

Chapter 2

Literature Review

This chapter contains a discussion of the major themes in this work -- sedimentary morphology (sand ridges, bedforms), sediment transport processes, and the relationship between sedimentary characteristics and side-scan sonar backscatter -- as they relate to similar published work and to the methods and data analyses used here to study the West Florida Shelf.

Shelf Sedimentary Morphology

Studies of the formation, maintenance, morphology, and stratigraphy of continental shelf sand bodies have been completed (Table 1) for the East China Sea (Yang and Sun, 1988); for the Bering Sea (Nelson et al. 1980); for areas in the North Sea (Huthnance, 1973, 1982a, 1982b; and McCave 1979); for the central Dutch coast (van de Meene et al., 1996); for the Belgian coast (de Maeyer and Wartel, 1988); for the northern Bahamas (Hine et al., 1981) ; for parts of the Atlantic coast of North America (Stubblefield et al., 1975, 1984; Swift and Field, 1981; Twichell, 1983; McBride and Moslow, 1991; Goff et al., 1999b, 2000); and for the west Florida gulf coast (Davis et al., 1993; Harrison, 1996; and Edwards, 1998). These investigations represented a variety of attempts to explain the origins and changing morphology of sandy bedforms by imaging the seafloor, by measuring and modeling hydrologic conditions, and by analyzing physical and mineralogic properties of sediments. The largest sedimentary features are most often referred to as ridges (Table 1), composed of smaller sand waves and containing a variety of smaller superimposed bedforms.

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Regions of parallel-oriented, relatively shallow water sand ridges occur all over the world on continental shelves (see Table 1). Theories of their origins vary from relict features resulting from transgression (Stubblefield et al., 1984; Yang and Sun, 1988) to topographically induced products of hydrologic sediment transport (Huthnance, 1982b). Swift et al. (1971, 1972), Stubblefield et al. (1984), and McBride and Moslow (1991) have proposed models explaining the formation of sand ridges as a function of Holocene sea-level rise, resulting in the detachment of barrier islands, island spits, and/or ebb tidal deltas. Key to the formulation of these models has been the study of the morphology and sedimentary characteristics of the sand bodies, including analyses of the present-day hydrologic conditions that modify their morphology.

A variety of tools have been utilized to analyze the characteristics of shallow water sand bodies. Carbonate sand bodies in the northern Bahamas were studied by Hine et al. (1981) (Table 1), using seismic profiling, bottom sampling, and aerial and space imagery. Sediment transport for sand banks on contrasting margins was inferred based on climatic factors and their interaction with tidal currents, as well as morphologic and sedimentary characteristics of the sand bodies. Net offbank transport, for example, was inferred along a leeward margin based on the migrating direction of sand waves superimposed on the larger sand body and from the composition of the carbonate sand (Hine et al., 1981). Although these sand bodies differ markedly in composition and morphology from those of other researchers summarized in Table 1, the methods used to determine sediment transport were similar those in other studies.

Nelson et al. (1980) used underwater cameras and side-scan sonar imagery over sand bodies in the Bering Sea (Table 1) to observe bedload movement and ripple migration. The most significant movements occurred during the lowest wave energy conditions, indicating dominance of tidal currents in determining observed sand body morphology (Nelson et al., 1980). Similarly, Twichell (1983) collected side-scan sonar imagery of sand

ridges on Little Georges Bank off the U.S. Atlantic coast (Table 1) and found bodies with asymmetrical morphologies that migrated with seasonal variations in climatic and hydrologic conditions. Twichell (1983) was unable to resolve the sand ridge morphology as a function of sediment transport, but found a spatial coherence in the direction of transport from sand ridge to sand ridge, indicating a response to specific hydrologic conditions.

In a series of studies, Huthnance (1973, 1982a, 1982b) mathematically modeled current flows that transport sands and govern the morphology of tide current-dominated sand ridges on the Norfolk Banks in the North Sea (Table 1). He found that tidal currents can be asymmetric due to shielding effects from sand body topography (Huthnance, 1973). As a result, sediment transport along the sand ridges is non-uniform, resulting in asymmetric sand ridge morphologies. McCave (1979), measuring currents in an area of the North Sea south of the Norfolk Banks (Table 1), hypothesized that more sand was transported in suspension on the decelerating phase of tidal currents, due to higher boundary layer shear stress, than the accelerating phase, again resulting in sand ridge asymmetry. Later, Huthnance (1982a, 1982b) further refined his bedform evolution model and explained that the steeper sides of asymmetric sand ridges obliquely faced the direction of net sediment transport, which he hypothesized to be the upslope, onto-bank component of the Norfolk Banks tidal currents. Bank heights were found to be proportional to spacing, with banks evolving to an equilibrium profile which is flat on top from wind-wave erosion and the inclination of tidal currents (Huthnance, 1982a). A critical component of the Huthnance model (1982b) was a seafloor "bump," or some other antecedent topographic feature, to provide initial sediment deposition perpendicular to the direction of tidal currents, in order for sand ridges to begin forming.

Jung et al. (1998), in their study of sedimentary features in the Yellow Sea, questioned the interpretation of all elongated, asymmetric sand ridges as being tidally

induced, noting that, stratigraphically, all the underlying materials may not be sands and thus do not fit the models predicting asymmetric sediment transport. They pointed to bathymetric control, stratigraphic differentiation, and variations in underlying sediment grain size and composition as factors which can interact both with tidal and wave-induced currents to produce the observed morphology.

Goff et al. (1999b) used a 95 KHz Simrad EM1000 sonar system (side-scan backscatter and multibeam bathymetry) to image sedimentary features on the New Jersey margin. They found that sand ridges on the northeast Atlantic shelf formed in the nearshore environment in response to storm driven flows. As transgression continued, sand ridges were transferred into an offshore hydrodynamic regime where storm currents were less influential and overall bottom currents were less constrained by coastal features. Goff et al. (1999b) found that the gross morphology of sand ridge features did not change beyond a water depth of ~20 m, and that ridge orientation mirrored bathymetric contours. Thus a combination of changing hydrologic conditions and antecedent topography produced the observed morphology.

Hydrologic conditions as modeled by Huthnance (1973, 1982a, 1982b) have been inferred by other researchers using physical sedimentary properties combined with spatial and temporal observations of sand ridge morphology. On the storm wave-dominated Maryland shelf of the United States, Swift and Field (1981) inferred the hydrologic conditions affecting the evolution of a region of sand ridges by studying side-scan sonar imagery and the distribution of sediment grain size. They found that grain size varied systematically with sand ridge topography, even at the maximum depths (30 m) of their study area. Swift and Field (1981) found coarsest sediments were located on the landward-facing flanks of sand ridges, indicating net erosion in the face of bottom flow currents, with the finest sediments on the seaward flanks. Sand waves and megaripples were absent where storm wave orbital velocities suppressed their formation (ridge crests or upper shoreface

sand ridges), but formed and persisted in troughs and the seaward flanks of lower shoreface sand ridges, indicating that storm wave surge relative to mean current flow decreased in importance with distance from shore (Swift and Field, 1981). Thus the grain size distribution and the bedstate of these sand ridges were direct functions of the hydrologic environment.

Studies similar to Swift and Field's (1981) were completed by de Maeyer and Wartel (1988) for sand ridges on the Belgian coast and by van de Meene et al. (1996) for the Dutch coast (Table 1). De Maeyer and Wartel (1988) were able to correlate grain size and sand ridge morphology, finding the largest average grain sizes on the seaward flanks of the Belgian sand ridges, inferring decreasing energy conditions from net sediment deposition on the landward flank. Van de Meene et al. (1996) found little correlation between grain size and ridge morphology on the Dutch coast, except for increased grain-size sorting at ridge crests and more wave-generated structures (megaripples) in the shoreward direction. Box core sections from sand ridges revealed low angle bedding and hummocky cross-stratification from wave action combined with high angle bedding from tidal current domination, with little spatial correlation of these structures over the area (van de Meene et al., 1996). In this case, the mixed hydrologic conditions did not provide a unique morphologic or sedimentary signature in the sand bodies, a result which has implications for identifying paleo-hydrologic conditions in the sedimentary record. However, no effort was made to assess temporal variations in surface characteristics that would explain the present hydrologic regime.

Stubblefield et al. (1975) also found sand body morphology and sedimentary characteristics were an admixture from varying hydrologic conditions on the New Jersey coast (Table 1). However, the authors discerned both spatial and temporal variations in grain size distribution and migration of bedforms, enabling them to hypothesize three stages of bottom energy activity which could produce these variations in the present time frame: 1)

fair weather circulation, with ridge activity mainly biogenic; 2) storms which fail to entrain the complete water column and/or water column stratification, where some fine sediments are winnowed from ridge crests to flanks and troughs; and 3) major storms where full water column entrainment results in scouring of trough sediments and the return of sands to the ridge flanks and crests. In addition, they later used the sedimentary and morphologic characteristics to propose a model of the origins of the features relating to Holocene sea-level transgression (Stubblefield et al., 1984).

Yang and Sun (1988) studied sand ridge morphology using shallow seismic profiling and sedimentary analysis in the East China Sea. Foraminiferal assemblages also were used to determine the conditions under which the sands were deposited, while current meter measurements were utilized to assess the present day hydrologic environment. Yang and Sun (1988) concluded that the East China Sea sand ridges were relict features of Holocene transgression, based on: 1) the weak tidal current environment, which they concluded was incapable of producing the present day observed morphology, and 2) the shallow water foraminifera found within the sand ridges, indicating sedimentary deposition at lower sea-level.

Finally, Berné et al. (1998) determined that there was no single model which could adequately explain subaqueous sand ridge formation. Rather, they proposed a spectrum of structures from entirely erosional to entirely constructional, corresponding to different combinations of sediment supply, sea-level change, and hydrodynamics (Table 1). The effects of these factors over time determined the observed morphology and underlying stratigraphy. Such an approach highlights the need to consider more than surficial morphology in interpreting the origins of sedimentary features.

Sedimentary Transport and Processes

The nearshore system is usually considered to be composed of two components: the fluid forcing and the sediment response (Holman, 1995). Observed patterns of Holocene sedimentation and morphology are, in part, a result of the physical processes of sediment transport (Woolfe et al., 1998). Both the processes and responses vary with location, water depth, sediment supply, and other factors which govern the hydrology of the nearshore system. The sediment response to forcing mechanisms results in morphologic characteristics of varying size scales, which change over time scales from seconds to centuries. These changes, in turn, produce feedback which affects the fluid forcing processes acting upon them (Holman, 1995). The overall patterns of sediment transport and deposition, over long time scales, shape rate of sedimentation on continental shelves and basins (Swift and Thorne, 1991). Wright (1995) used the term "morphodynamics" to describe the coupled suite of mutually interdependent hydrodynamic processes, seafloor morphologies, and sequences of change that occur in coastal systems (Figure 2). Studies of the geology of the coastal ocean often involve the interactions of two or more of these processes. Undertaken less frequently are studies which integrate a range of spatial or temporal scales of one or more processes. Moreover, understanding these hydrologic processes and resulting sedimentary morphology in the coastal ocean help provide modern analogs for interpretation of structures in the geologic record (Héquette and Hill, 1995).

Studies on Smaller Temporal and Spatial Scales. Sediment response can be examined at the small-scale level (grain by grain movement responding to fluid shear stress) and the large-scale level (morphology) (Holman, 1995). Holman (1995) implies that, although it is assumed that large-scale models are simply the integral of the small-scale behavior, this assumption is not well tested. Indeed, Larson and Kraus (1995) concluded that even though calculations of coastal sediment transport at different scales can be related

Figure 2

and reconciled, mega-scale transport is not just an integration of calculations at smaller scales. Nevertheless, understanding processes at small spatial and temporal scales is necessary to interpret both larger-scale morphology and small-scale features, especially in the geologic record where processes must be inferred from observed structures.

Clifton (1976) devised a conceptual model for explaining observed sedimentary structures (bedforms) in terms of near-bottom wave orbital velocities, velocity asymmetry, median sediment grain size, and wave period. Combinations of these parameters produced results of no sediment movement, symmetric bedforms, asymmetric bedforms, or a flat bed (sheet flow) (Clifton, 1976). Later, Grant and Madsen (1979) developed an analytical theory to describe the combined motion of waves and currents in the vicinity of a rough bottom, in terms of the associated shear stress, which was a more specific measure of the force necessary to initiate sediment movement. At the time, though, there was a lack of empirical data against which to test the theory. Later researchers were able to compare their field measurements against Grant and Madsen's (1979) model.

Drake and Cacchione (1992), Drake et al. (1992), and Gross et al. (1992), working with similar data sets from different water depths on the northern California shelf, used empirical data to calculate shear stress/velocity and bed roughness from grain size and current velocity measurements and compared them with predicted values from the Grant and Madsen (1979) model. They all found that sediment transport, explained in terms of initiation of movement when critical shear stresses are obtained, were sensitive to assumed parameters and constants, such as drag coefficients. Such parameters can vary spatially over small areas, depending on the homogeneity of sediments and the consistency of the forcing mechanisms acting on the sediments.

Thus, while able to verify Grant and Madsen's (1979) original relationships between grain size, shear stress, and sediment movement, Drake and Cacchione (1992), Drake et al. (1992), and Gross et al. (1992) found that the results were sensitive to the conditions in

different environments, making it difficult to extrapolate the results from one area over a larger area or over a large range of water depths. Li (1994) investigated this with direct skin friction measurements over movable ripples, attempting to determine the effects of form drag and flow stress partitioning on shear velocities. Li (1994) found that higher and longer ripples produced stronger form drag and higher total shear velocities for a given mean velocity, but produced lower skin friction shear velocity, estimated from empirical regressions. These results added to the developing knowledge that variations in sedimentary bedforms can create varying feedback mechanisms that affect near-bed currents and their interactions with sediment particles.

Explanations of small-scale changes in morphology (e.g., changes in bed elevation or the formation of certain bedforms) in terms of sediment transport were developed from the modeling of the critical factors determining initiation of sediment movement. Cacchione et al. (1995) measured changes in bed elevation that resulted from sediment transport/deposition, observing suspended sediment concentrations in the bottom boundary layer as well as current velocities and wave data. They estimated shear velocity from the hydrologic data. They noted that shear velocity is determined by the combined flows of waves and currents that interact non-linearly to produce sediment suspension and transport. This was used to explain bed elevation changes over the study period (Cacchione et al., 1995).

Amos et al. (1996) used similar data to explain observed hummocky cross-stratification after winter storms on the outer-Scotian shelf, calculating and comparing the wave and current Shields parameters as measures of the range of velocities and sediment grain sizes over which movement would take place. They found that near-bed wave motion during deposition events exceeded steady currents by an order of magnitude and was the dominant factor in determining the hummocky bedforms observed (Amos et al., 1996). Li and Amos (1999) also observed that such bedforms formed under wave-dominant

combined flows and over a range of sediment grain sizes. Lund-Hansen et al. (1999) also compared wave and mean current shear stresses (calculated from measured current velocities and drag and friction coefficients) to determine the mechanism dominating vertical sediment fluxes during periods of increased surface wave activity in a shallow lagoon. Wave induced resuspension of sediment dominated. However, Vincent et al. (1998) found that sand resuspension was mainly due to waves while transport was dominated by a few hours when large waves coincided with peak flood currents.

Thus the observations of hydrologic and geologic data over limited spatial and temporal scales have been used to explain small scale geomorphology and to model sediment transport processes which are responsible for observed sedimentary features. The variations over small spatial scales combine to produce the larger scale sedimentary morphology in the marine environment. It is critical to develop successful integrations of these smaller scale observations to explain and predict on larger spatial and longer temporal scales.

Studies on Greater Spatial and Temporal Scales. Larger scale models of sediment transport are not as concentrated on the physics of sediment grain movement or on small bedforms. Rather, these studies are more directed toward regional sediment budgets, coastal region behavior over periods of years or longer, and long term sedimentation rates on continental shelves or in basins which can be correlated with meso- and mega-scale observations from the geologic record. Swift et al. (1972) documented the models and processes by which their concept of the *palimpsest* shelf (central and southern Atlantic shelf) could be illustrated, including several models explaining formation of various types of sand bodies. While these were not all based on their own empirical research, they were able to synthesize concepts of shelf sedimentary processes in order achieve an overall empirical model of their observations (Swift et al., 1972).

Gadd et al. (1978) developed a regional description of the New York shelf and of the near-bottom current velocity field, from their data, combined with empirical transport formulae from theoretical researchers. Maps of sediment transport superimposed over grain size distribution data, and the empirical formulae, allowed them to transform current velocity readings into a sediment transport rate. Such an approach ignored small scale variations in favor of an aggregate result. Kana (1995) used a similar approach, compiling the transport rates of 25 different coastal cells around Long Island, New York, to formulate a coastal sedimentary budget. Byrnes and Hiland (1995) quantified large-scale sediment transport patterns from St. Andrews Sound, Georgia to Nassau Sound, Florida, using historical records to evaluate long-term coastal change within the framework of a sediment budget.

Similarly, McBride et al. (1995) produced a geomorphic response-type model for barrier coastlines, based on quantitative documentation of historical changes in shoreline positions. They established eight classifications for large scale changes (lateral movement, advance, dynamic equilibrium, retreat, in-place narrowing, landward rollover, breakup, and rotational instability), over spatial scales of 10-100 km, noting that shoreline response was heavily influenced by sediment supply (McBride et al., 1995).

Beyond sedimentary budgets, other researchers have tried to explain changes in the morphology of coastal environments through aggregate models involving sediment transport. Cowell et al. (1995), in their study of the southeastern Australia coast and shelf, applied a large scale model of coastal behavior to explain morphologies observed from post-glacial transgression. They stressed the importance of small residual sand movements that have accumulated through time to create large scale changes, noting that the measure of a model's success is its ability to reproduce observed features in nature.

A more quantitative approach to large scale modeling has been taken by Green et al. (1988) and Wright et al. (1991) using similar data sets from the Middle Atlantic Bight. The

Green et al. (1988) model calculates a time averaged sedimentary transport rate from empirical data (current velocity, bed slope, settling velocity, fluid density), testing the theoretical links between the properties of the velocity distribution and sediment transport. Though the model failed in some respects (e.g., as an indicator of bed response under storm conditions), it was able to predict sediment transport rates under a variety of conditions (Green et al., 1988). Wright et al. (1991) extended this model in an attempt to identify the modes, directions, relative rates, and causes of shore-normal sediment flux over the shoreface in response to different energy conditions. They found that the flux varied temporally in ways that were only partly predictable, but concluded that, based on their data, a common storm can transport more sediment offshore in an hour than fair weather processes can move onshore in two or more days.

Large scale modeling efforts, then, have had relative success in using aspects of sediment transport to explain morphologic change. Integrating data from different scales to make larger scale predictions in sedimentary morphology, and the pitfalls of such efforts, has also been researched and is discussed next.

Data and Models Over Different Scales. Almagor and Karnieli (1996), in using an analysis of clay microfabric to infer sediment transport, noted that better methods were needed for correlating micro-scale and macro-scale sedimentary structures and for interpreting morphologic origins of structures from micro-scale data. The problem of integrating data from different scales, and of making interpretations at one scale from data of another, has been specifically addressed by Larson and Kraus (1995). They found that coastal sediment transport data from different scales -- micro-, meso-, macro-, and mega-scale -- can be related and reconciled if limitations in prediction are recognized from initial boundary conditions and the fluid forcing mechanisms.

Quantitative approaches at different scales are not necessarily contradictory in their results; however, mega-scale calculations are not just an integration of calculations at smaller scales (Larson and Kraus, 1995). However, Cowell et al. (1995) may have been guilty of that assumption in their attempt to model large-scale changes in coastal morphology as a function of small-scale residual sand movements over time. The feedback mechanisms from small scale movements, which can either enhance or diminish the sum total of all such movements, cannot always be included in time-scale integrative models. These feedback mechanisms are, however, critical to modeling any morphodynamic system (Wright, 1995). The time averaging in the model of Green et al. (1988) made it more accurate in predicting sediment movement over longer time scales but caused it to fail in predicting transport associated with individual high current velocity events (storms). Kana (1995) was able to successfully create a meso-scale sedimentary budget from aggregating transport rates of 25 coastal cells. However, such an aggregation can work because the details of the results of sediment transport -- bedforms, distribution, etc. -- become moot in a budgetary process. The goals of determining "sediment in" and "sediment out" override any need to extract intermediate data in the process.

Thorne et al. (1991) recognized the limitation of their analytical approach to identifying storm bed formation and preservation in the shallow marine environment. Storm bed thickness was approximated as a power function of storm return period, wave climate, water depth, and grain size distribution. However, the limiting assumption that the bed response to an extreme storm event was independent of the history of preceding smaller events, in effect having the larger event erasing the record of all previous smaller events, caused the model to make erroneous predictions for bed sedimentary bed thickness. The model also was inaccurate for sediment-starved environments because of the dependence of several variables on the rate of accumulation, which may approach zero over a large area but be highly variable over smaller spatial scales (Thorne et al., 1991). Recognizing the

limitation, however, leaves room for later refinements which can account for geologic feedback in sediment transport processes.

The SEDTRANS92 computer model of Li and Amos (1995) derived bottom shear stresses and calculated sediment transport rates for given grain sizes by applying combined wave-current bottom boundary layer theories. They found that the results of their model compared favorably to field measurements. Such a model, which uses seven different algorithms for computation, has promising potential to predict aggregate effects of small-scale sediment transport events over a larger area. Likewise, time series of multibeam bathymetric data has been cited as a new technique for quantitative estimation of sediment transport rates in large scale sediment waves (Hughes-Clark et al., 1996). It remains to be seen whether these time series will be effective over long time scales or whether the long term and short term data are reconcilable.

Applications of Sediment Transport Research. Scientists continue to study the shallow marine sedimentary environment to understand its connection with nearshore and beach processes, which affect areas of high socioeconomic impact such as barrier islands. New techniques in sediment transport research deal directly with the movement of sands in beach and ridge environments. For example, Olmez et al. (1994) have developed a particle-labeling technique, using metals such as Au and Ag, which can be detected at ng/g levels, to identify sediments and track their movement. In this way, lateral beach and sand ridge movements can be quantified in terms of speed, direction, and quantity (Olmez et al., 1994). Sediment transport modeling and tracking can also be used in other environments, such as for monitoring deep-ocean dump sites, where hazardous materials, such as low level radioactive soils, are being stored (Bonner et al., 1992). Monitoring of these sites over time and determining the magnitude and direction of material transport is important in preventing hazards to human populations which may be nearby.

Relationship Between Sedimentary Properties and Sonar Backscatter

Monitoring and prediction of sedimentary morphology and movement can be aided through the use of side-scan sonar imaging. The acoustic backscatter signal from side-scan is particularly suited to detecting sediment cover on the seafloor, providing a graphic image that can be interpreted with the aid of sampling. However, deeper analysis is necessary to determine sediment properties and characteristics from the side-scan signal without the benefit of concurrent sediment samples. Many researchers have undertaken studies of the geotechnical and geoacoustic properties of various sedimentary types to establish relationships that can be used to interpret remotely sensed data. Still others have drawn direct correlations between side-scan data (in the form of the signal power spectrum or a proxy thereof) and sedimentary properties, to construct empirical models for interpreting side-scan data. The most advanced research is in the attempt to create sediment classification models which can be applied to acoustic data as it is returned, enabling the creation of image maps which also provide data on sedimentary properties.

Geotechnical and Geoacoustic Properties of Sediments. Acoustic remote sensing of the characteristics of sedimentary environments is dependent upon the variations in the return signal that result from differences in and between the properties of sediments and substrates (Blondel and Murton, 1997). Geoacoustic properties (e.g., compressional wave velocity) and geotechnical properties (e.g., specific gravity, water content, void ratio) define the way sound is reflected, refracted, and attenuated through rocks and sediments (Talbot et al., 1994; Muthukrishniah et al., 1995). Investigation of these properties in relation to acoustic signals has provided the basis for empirical models for classifying sediments based on acoustic returns.

Talbot et al. (1994) were able to relate one geotechnical property, void index (a function of sediment structure), to differences in acoustic signature to identify sedimentary successions, and used those results to model depositional history of sediments. Their geotechnical profiles contained the record of the history of accumulation, compression, and fabric adjustment undergone during and after deposition (Talbot et al., 1994). Stoll et al. (1994) designed three tools (a torsional shear-wave generator, a 22-caliber vertical seismic pulse generator, and a cone penetrometer) to measure geoacoustical and geotechnical properties (shear wave velocity and shear strength) *in situ* to provide data on these properties without having to sample.

In laboratory experiments, Cisneros et al. (1995) developed a 1-D wave propagation model by measuring the acoustic properties of natural sediments to get the acoustic signature of their mechanical properties. They successfully identified wave amplitudes and phase characteristics for a water layer and a silty-clay layer; however they found that their model was not effective in sandy sediments (Cisneros et al., 1995). This difficulty with sands was also experienced by Muthukrishniah et al. (1995) in their study of the acoustical, electrical, and geotechnical properties of sediments. By measuring and predicting permeability of sediments (using a consolidometer and the Biot-Stoll acoustic model, respectively) Muthukrishniah et al. (1995) were able to correlate velocity and physical sedimentary properties for site-specific samples of clays. However, like Cisneros et al. (1995), they found that it was difficult to successfully test sandy sediments using their methods because of the lack of homogeneity in sands compared to clays. Others, most notably LeBlanc et al. (1992), DeBruin (1995), and Panda et al. (1994), have had more success using impedance inversion to relate geoacoustic and geotechnical properties of sands to acoustic signature.

Quantifying the Relationship of Sonar Backscatter and Sediment Properties.

Building on the use of geotechnical and geoacoustic properties and their relationship to acoustic signature, researchers using side-scan sonar systems have attempted to quantify the relationship between sediment properties and sonar acoustic backscatter in order to enhance interpretation of side-scan images. This interpretation has required extensive ground-truthing of ensonified sediments to establish these relationships (Goff et al., 1999a), and to find ways to quantify the side-scan signal, or a proxy thereof.

Davis et al. (1996) hypothesized that spatial trends in backscatter strength should correspond to changes in the texture and microtopography of the sediments. They reasoned that backscatter strength is a function of grain size, volume scattering (a relative measure of the scattering strength of a given volume of sediment (LeBlanc et al., 1995)), and bottom roughness (which affects surface scattering, especially at scales comparable to the sonar's wavelength (Blondel and Murton, 1997)), all of which are related to sediment texture and microtopography. They quantitatively examined first order relationships between surficial sediment properties and side-scan sonar data. Their results suggested that sediment grain size was the dominant variable controlling backscatter strength, with carbonate content and roughness also contributing, but that other factors must account for variability not explained by these properties. The variability of backscatter strength associated with fine sands was nearly twice that associated with medium and coarse sands, due in part to the sporadic occurrence of lag shell material or bedforms in fine sand areas (Davis et al., 1996). Carbonate content was strongly related to backscatter strength because of its relationship to large grain size and the more reflective shape (flat surfaces, angular shape) of carbonates compared to siliciclastics.

The relationship between grain size (and carbonate content) and acoustic backscatter strength has been confirmed by other researchers (Ryan and Flood, 1996; Goff et al., 1999a, 2000). However, it is neither a linear nor consistent relationship. Goff et al. (1999a)

found that the observed correlation between grain size and backscatter can be degraded if the sediments included even a few extra weight percent of the largest grain sizes (> 4 mm). Further, the best correlations occurred with sediments which were well sorted and unimodal in distribution (Goff et al., 1999a). Ryan and Flood (1996) found a poor correlation between image pixel values and the percent gravel content or percent sand content of sediments because of the non-linear relationship between grain size expressed in terms of % gravel or % sand and actual sediment size. Thus, while there is a strong correlation between backscatter strength and grain size, the relationship is not always consistent and other factors influence the side-scan signature.

Ryan and Flood (1996), Gao et al. (1998), and Goff et al. (2000) all used the relationships between grain size and backscatter to develop models from which at least some sedimentary characteristics could be predicted from the side-scan signal or signal proxy. Goff et al. (2000) graphically compared the backscatter intensity in decibels (dB) with grain size and bathymetric data in areas of the New Jersey margin to establish a qualitative relationship, by plotting grain size vs. signal strength in dB. The trend of a linear regression line fit the data, but was suspect because most of the data were grouped at low signal strength and fine sediment grain sizes, while only a few outlying points at coarser mean grain sizes and higher backscatter really determined the slope of the line. Their conclusion that backscatter response in their samples was dominated by the largest grain sizes was somewhat premature, as sorting, carbonate content, and other factors were not taken into consideration.

Ryan and Flood (1996) used the side-scan backscatter power spectrum and textural analysis involving gray level co-occurrence matrices and the fractal properties of neighboring pixels to relate sediment properties and the side-scan signal. Multiplication of pixel values (a proxy for the backscatter signal) between two images at different frequencies established a two-level image of well-defined light and dark regions. Sediment sampling

properties were compared to average pixel values from 3 m and 15 m diameter areas centered around each sample site. Principal component analysis was used on the dual frequency data, producing three combinations of the sonar images that accounted for 99.1% of the data variance (Ryan and Flood, 1996). They noted that subsurface interfaces affecting lower frequency signals, or unquantified characteristics such as changing bottom slope, could have impacted variations in the image values.

Gao et al. (1998) developed a technique for interpreting Deep-Tow side-scan images using a gray level co-occurrence matrix, to extract texture attributes from backscatter images, and Fourier fractal analysis, a power law relationship between power spectral density and frequency after a two-dimensional discrete Fourier transform. Point relational statistics were used to emphasize the spatial relationships between the gray value of a pixel (a direct proxy for backscatter intensity) and those of nearby pixels. This technique was successful for Deep-Tow side-scan, with a frequency of 110 kHz and image pixel sizes of 1 m x 1 m which were aggregated into larger aggregated texels (Gao et al., 1998). It is uncertain whether this technique would exhibit equal success with the increased signal variability added with higher frequency side-scan (lower signal to noise ratio, higher surface and volume scattering) and higher resolution images (smaller pixel size).

Recent efforts to develop real-time sediment classification maps from sonar data have been attempted using chirp systems. LeBlanc et al. (1992) developed an empirical equation which equated relaxation time (of ensonified grains) to grain size, as a first step towards direct recognition of sediment properties from acoustic backscatter. Panda et al. (1994), using chirp sub-bottom profiles, used impedance and attenuation to relate sediment properties and acoustic properties for a given depositional environment for predicting sub-bottom sediments. LeBlanc et al. (1995) concentrated on volume scattering (both coherent, as from a sediment boundary, and incoherent) in studying the relationship of backscatter and sediment characteristics. They found that sediments with large grain components

produced larger volume scattering coefficients (a measure of the scattering strength of a cubic meter of sediment), and that sub-bottom volume scattering measurements, when combined with side-scan surface scattering measurements, will be useful in extrapolating seafloor sediment predictions over very large areas.

Summary. The relationships between sedimentary properties and side-scan sonar backscatter, while not always clear-cut, are nevertheless quantifiable. Heterogeneity appears to be one obstacle, in that the consistency of relationships in the models discussed above is often unique to only a small area or specific sediment type. It is important, then, that these relationships be explored further in as many sedimentary environments as possible, so that more comprehensive models, rather than site-specific empirical ones, can be developed.

The next section discusses the need for additional investigation on the West Florida Shelf in the context of research both in side-scan modeling of sedimentary properties, as well as with the study of sediment transport and morphology in this area.

The Need for Further Study on the West Florida Shelf.

Studies of different regions of the West Florida Shelf have been completed recently by Twichell et al. (1996), Harrison (1996), Edwards (1998), and Donahue (1999), using sedimentary analyses and side-scan and seismic sonar to study the morphology and characteristics of sedimentary cover in the nearshore to midshelf regions of Florida's gulf coast. Though aggregated as a single sedimentary province by Davis et al. (1992), west Florida's barrier island coast appears to vary in its sedimentary morphology, and relationships between the varying areas within the region are not yet clear.

Subaqueous Sand Ridges on the West Florida Shelf. Davis et al. (1993), Twichell et al. (1996), Harrison (1996), and Edwards (1998) have examined parallel sand ridges on the

west Florida gulf coast. Davis et al. (1993) examined sand bodies in an area near Cape Romano on the southwest Florida gulf coast. They used 24-hour current meter readings to describe the hydrologic conditions, in addition to analyzing sediment grain size, vibracore sections, and 100 kHz side-scan sonar imagery. The sand bodies were found to be remarkably similar to those in the North Sea (Huthnance, 1973, 1982a, 1982b; McCave, 1979), except for their location in shallower water. All factors indicated formation and maintenance by the dominant tidal currents, with bedforms such as sand waves and ripples plainly showing tidal current direction across the sand ridges. Grain size distribution was predictable and spatially consistent, with coarsest grain sizes on stoss flanks and finer grain sizes on lee flanks (Davis et al., 1993). Very little wave influence was observed.

Twichell et al. (1996) examined the surficial geology of the inner shelf west of Sarasota, Florida (Figure 1). Bathymetric data revealed several discontinuous, low-relief ridges on the flat offshore part of their study area. They were oriented NE-SW slightly oblique to the shoreline, 1.5-3.0 m high, 1-2 km wide, in discontinuous segments 1-4 km long. Sub-bottom profiles indicated that bedrock control was not a factor in the location or morphology of these ridges. A complex and highly variable set of acoustic patterns on this inner shelf area identified three distinctive facies. Two acoustic patterns were associated with the ridges, one, a low backscatter return on the southeastern ridge flanks, and another, a high backscatter return on the northwestern flanks. A third high backscatter acoustic facies was associated with the intervening troughs. Fine-grained sediments correlated with the low backscatter areas and coarse sediments with the high backscatter (Twichell et al., 1996).

More recently, Harrison (1996) and Edwards (1998) studied a field of sand ridges located west of Pinellas County, Florida (see Figures 3 and 4). These sand bodies, oriented approximately NW-SE, oblique to the shoreline, and overlying Miocene limestone bedrock, displayed a trend toward increasing spacing and thickness with distance from shore (Harrison, 1996). Harrison (1996) completed a series of 100 kHz side-scan sonar surveys

Figure 3

Figure 4

over the area, as well as analyses of sedimentary characteristics, vibracore and seismic stratigraphy, and current meter data. From these data and SCUBA diver observations, Harrison (1996) identified a hierarchy of bedforms associated with the sand ridges. First order bedforms, the sand ridges themselves, were characterized as 1-2 km in wavelength. Second order bedforms, obliquely overlying the base sand ridges, had wavelengths of 40-300 m. Third order bedforms, at a variety of orientations to the second order bedforms, had wavelengths of 10-40 m. Fourth order bedforms, within current lineations superimposed on the sand ridges, had wavelengths of <10 m (Harrison, 1996). Fourth order bedforms were resolvable using the 100 kHz side-scan, but only on individual records. These features disappeared when all side-scan records were merged into a mosaic. Sonar mosaics were created from surveys completed eight months apart, which provided an opportunity to observe temporal variations in the bedform hierarchy. Some sand ridge migration was observed, but Harrison (1996) was unable to assess the significance of the shifts observed with regard to bottom flow.

Grain size distribution from one sampling transect showed coarser grain sizes on the southwest flanks and finer grain sizes on the northeast (Harrison, 1996). This distribution did not correlate well with the limited current meter data, which indicated symmetrical ebb and flood currents in a roughly NNE-SSW orientation (Harrison, 1996). Coarse grain size has been associated with stoss flanks (Swift and Field, 1981; de Maeyer and Wartel, 1988). Thus in Harrison's (1996) study area, there were indications of sediment transport under conditions other than tidal current dominance. However, additional current meter data, as well as more rigorous sediment sampling, are necessary to fully understand the hydrologic conditions regulating sediment transport in this area.

Hydrologic Conditions. The shelf surface is subjected to complex and varying hydraulic conditions over short time periods (Swift and Thorne, 1991). The relative

contributions made by different transport mechanisms vary spatially and temporally (Wright et al., 1991). Combined flow from tidal currents and storm waves has a significant effect on shelf sedimentation processes (Snedden et al., 1988; van de Meene, 1996). Despite recording the effects of two storm events, Harrison's (1996) current meter data were collected over only 28 days during a period of low wave energy for the Pinellas County coastal region (September/October 1995). Data need to be collected for longer time periods to assess the full range of hydrologic conditions on the Pinellas County inner shelf, as well as the temporal variations and effects of combined flow.

Geographic Extent of the Sand Ridges. The extent of the sand ridges west of Harrison's (1996) study area are not known. Harrison found increased size and spacing of sand ridges with increasing water depth within his study area. Therefore, it would be valuable to determine the extent of the sand ridge field to assess whether changes in morphology continue throughout the region. In addition, Harrison (1996) found that processing and mapping 100 kHz side-scan sonar data degraded image resolution such that smaller scale features were no longer resolvable. Higher frequency side-scan is now available in the form of 500 kHz sonar which, theoretically, has the ability to resolve features at a finer scale than 100 kHz. Mapping with this higher frequency sonar may allow resolution of the fourth order bedforms identified by Harrison (1996).

Sedimentary Characteristics of the Sand Ridges. Harrison's (1996) sediment study was limited to grain size and mineralogic analyses from one transect across a sand body for one time period. Samples from a series of transects across a sand body would show spatial variations in grain size and mineralogy within it. A similar set of transect samples in a second area, for example from a sand ridge in deeper water, would show any spatial variation between the two sand ridges, from which variations in their respective hydrologic

environments could be inferred. Finally, a time series of these samples would reveal short term variations in grain size distribution and mineralogy, that, with the hydrologic data collected, would indicate sedimentary responses to temporal variations in the hydrologic setting.

Summary

Studies of the sand bodies on the West Florida Shelf have generated many new questions concerning their origin and the modern-day processes which affect them. The geographic extent of the sand ridge field is not yet known, nor are the extent and variation of its sedimentary, morphologic, and acoustic characteristics. Comprehensive hydrologic data for the inner shelf are lacking. Thus, attempts to explain the formation and maintenance of the sand bodies in light of sediment transport have been incomplete. This study builds upon the literature discussed above by attempting to ascertain the variations, on both spatial and temporal scales, in what has been initially perceived as a homogeneous group of features on the West Florida Shelf.

