave motion was not considered. The asymmetry of ridges along the major axis was explained by tidal asymmetry that is prevalent along much of the Norfolk coast of the UK for which the model was originally developed.

Three major constraints exist that must be met in order

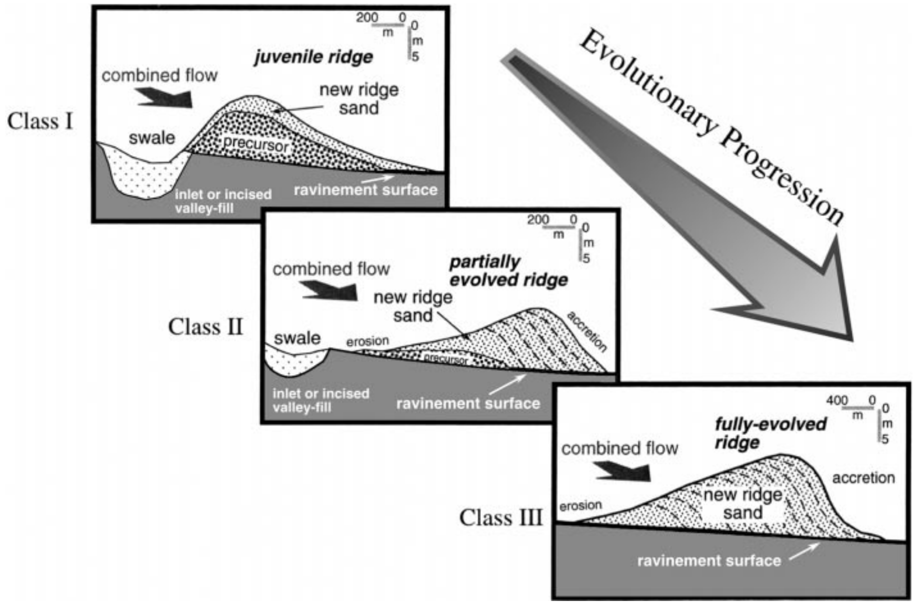

Figure 6. Schematic diagram of ridge classes. From SNEDDEN and DALRYMPLE (1999). The precursor in the case of the Class I and II ridges is a pre-existing bathymetric feature, sometimes associated with a shoreline or inlet, which provides the nucleation point for the ridge via the Huthnance process. Subsequently, this precursor may be removed or reduced in size through current erosion and ridge migration. Accretion on the landward side of the juvenile ridge (Class I) is largely induced by fair-weather wave transport from the ridge crest and is not expected to occur in ridges developed in deeper water, as with Classes II and III. New ridge sand is primarily deposited in shelf waters by combined flows associated with storm passage.

for the Huthnance theory for the genesis of ridges to work: (1) a sufficient quantity of loose sand; (2) currents capable of moving the sand; and (3) a pre-existing irregularity.

In order to take issue three into account, many of the recent workers favor an idea presented by MCBRIDE and MOSLOW (1991). Under this theory, the pre-existing irregularity is the ebb-tidal delta of an inlet through an adjacent barrier island. The inlet migrates downdrift, leaving a piece of its ebb-tidal delta behind that becomes the core of the new sand ridge formed by the process outlined by HUTHNANCE. The inlet continues to migrate until it eventually closes and a new inlet forms and the process starts all over again. SNEDDEN and DALRYMPLE (1999), in an excellent summary paper on sand ridges, are strong proponents of this idea and indicate that the migrating inlet is responsible for the swale on the landward side of the new ridge.

Another theory of preservation postulated by TROWBRIDGE (1995), who also discussed the ridges on the Mid-Atlantic Bight shelf, proposed that storm-driven southerly currents veer offshore over the ridge crests, as the data of SNEDDEN *et al.* (1994; see Figure 5) clearly show. Trowbridge also stated that the “exponential growth of shore-oblique features is a result of offshore deflection of storm-driven alongshore flows at ridge crests, which leads to convergence of sediment flux because the effective carrying capacity decreases with increasing distance offshore.” The Trowbridge model effectively replaces the asymmetric tidal currents of the HUTHNANCE (1982) model with currents having a dominant southerly direction generated by the prevailing northeasterly storm waves.

Limitations and outstanding questions remain with all of these theories, thus the search for the different precursors (initial irregularity) required to fulfill the Huthnance theory continues. A number of possible initial irregularities exist, as discussed by MCBRIDE and MOSLOW (1991, Table 3, *e.g.,* submerged pieces of relict barrier islands). In the evolutionary progression for the sand ridges proposed by SNEDDEN and DALRYMPLE (1999), the precursor element may eventually be preserved, reworked, or eroded as the migrating ridge migrates offshore across the shelf (illustrated in Figure 6).

SNEDDEN *et al.* (1999) proposed a model for the evolution of sand ridges from the inner shelf (depths less than 20 m) through to the outer shelf (depths greater than 20 m). For the inner shelf shoals and ridges the onshore migration of these features is attributed to Stokes Drift (*i.e.,* the Lagrangian component of mass transport) based on the work of MCHONE (1973). In deeper water (approximately greater than 20 m), the role of waves diminishes and is overwhelmed by offshore-directed ocean currents that cause these features to migrate offshore.

Another formation process or explanation of origin of ridge and shoal features relates to stratigraphically controlled features. These features consist of sand deposited over Pleistocene sediment units and are particularly prevalent along the North Carolina coast (RIGGS *et al.,* 1995). The stratigraphy of such features has important implications regarding size of sand reserves and potential impacts of dredging. Also, the form and crest elevation of the Pleistocene core may provide valuable information on the extent of dredging that could take place on a ridge consisting entirely of sand without risking natural deflation of the feature. Providing there was sufficient supply of sand available locally around the base of the shoal that is dredged, presumably it could rebuild with time from the remaining nucleus (just at the Pleistocene-cored shoal grew originally). However, there are several complications in transferring the Pleistocene-cored model for growth and maintenance to the present related to defining the sea level and wave climate at the time of original formation.

In conclusion, while significant effort has been invested in development of theories for origin and maintenance of these features in tide-dominated environments or nearshore wave-dominated environments, there has been surprisingly little research or explanation of how these features manage to maintain their form in an active wave environment located offshore on the OCS in water depths of less than 20 m.

A NEW CONCEPTUAL MODEL FOR THE MAINTENANCE OF RIDGE AND SWALE FEATURES

The direct influence of wave action has received little attention in the literature with regards to the maintenance (and migration) of shelf ridge and swale features. The fact that most features continue to have their major axis aligned with the dominant direction of wave approach even after being detached from the littoral zone points to the importance of wave action and the related sediment transport for maintaining these features. Other theories of origin and maintenance such as those of HUTHNANCE (1982) and TROWBRIDGE (1995) do not provide a complete explanation for the maintenance of these features in their form and orientation in areas where they are detached from the coast with little influence from wave- and tide-generated currents.

The part of the evolution model of SNEDDEN *et al.* (1991) that addresses migration of these features due to Stokes Drift under fair-weather waves (after MCHONE, 1973) in water depths less than 20 m does not explain the maintenance of these features. Also, NAIRN (1990) has shown that the Stokes Drift component has very little influence on onshore-directed (*i.e.,* in the direction of wave propagation) sand transport for depths in the range of 0 to 10 m corresponding to the depth of water over the crest of shoals located in water depths of 20 m or less.

A Boussinesq wave model (phase resolving) was applied to assess the influence of waves on the group of shoals offshore Maryland and Delaware (Fenwick, Weaver, and Isle of Wight Shoals) shown in Figure 1. The MIKE21 Boussinesq Wave Module (M21BW) is a two-dimensional finite difference model developed by the Danish Hydraulic Institute for the simulation of short-crested waves. The model has the ability to simulate irregular multi-directional waves and includes full and partial reflection, current interaction, and other features. A full technical description of the model may be found in MADSEN *et al.* (1991), MADSEN and SØRENSEN (1992) and MADSEN and SØRENSEN (1993). A phase-resolving model was selected for application here to be able to produce an animation of the wave surface to provide more realistic visual representation of the processes. This model helps in elucidating key processes that are explained below.

A M21BW model simulation was completed for a wave representative of northeasterly storm conditions with an incident direction of ENE, a significant wave height of 3 m, and a wave period of 16 seconds. Figure 7 provides a snapshot of an animation of the Boussinesq model simulation of waves approaching from the northeast and interacting with the shoals. Refraction causes waves to shoal and refract around either side of Fenwick Shoal and converge on the crest. This crossing pattern at the crest of the shoal may be the key factor to maintenance of shoal features aligned with the dominant wave direction. The existence of converging waves on the crest suggests that convergence of sand transport over the crest occurs.

To assess the influence of the waves on sand transport, the orbital velocity and steady currents generated by the Boussinesq model were used to predict sand transport rates and direction throughout the model domain. Depth-averaged fluxes in X and Y directions were divided by the total instantaneous water depth to get a depth-averaged velocity time history with a duration of 15 minutes and a time step of 0.5 seconds. Sediment transport rate vectors were calculated on a wave-by-wave basis using the formula of Dibajnia and Watanabe (DIBAJNIA *et al.,* 2001). The formula has been derived for sheet-flow transport under nonlinear irregular oscillations and superimposed steady currents. The results are presented in Figure 8, showing time-averaged (for the 15 minute simulation period) vectors of sand transport giving magnitude (*i.e.,* the size of the arrow head) and direction overlaid on the bathymetry of Fenwick Shoal. These results demonstrate how waves shoaling and refracting up either side of Fenwick Shoal result in convergence of sand transport along most of the crest of this shoal. Net sand transport direction in shallow water, where waves are rapidly shoaling and breaking, is determined by the balance of the two main components of transport consisting of the onshore-directed component driven by non-linear orbital velocities (with the stronger, shorter orbital motion in the direction of wave propagation) and a steady undertow velocity directed against the wave propagation direction (see NAIRN and SOUTHGATE, 1993). However, in the case of a shoal where there is no above-water beach, a strong undertow velocity will not be generated, leaving the non-linear orbital velocity component of sand transport as the primary force driving net sediment motion. There will be situations with smaller linear waves where ripples form and the direction of sand transport is far more difficult to determine. However under conditions of large waves, strong shoaling and some breaking (when most sand moves) sheet-flow and flat-bed conditions prevail and net onshore transport will exist as explained by NAIRN and SOUTHGATE (1993). This explains why the net sand transport will be in the direction of local wave propagation approaching the crest of a shoal feature.

Referring again to Figure 8, a mechanism also appears to exist to extend the shoal in the direction of the incident wave propagation at the tip of the southwest end of the shoal, explaining the presence of a wide shelf-like feature in this area. In addition to convergence over the crest, there is net sand transport towards the steep shoreward flank of the shoal (SW or bottom left corner in Figure 8). Several authors have reported on observed migration of ridges in the direction of the

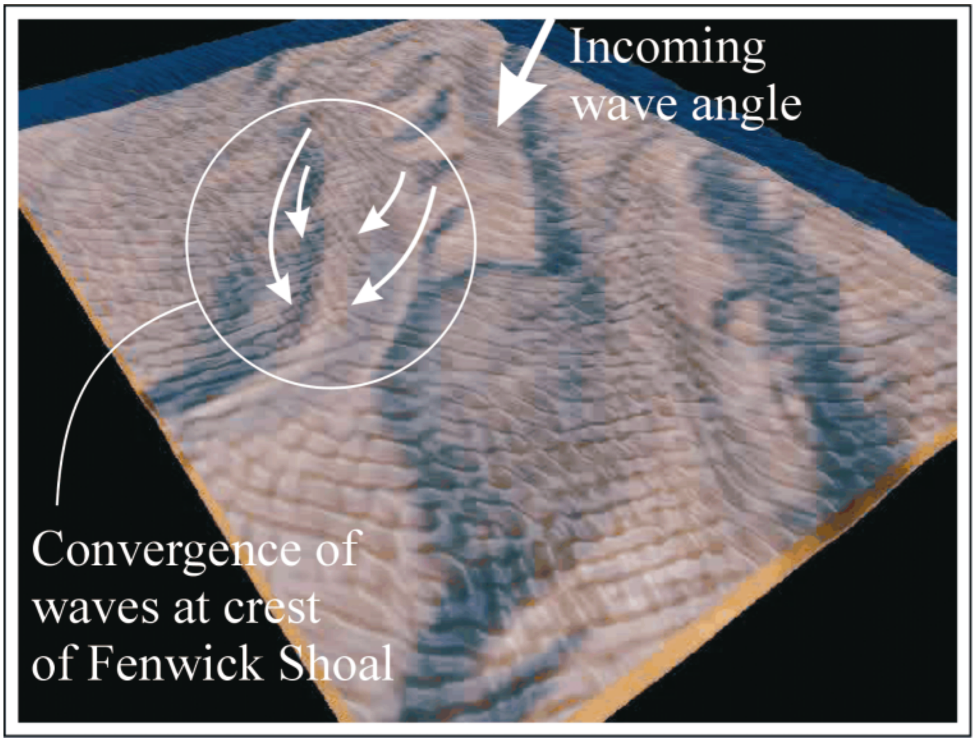

Figure 7. Snapshot of an animation of wave action predicted with a Boussinesq numerical model over the Fenwick and Weaver Shoals. The results are for a 3 m significant wave height, 16 second period and ENE direction. Waves wrap around and up the slopes on either side of the shoal, converging at the crest.

steep edge of the shoal. HOOGENDOORN and DALRYMPLE (1986) reported that ridges migrate 50 m per year off Sable Island. BYRNES *et al.* (1999) note evidence for migrating shoals offshore Alabama through comparison of bathymetry from historic and recent hydrographic surveys. DUANE *et al.* (1972) reported that a ridge moved 3,600 m in 53 years (off Virginia coast) and that one moved 76 m during the Ash Wednesday storm of 1962 (off Delaware). SNEDDEN *et al.* (1999) propose an evolutionary model illustrated in Figure 4 that explains the onshore migration of shoals over the inner shelf (Class I features in depths less than about 20 m) and offshore migration over the middle shelf (Class II and III features depths greater than 20 m).

This new explanation of convergence for wave-dominated environments only works for one direction of wave attack. For example, SE waves would not have resulted in the same strong convergence of sand transport as shown in Figure 8. Therefore, strongest convergence is associated with a linear shoal orientation aligned in the same direction as dominant wave attack (roughly from the NE along much of the Atlantic coast and to the SE along the Alabama coast).

The approach proposed here provides a description of the processes of maintenance for linear shoal features in wave-dominated continental shelf environments. HUTHNANCE (1982) presented a maintenance process for tide-dominated environments. The HUTHNANCE approach relied on asymmetric tidal currents for the explanation of converging sand transport and asymmetric shoal cross-sections along the major axis. Most targeted sand mining areas on the OCS of the Atlantic and Gulf coasts of the US (see MICHEL *et al.,* 2001) are wave-dominated and the tides in these areas are mostly symmetric or only weakly asymmetric. The model of TROWBRIDGE (1995) applies to nearshore wave-dominated environments where currents generated by wave radiation stresses are strong and the presence of a shoreline promotes the transfer of momentum from waves to longshore currents. The fair-weather wave influence through Stokes Drift proposed by MCHONE (1973) and adopted by SNEDDEN *et al.* (1999) to explain the onshore migration of shoal features is replaced by this new approach. The new approach presented here relies on the non-linearity (asymmetry) of refracting and converging waves to maintain these features and does not require either a tidal or storm-generated current. This process occurs under both fair-weather and storm waves (contrary to the model of SNEDDEN *et al.,* 1999 and MCHONE, 1973) and therefore better explains why these features are aligned parallel to the direction of storm wave attack. It is likely that both steady currents (generated by tides, waves, or other influences) and non-linear orbital motion of waves have some degree of influence at all locations where sand ridges and linear shoals exist, as proposed by SNEDDEN *et al.* (1999), with the influence of waves diminishing with increasing water depth.

In summary, the action of waves converging over the crest

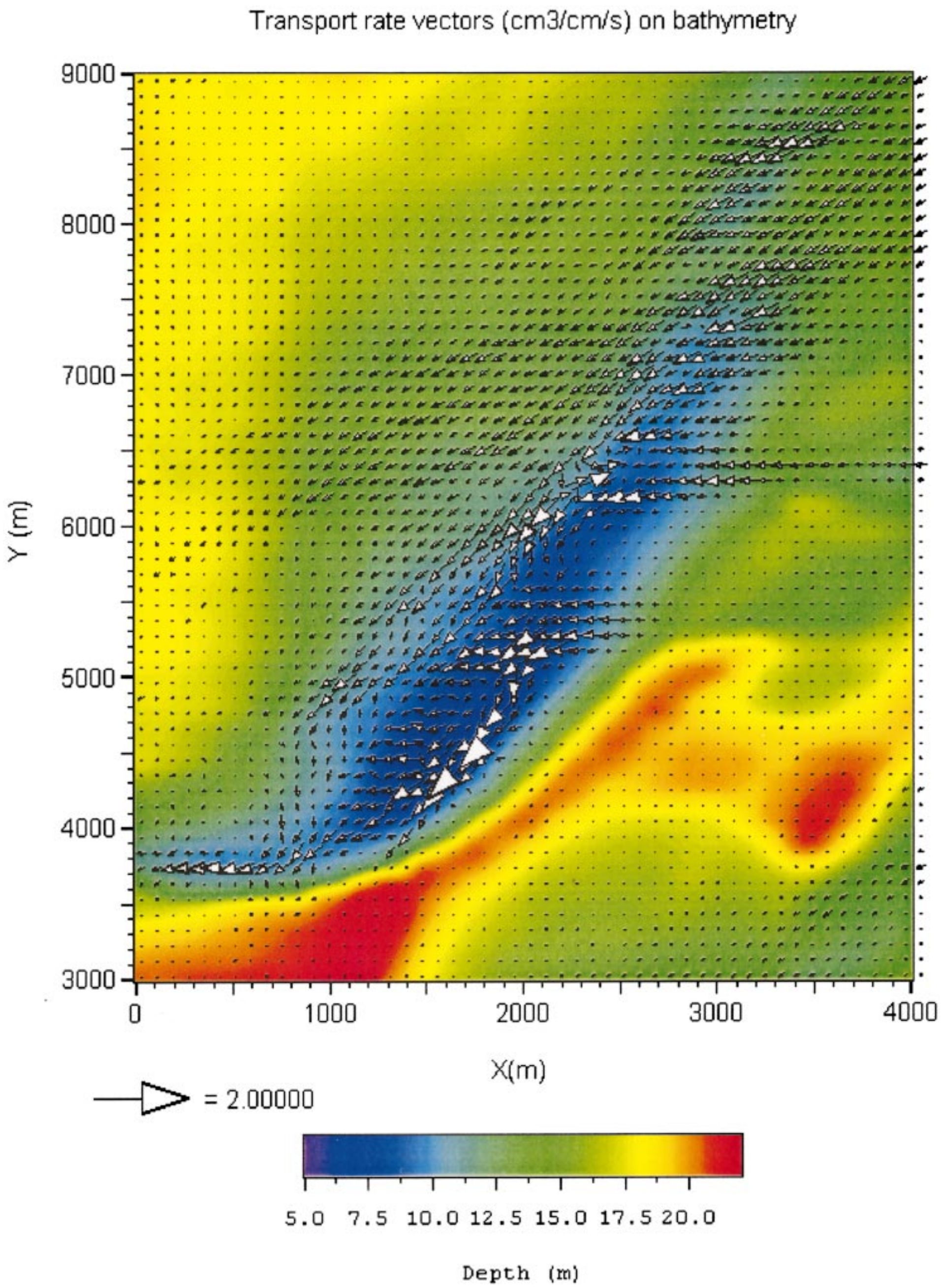

Figure 8. Time-averaged sand transport predictions for the steady and unsteady flows generated by the Boussinesq model over Fenwick Shoal for a significant wave height of 3 m, a wave period of 16 seconds, and ENE direction. A convergence of sand transport occurs along most of the crest of the shoal and there is net shoreward sand transport towards the steep flank of the shoal.

of the shoal leads to convergence of sand transport over the crest of the shoal. This process is driven by non-linear orbital velocities that feature a stronger, shorter shoreward flow under the crest of each wave. This process preferentially transports larger, heavier grains and may explain the presence of coarser sand on the crest and shoreward side of these features noted by STUBBLEFIELD *et al.* (1984) and others.

IMPACT OF DREDGING

One of the concerns during development of the monitoring protocols was the ability to determine whether there might be a limit beyond which the removal of sand from a ridge and swale feature would lead to the deflation or eventual disappearance of the bathymetric feature. For example, this may occur if the converging wave pattern is reduced in strength and importance, or if the depths are increased to the extent that the non-linear orbital velocities that generate the converging sand transport pattern are diminished or eliminated.

From a physical impact perspective, the disappearance or deflation of a shoal feature could have serious consequences. This outcome could result in dramatic change to wave patterns between the shoal and the shoreline. In turn, this could lead to a change in longshore and cross-shore sand transport patterns and changes in shoreline erosion and accretion rates. MICHEL *et al.* (2001) noted that important and unique biological characteristics were associated with the form and related texture of the shoals. These characteristics appear to provide a unique assembly of micro-habitats around the shoals. The literature review conducted into the ecological utilization of ridge and shoal features by fish species indicated that little is known or has been published on the subject.

Therefore, a better understanding is needed of the importance of the shoal form as habitat and the potential for these features to deflate or disappear in response to repeated dredging. The physical and biological protocols suggested by MICHEL *et al.* (2001) have been designed to help develop additional information on the biophysical interactions associated with the shoal form and surface texture and to monitor for long-term change to the form of the feature.

The methodology proposed here for investigating the maintenance of linear shoal and ridge features in wave-dominated environments, consisting of the application of a phase-resolving wave and hydrodynamic model with a two-dimensional sand transport model, should be applied to assess the change to the convergence of sand transport before and after the shoal is dredged. A fully spectral model (*i.e.,* in frequency and direction) could be applied in place of the phase-resolving model, provided that the two peaks of the directional spectra that develop over the crest of the shoal are considered independently in hydrodynamic calculations for non-linear orbital velocities. If only the dominant wave direction is considered (which in fact would be an average of two very different crossing wave directions), the convergence will be significantly understated or missed altogether. Additional investigation may yield a simpler method to identify the critical depth below which the features should not be dredged by linking this threshold depth to a depth where non-linear wave orbital motion no longer occurs on a frequent basis. For both the modeling and simpler approaches, a key to simplifying an evaluation of the potential for dredging to result in the deflation of a shoal will be to define a single representative wave condition for the wave climate, if possible.

It is recommended that additional research be undertaken through a combination of field measurements, physical and numerical models to improve and confirm the proposed mechanism for maintenance of linear shoals and ridges in wave-dominated environments, and to determine the relative role of tidal currents at locations where tidal currents are significant.

SUMMARY

No apparent consensus exists on the processes that work to maintain the shape of the ridge and swale shoal structures that represent the form of many identified OCS borrow sites. Theories for the maintenance of linear shoals have been developed for nearshore zones and tide-dominated offshore environments. The direct role of wave action (*i.e.,* aside from currents generated by storm or fair-weather waves) appears to have been entirely neglected in the literature. Sand transport in the direction of wave propagation driven by the nonlinearity of wave orbital velocities represents the most likely mechanism for maintenance of these features in wave-dominated environments on the OCS (*i.e.,* water depths less than 20 m). No direct references were found in the literature, however, the form of these sand body features may have an important influence on the structure and distribution of biological communities inhabiting them. Monitoring for changes to the form of the shoal, grain-size characteristics, and the related biological communities is essential. In addition, further development of the conceptual model for the maintenance of these features by wave-generated sand transport is recommended so that this can be applied before dredging projects are completed to assess how much sand can be removed from a shoal feature without disrupting the processes that maintain the feature.

LITERATURE CITED

BAGNOLD, R.A., 1956. The flow of cohesionless grains in fluids. *Philosophical Transactions of the Royal Society A,* 249, 235–297.

BOCZAR-KARAKIEWICZ, B. and BONA, J.L., 1986. Wave-dominated shelves: A model of sand ridge formation by progressive, infragravity waves. *In*: KNIGHT, R.J. and MCLEAN, J.R. (eds.), *Shelf Sands and Sandstones.* Calgary, Alberta: Canadian Society of Petroleum Geologists Memoir 11, pp. 163–179.

BYRNES, M.R.; HAMMER, R.M.; VITTOR, B.A.; RAMSEY, J.S.; SNYDER, D.B.; BOSMA, K.F.; WOOD, J.D.; THIBAUT, T.D., and PHILLIPS, N.W., 1999. *Environmental Survey of Identified Sand Resource Areas Offshore Alabama: Volume I: Main Text, Volume II: Appendices.* Herndon, Virginia: Minerals Management Service OCS Report MMS 99-0052, 326 pp. + 132 pp. appendices.

CASTON, V.N.D., 1972. Linear sand banks in the southern North Sea. *Sedimentology,* 18, 63–78.

DIBAJNIA, M.; MORIYA, T., and WATANABE, A., 2001. A representative wave model for estimation of nearshore local transport rate. *Coastal Engineering,* 43(1), 1–38.

DUANE, D.B.; FIELD, M.E.; MEISBURGER, E.P.; SWIFT, D.J.P., and WILLIAMS, S.J., 1972. Linear shoals on the Atlantic inner continental shelf, Florida to Long Island. *In*: SWIFT, D.J.P.; DUANE, D.B., and PILKEY, O.H. (eds.), *Shelf Sediment Transport: Process and Pattern.* Stroudsburg, Pennsylvania: Dowden, Hutchinson, and Ross, pp. 447–498.

GOFF, J.A.; SWIFT, D.J.P.; DUNCAN, C.S.; MAYA, L.A., and HUGHES-CLARKE, J.E., 1999. High-resolution swath sonar investigation of sand ridge, dune, and ribbon morphology in the offshore environment of the New Jersey margin. *Marine Geology,* 161, 307–337.

HOOGENDOORN, E.L. and DALRYMPLE, R.W., 1986. Morphology, lateral migration and internal structures of shoreface-connected sand ridges, Sable Island Bank, Nova Scotia, Canada. *Geology,* 14, 400–403.

HUTHNANCE, J.M., 1982. On one mechanism forming linear sand banks. *Estuarine and Marine Coastal Science,* 14, 79–99.

MCBRIDE, R.A.; ANDERSON, L.C.; TUDORAN, A., and ROBERTS, H.H., 1999. Holocene stratigraphic architecture of a sand-rich shelf and the origin of linear shoals: Northeastern Gulf of Mexico. *In*: BERGMAN, K.M. and SNEDDEN, J.W. (eds.), *Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation.* Tulsa, Oklahoma: SEPM (Society for Sedimentary Geologists) Special Publication No. 64, pp. 95–126.

MADSEN, P. A.; MURRAY, R., and SØRENSEN, O. R., 1991. A new form of the Boussinesq equations with improved linear dispersion characteristics (Part 1). *Coastal Engineering,* 15, 371–388.

MADSEN, P. A. and SØRENSEN, O. R., 1992. A new form of the Boussinesq equations with improved linear dispersion characteristics (Part 2): A slowly-varying bathymetry. *Coastal Engineering,* 18, 183–204.

MADSEN, P. A. and SØRENSEN, O. R., 1993. Bound Waves and Triad Interactions in Shallow Water. *Ocean Engineering,* 20 (4).

MCBRIDE, R.A. and MOSLOW, T.F., 1991. Origin, evolution, and distribution of shoreface sand ridges, Atlantic inner shelf, U.S.A. *Marine Geology,* 97, 57–85.

MCCLELLAND, C.E., 1973. New Jersey shelf near bottom current meter records and recent sediment activity. *Journal of Sedimentary Petrology,* 43 (2), 371–380.

MCHONE, J.F., JR. 1973. Morphologic time series from a submarine sand ridge on the southern Virginia coast. Norfolk, Virginia: Old Dominion University, M.S. thesis, 55 pp.

MICHEL, J.; NAIRN, J. R.; JOHNSON, J., and HARDIN, D., 2001. *Development and Design of Biological and Physical Monitoring Protocols to Evaluate the Long-term Impacts of Offshore Dredging Operations on the Marine Environment.* Herndon, Virginia: Minerals Management Service OCS Report MMS 2001-089, 116 pp. + appendices.

NAIRN, R.B., 1990. Prediction of Cross-Shore Sediment Transport and Beach Profile Evolution. Ph.D. Thesis. London, UK: Imperial College of Science and Technology, University of London, 391 p.

NAIRN, R.B. and SOUTHGATE, H.N., 1993. Deterministic profile modeling of nearshore, processes. Part 2, Sediment transport and beach profile development. *Coastal Engineering,* 19, 57–96.

NAIRN, R.; JOHNSON, J.A.; HARDIN, D., and MICHEL, J., 2002. Development and design of a biological and physical monitoring program for the evaluation of long-term impacts to the marine environment from offshore sand dredging operations in the U.S. Outer Continental Shelf. This volume.

PENLAND, S.; BOYD, R., and SUTER, J.R., 1988. Transgressive depositional systems of the Mississippi delta plain: A model for barrier shoreline and shelf sand development. *Journal of Sedimentary Petrology,* 58, 932–949.

RIGGS, S. R.; CLEARY, W. J., and SNYDER, S.W., 1995. Influence of inherited geologic framework on barrier shoreface morphology and dynamics. *Marine Geology,* 126, 213–234.

SNEDDEN, J.H.; KREISA, R.P.; TILLMAN, R.K.; CULVER, S.J., and SCHWELLER, W.J., 1999. An expanded model for modern shelf sand ridge genesis and evolution on the New Jersey Atlantic shelf. *In*: BERGMAN, K.M., and SNEDDEN, J.W. (eds.), *Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation.* Tulsa, Oklahoma: SEPM (Society for Sedimentary Geologists) Special Publication No. 64, pp. 147–164.

SNEDDEN, J.W. and DALRYMPLE, R.W., 1999. Modern shelf sand ridges: From historical perspective to a unified hydrodynamic and evolutionary model. *In*: BERGMAN, K.M., and SNEDDEN, J.W. (eds.), *Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation.* Tulsa, Oklahoma: SEPM (Society for Sedimentary Geologists) Special Publication No. 64, pp. 13–28.

SNEDDEN, J.W.; KREISA, R.D.; TILLMAN, R.W.; SCHWELLER, W.J.; CULVER, S.J., and WINN, R. D., 1994. Stratigraphy and genesis of a modern shoreface-attached sand ridge, Peahala Ridge, New Jersey. *Journal of Sedimentary Research,* B (64), 560–581.

STUBBLEFIELD, W.L.; MCGRAIL, D.W., and KERSEY, D.G., 1984. Recognition of transgressive and post-transgressive sand ridges on the New Jersey continental shelf—a reply. *In*: TILLMAN, R.W. and SIEMERS, C.T. (eds.), *Siliciclasitic Shelf Sediments.* Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists Special Publication No. 34, pp. 37–41.

SWIFT, D.J.P.; DUANE, D.B., and MCKINNEY, T.F., 1973. Ridge and swale topography of the middle Atlantic bight: Secular response to Holocene hydraulic regime. *Marine Geology,* 14, 1–43.

SWIFT, D.J.P. and FIELD, M.E., 1981. Evolution of a classic sand ridge field: Maryland Sector, North American inner shelf. *Sedimentology,* 28, 461–482.

TROWBRIDGE, J. H., 1995. A mechanism for the formation and maintenance of shore-oblique sand ridges on storm-dominated shelves. *Journal of Geophysical Research,* 15 August 1995, 16,071–16,086.

UCHUPI, E., 1968. *The Atlantic Continental Shelf and Slope of the United States (Physiography).* Washington, D.C.: U.S. Geological Survey Professional Paper 529-I, 30 p.

VIMS (VIRGINIA INSTITUTE OF MARINE SCIENCE), 2000. *Environmental Survey of Potential Resource Sites Offshore Delaware and Maryland.* Herndon, Virginia: Minerals Management Service OSC Study MMS 2000-055, 72 pp. + appendices.